TRANSPORTATION DECISION-MAKING: COMPARISON OF HIERARCHICAL TREE AND REASONING MAP STRUCTURES

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ABSTRACT

Planning and decision-making of urban transportation systems is a multi-disciplinary process, which requires the consideration of a set of performances and the needs of diverse group of stakeholders. Different stakeholders have different perspectives and, as a result, they advocate conflicting goals and objectives. Traditional decision-making approaches model the decision systems under a hierarchical tree structure and evaluate the composite performance of individual alternatives using weighting schemes. However, such approaches may not reasonably replicate decision-makers' minds and may cause considerable controversy and difficulty to justify the decision to the public. This paper proposes a reasoning map for structuring professional planning work, public participation in planning, and helping find the preferred transportation alternative for a complex transport problem. This mapping can efficiently model how experts, analysts, and the public perceive and reason about transportation alternatives to achieve the project goals. It presents the interactions and causal relations between the characteristics of each alternative and its consequences and impacts. Each transportation alternative is evaluated by the degree of belief by which it achieves the project's goals. The capabilities of the proposed reasoning map structure are compared with the hierarchical tree structure through an analysis of transit alternatives proposed as a circulator transit system for a large commercial development in the U.S. The paper examines the characteristics of the methods and discusses their benefits and limitations.

Keywords: Transportation Planning, Decision-making, Transit mode selection, Reasoning Map

1. INTRODUCTION

> *"I have been very struck by the paradox in the culture of government lawyers* [planners], *which is that the less certain the law* [future plan] *is, the more certain their views become."* [1]

Planning and decision-making of urban transportation systems is a multi-disciplinary process governed by laws in most countries. It requires the consideration of a comprehensive set of impacts on the society and the needs of a diverse group of stakeholders who are motivated by different purposes served by the transportation system. Different stakeholders have different perspectives and, as a result, they advocate achievement of conflicting goals and objectives. Transportation decision-making is therefore complicated because it must satisfy different groups of people with a wide range of views about benefits and needs, and about paying for its costs.

In the past several decades planners and analysts of transportation project development have supplemented benefit-cost analyses (BCA) with multi-criteria decision-making methods (MCDM) in different planning stages (e.g. alternatives screening, alternatives analysis, and project evaluation) and different decision problems (e.g. route selection, mode selection, and facility location (UMTA, 1990; Zak, 2005; Zak and Fierel, 2007; Bruun, 2007; FTA, 2009). Various numerical and analytical MCDM methods have been available to transportation planners and have become even more influential and accepted than benefit-cost analyses. The purpose of these MCDM methods is to find the transportation alternative that would satisfy several criteria and best meet a wide variety of objectives.

Most MCDM methods decompose the decision-making system into many subsystems (or elements). They require experts and analysts to assess each subsystem on several qualitative and quantitative measures, and finally combine those measures into a single value through certain procedures and assumptions (Triantaphyllou, 2000). They simplify the structure of the problem, and sometimes reduce the evaluation process into a "black box" where the inputs and the relations between inputs and outputs are not fully presented. This can cause considerable controversy and difficulty to justify the decision when presenting it to the public.

This paper proposes a new method for supporting decision-making that improves rationality and transparency in planning process. The paper is organized as follows. First, the current transportation decision-making methods and their issues are discussed. Second, the proposed methodology is presented. Finally, the paper compares the proposed method with the current method through a case study in the selection of a transit mode circulator in a large commercial development.

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[1] Jack Straw, a British Labour Party politician, in a letter to Lord Goldsmith quoted by John Barrow (2012). [Inserts in the parentheses by the authors].

2. CURRENT TRANSPORTATION DECISION-MAKING METHODS

Although several versions of MCDM methods are available in the literature, the most widely applied method in transportation decision-making problems is the weighting and linear scoring method (numerous references, e.g. Bruun 2007, Saaty 2005 for Analytic Hierarchy Process-AHP, Zak, 2005). The U.S. Federal Transit Administration has applied the weighting and scoring method to evaluate the FTA *New Starts* projects in financing recommendations. (FTA, 2011, 2012) This traditional method uses a hierarchical tree structure, which classifies the elements of a public transportation system into various levels. The method requires experts to rate the potential performances of each transport alternative according to a set of criteria by either linguistic terms (e.g. low, medium, high) or numerical scores (e.g. 1 to 5.) The scores are then combined to calculate the composite performance by using aggregate operators and weighting schemes.

Figure 1 shows a typical hierarchy (or a tree structure) of MCDM applied in transportation alternative evaluation and decision-making. The underlining assumptions of the traditional decision-making method—the weighting and scoring method with a tree structure—are of two kinds. Firstly it is assumed that information and knowledge for evaluating performance of the alternatives is complete and consistent among the alternatives and the experts; in other words, the analysts are able to precisely specify the predicted performance and the values of the weights for each alternative. Secondly, the evaluation criteria (*C*) and evaluation sub-criteria (*S*) are independent and quantifiable.

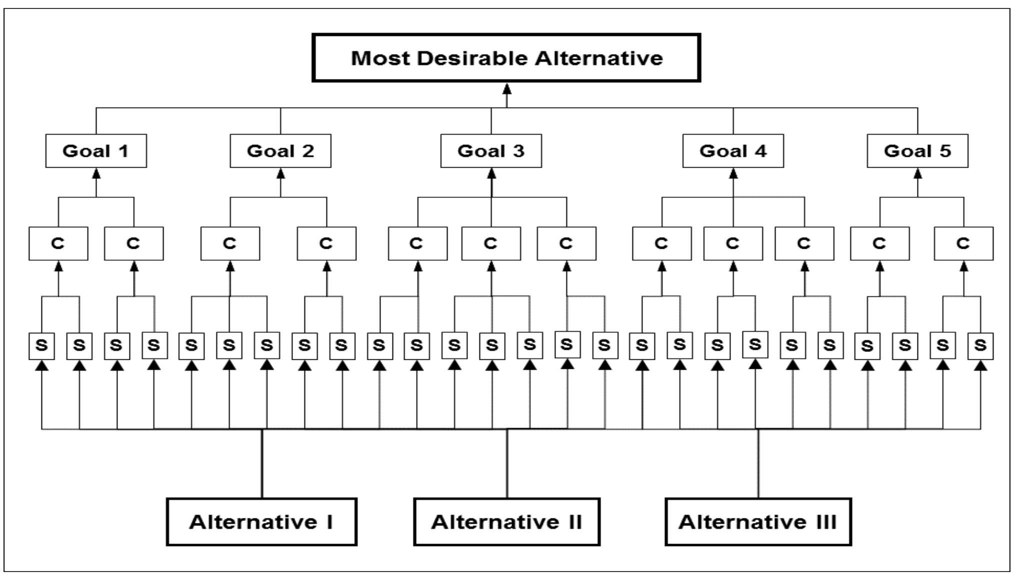

Figure 1 – Typical hierarchical tree structure for public transportation decision-making

However, experientially, two issues usually arise when using the traditional method. First, when applying scoring method, many important measures are difficult to quantify in reality, and as a result, varying degrees of ambiguity exist in the minds of the analysts about the performance of the alternatives. Therefore, the values of the weights are subjective and the composite scores are, of course, sensitive to the values of weights.

The second issue derives from the first: what is the justification of the proposed transportation alternative and to what extent the preferred alternative achieves the goals of the project. Most transportation planners need to recommend the preferred alternative, and as a result, transportation projects often are not as successful as expected. Pickrell (1990) showed evidence about the inaccuracy of travel demand and cost forecasting (over-estimated ridership and under-estimated costs) in the appraisal of transit projects. Boyle (2011) discussed the failure of several downtown transit circulators in the U.S. The traditional evaluation and decision-making methods seem to oversimplify the structure of the problem and may not even present them in a valid way. Consequently, honest justification of a decision may be difficult or even identify on what grounds it was made.

When evaluating a complex system, like a transportation system, modelling the decision structure is an important phase in the decision-making process. It defines how decision-makers and analysts approach the decision problem and what information and data are needed in the evaluation. Different decision structures may lead to different views about the alternatives. Therefore, it is desirable to model the system with a robust decision structure.

3. PROPOSED METHODOLOGY

This study proposes and applies a new decision-making method, called ‘Belief Reasoning method’, for evaluating public transportation systems in the planning process. The Belief Reasoning method proposes a reasoning map as a new decision structure to model how experts and planners reason a transportation alternative to lead to the expressed goals of a transportation project and proposes a belief measure as an indicator to present the degree of trust experts and planners assign to the outcomes of a particular plan and how much they believe in their reasons for the recommended decision.

Steps of Analysis in Transport Decision-Making Process[2]

The main input to decision-making in transportation planning is to evaluate the overall performance of each alternative and/or prioritize them from technical viewpoint. Different decision structures use different decision mechanisms to evaluate the overall performance. Figure 2 shows the steps in the evaluation process and the mechanisms applied under two methods: weighting and scoring method under a hierarchical tree structure (also in Figure 1), and proposed belief reasoning method under a reasoning map structure. The steps are the following.

1. Define the physical and operational characteristics of each of the proposed alternatives.
2. Develop a decision structure (either a hierarchical tree structure or a reasoning map structure) to model the system variables and connect them to the goals of the project.
3. Provide inputs to the evaluation process.

   For a hierarchical structure, the inputs are the performance values predicted by planners and experts, often using transportation models. The scores are then assigned to each performance.
   For a mapping structure, the inputs are the 'belief' (or 'truth') values associated with the characteristics of each alternative and the 'belief' (or 'truth') values associated with the causal relations along the reasoning chains.
4. Execute the model.

   For a hierarchical structure, the weights are assigned to each element of the system. The weights are either given directly or determined through pairwise comparison by experts. Then, the performance scores are aggregated using assigned weights for each alternative.
   For a reasoning map structure, the 'truth' values are propagated through the inference process from the characteristics of the alternative to the goal of the project.
5. Evaluate and compare the overall performance of all the proposed alternatives.

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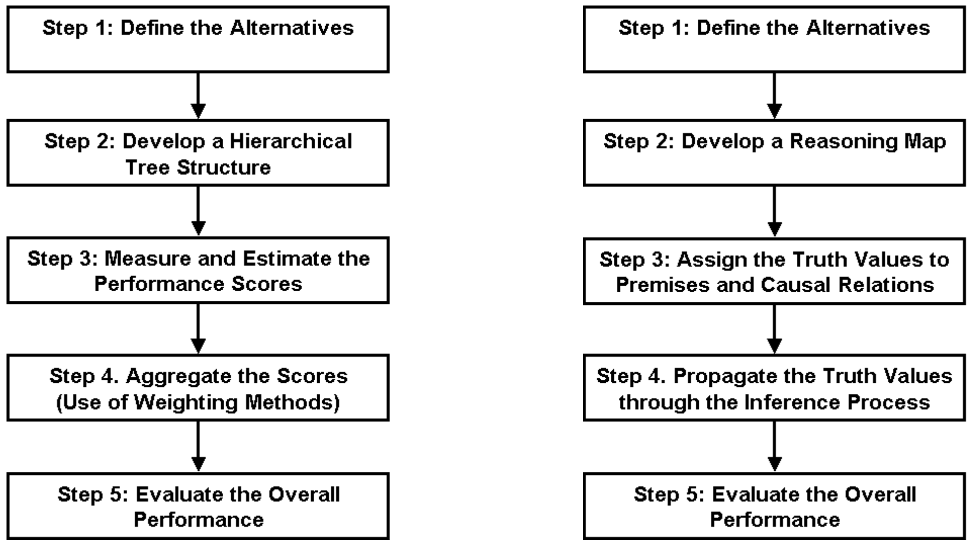
[2] The classical methods of evaluation and decision-making—benefit-cost analysis (TRB 2002), multi-criteria decision-making (FTA 2011, Saaty 2005), and Bayesian Inference—are well-known and not reviewed here. Briefly said, under the Bayesian Inference approach the reasoning process is similar to the reasoning map approach. Experts assign values of 'truth' to each node and link, and these values are propagated along the links and the probabilities of achieving individual goals are determined. However, the Bayesian aggregation takes the average value of the evidence of each proposition, which does not include "I don't know" and AHP approach does not consider uncertainty at all in the outcomes. Thus, besides being different from the proposed reasoning map approach in handling uncertainty and goal achievement (for comparison, Kronprasert 2012), AHP and Bayesian Inference are also computationally more onerous.



2(a) Hierarchical tree structure   2(b) Reasoning map structure

Figure 2 – Mechanisms in evaluation process under different decision structure

Decision Structure: Reasoning Map

A reasoning map is proposed as a decision structure for evaluating transit alternatives in the face of complicated chains of reasoning. The reasoning map, as shown in Figure 3, presents the causal relations between *decision variables* (*D*) of transportation alternatives and consequences and impacts (P) of a transit project.

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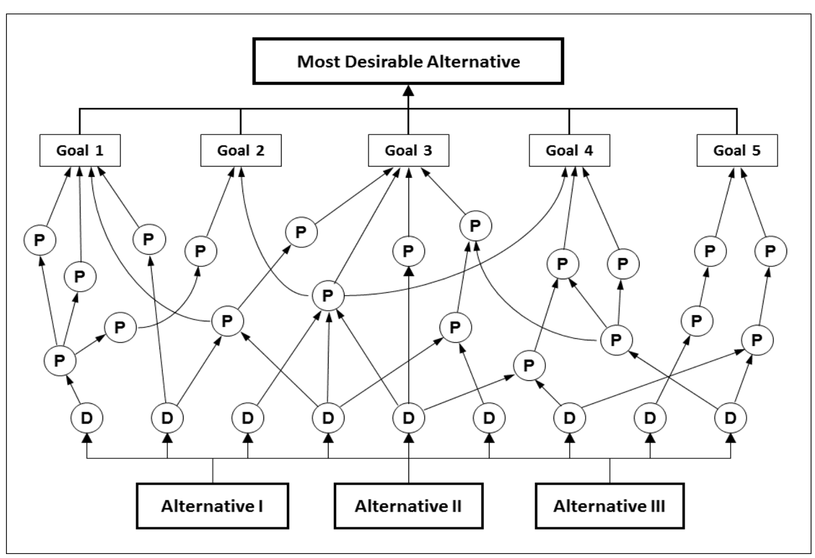

Figure 3 – Proposed reasoning map structure for public transportation decision-making

Knowledge Elicitation

Once the chains of a reasoning map are developed, the knowledge about every premise and every relation are elicited by aggregating opinions from experts. The knowledge is given by the belief values associated with every state in premise (X), $m(X)$, and every state in relation ($X \rightarrow Y$), $m(X \rightarrow Y)$. The unique characteristic of the belief value in Dempster-Shafer theory of evidence (Dempster, 1968; Shafer, 1976; Yager et al., 1994; Beynon et al., 2000) is that it allows experts also present their uncertainty and ignorance by stating "I don't know (IDK)" to any premises or relations.

For example, consider that the 'transit headway', X, has three outcomes, Low (X_1), Medium (X_2), and High (X_3), and 'passenger waiting time', Y, has also three outcomes, Short (Y_1), Medium (Y_2), and Long (Y_3). For the premise "Headway is …", the knowledge about this premise can be given as probabilities or weights $m(X_1)$, $m(X_2)$, $m(X_3)$, and $m(X_1 \cup X_2 \cup X_3$, that is any of the outcomes may occur-an IDK. For the relation "If Low Headway, then Waiting time is …", the knowledge about this relation can be given as $m(X_1 \rightarrow Y_1)$, $m(X_1 \rightarrow Y_2)$, $m(X_1 \rightarrow Y_3)$, and $m(X_1 \rightarrow Y_1 \cup Y_2 \cup Y_3)$. Knowledge as "I don't know" (i.e., $m(X_1 \cup X_2 \cup X_3)$ and $m(X_1 \rightarrow Y_1 \cup Y_2 \cup Y_3)$) is useful in transportation planning and conserved in the proposed method to account for uncertainty and ignorance of planners, experts, and laity.

Belief Propagation

To evaluate a (transit) alternative, the belief values are propagated from the premises (starting nodes) to the goals (the end nodes) and the belief value (or degree of achievement) of individual goals are eventually obtained. Given knowledge about the premise X and knowledge about the relation $X \rightarrow Y$ (i.e. $m(X)$ and $m(X \rightarrow Y)$, one can infer knowledge about the conclusion Y, $m(Y)$

$$m(Y_j) = \Sigma_i \{m(X_i) \cdot m(X_i \rightarrow Y_j)\} \quad \text{where } X_i \subseteq X \text{ and } Y_j \subseteq Y.$$

More technical details about belief propagation in Dempster-Shafer theory are in the Annex. For detailed discussions and examples of the Bayesian method, AHP, and the Dempster-Shafer theory the readers are referred to the literature on the topic. (Beynon et al 2000, Lee et al., 1987; Yager et al., 1994; Klir and Wierman, 1999; Kronprasert and Kikuchi, 2011; Kronprasert, 2012)

4. APPLICATION TO TRANSIT MODE SELECTION PROBLEM

The proposed reasoning method is illustrated and compared with the weighting and scoring method by applying it to the evaluation of a transit circulator system in a large commercial development in Northern Virginia, USA. The system is to support transit riders from and to four metro stations as shown in Figure 4. The goal is to provide a fast and convenient transit system connecting between the metro stations and developments in the commercial centers. Because the intent is to show the usefulness of the method, the values used in the analysis are assigned by the authors. For an application where the values and the reasoning map were developed by transit planners is in Kronprasert (2012).

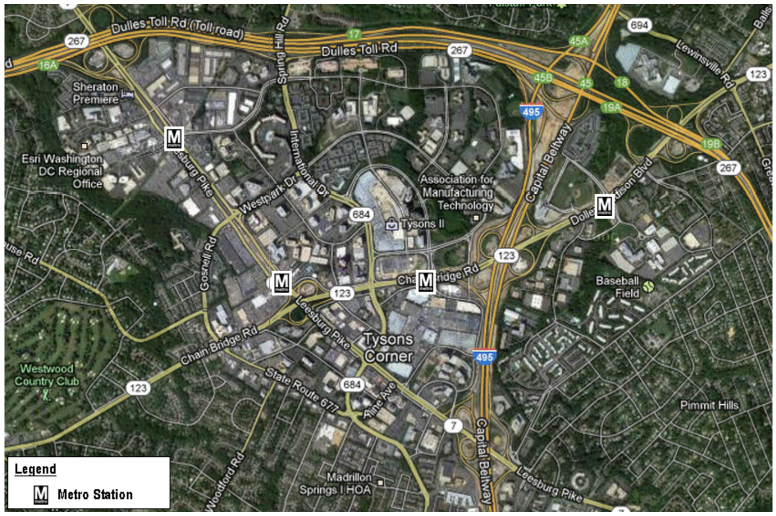

Figure 4 – Transit circulator study area, Northern Virginia

Weighting and Scoring Method

The hierarchical tree structure for evaluating the most desirable transit mode in this example is shown in Figure 5. The hierarchical structure consists of four levels (overall goal, stakeholders, criteria, and alternatives.) In this example the goal is to find the most desirable transit mode. Three transit mode alternatives are compared: Personal rapid transit (PRT), Circulator bus, and Streetcar. Three groups of stakeholders are considered: transit users, planners, and the community. The user group regards six criteria: accessibility, mobility, availability, capacity, comfort, and safety. The planner group regards five criteria: fare revenues, capital costs, operating costs, transit riders, and system reliability. The community group regards four criteria: economic impact, aesthetic quality, environmental condition, and quality of life. These criteria are taken from *Transit Capacity and Quality of Service Manual* (TRB, 2003).

The study conducts the Analytical Hierarchy Process (AHP) method as follows. First, the pair-wise comparisons among stakeholders are conducted, and the weight associated with each stakeholder group is calculated. Second, the pair-wise comparisons among criteria for each stakeholder are made, and the weight associated with each criterion is calculated. Third, each transit mode is evaluated through a list of criteria by rating the scores from 1 to 5 (1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high). Finally, the overall score for each transit mode is calculated using weighted linear function (Saaty, 1980; 2005; Banai; 2006).

Table 1 shows the rating scores associated with each criterion for individual transit mode. The final overall ratings of three transit modes are Medium for PRT alternative, High for Bus alternative, and Medium for Streetcar alternative. The final output of the AHP method and weighting and scoring methods are the ranking among alternatives. However, the rating scores may not have specific meaning.

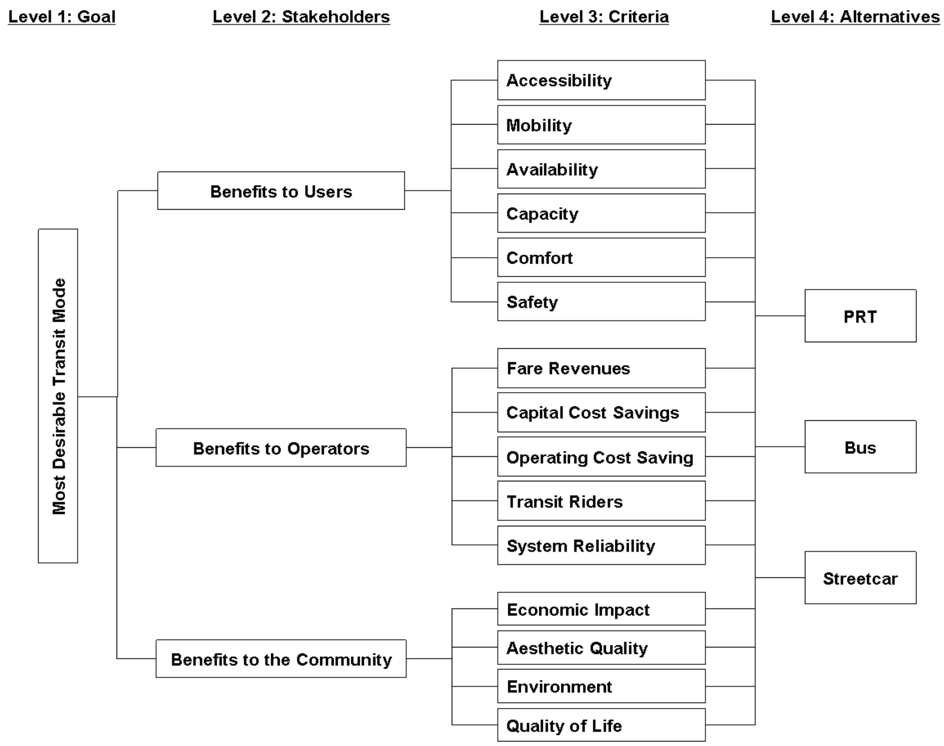

Figure 5 – AHP hierarchy for transit mode selection

Table 1 – Ratings of individual transit modes

Stakeholder Group	**Criteria**	**Relative Weight** [a]	**Transit Mode Alternatives**		
			PRT	**Bus**	**Streetcar**
Users (w = 0.282) [a]	Accessibility	0.184	4	3	3
	Mobility	0.176	5	3	3
	Availability	0.219	4	3	3
	Capacity	0.154	3	4	4
	Comfort	0.125	5	2	3
	Safety	0.142	5	3	4
	Subtotal	1	4.1	3.0	3.3
Planners (w = 0.540) [a]	Fare Revenues	0.160	4	3	4
	Capital Costs	0.487	1	5	2
	Operating Costs	0.161	3	3	4
	Riders	0.138	2	3	3
	System Reliability	0.055	4	3	4
	Subtotal	1	2.1	4.0	2.9
Community (w = 0.177) [a]	Economic	0.254	3	3	4
	Aesthetic	0.199	4	4	5
	Environment	0.247	4	2	5
	Quality of Life	0.299	5	3	4
	Subtotal	1	4.0	3.0	4.4
Overall Score [b]			3.0	3.53	3.28
Overall Rating [c]			Medium	High	Medium

[a] *Derived from AHP method*
[b] *Calculated by the weighted-sum method*
[c] *1 = Very low, 2 = Low, 3 = Medium, 4 = High, and 5 = Very high*

Belief Reasoning Method

The transit mode selection problem is now evaluated through the proposed Belief Reasoning method. The reasoning map structure is applied using the belief propagation mechanism of the Dempster-Shafer theory (see the Annex). The reasoning map method connects the attributes of the system into a series of chained reasons starting from the decision variables of transit modes to the overall goal of the project.

Figure 6 shows the reasoning map structure for evaluating the transit modes developed by a group of five experts in this example. Three transit modes are defined based on ten characteristics: right-of-way, type of supports, vehicle size, vehicle speed, type of power, vehicle operation, stopping operation, type of service, headway, and station location. In addition to the goal and criteria applied in the AHP method, eight attributes are included to express the causalities: fleet size, travel time, auto users, traffic congestion, land use pattern, transit-oriented development (TOD), emissions, and gasoline consumption.

Using a reasoning map structure, the assignment of variables to serve certain goals or users is not needed because the method allows free presentation of the interrelationships among attributes in the system. The reasoning map structure thus explicitly addresses the redundancy issue in evaluation. Figure 6 shows that improved mobility not only increases the users' satisfaction due to travel time saving, but also attracts more transit riders valued by the planners and as well as reduces automobile users. This in turn benefits the community by reducing environmental impacts and improving quality of life. In addition to evaluating the overall goal for each transit mode, the proposed method allows analysis and judgments about the validity of reasoning and the uncertainty and usefulness of information be evaluated for each goal.

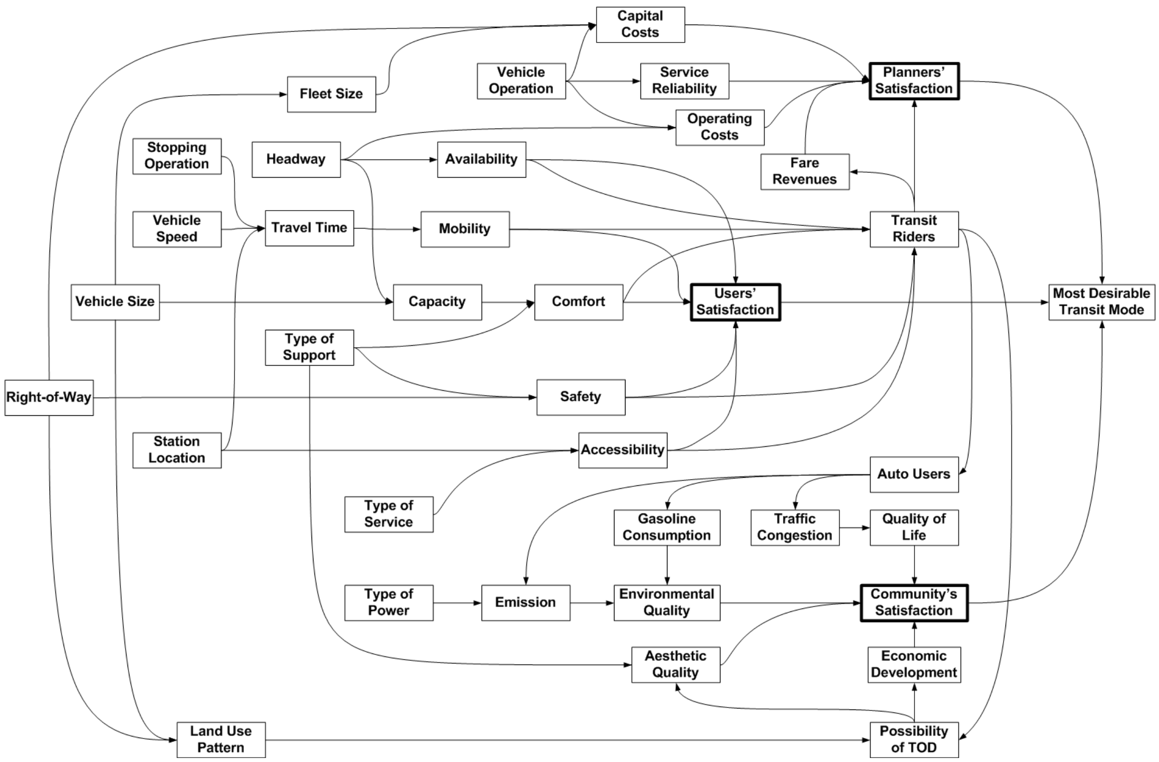

Figure 6 – Reasoning map structure for transit mode selection

Table 2 shows that three transit alternative achieves the 'High' level of overall satisfaction with different degrees of belief: Bus (0.52), PRT (0.38), and Streetcar (0.32). It is believed that under certain expert knowledge the Bus alternative would be the most satisfactory transit mode in this case study.

It is also shown in Table 2 that the belief values of "I don't know" for attributes associated with PRT alternative are higher than those of Bus and Streetcar alternatives. It indicates that the degree of expert uncertainty to the PRT alternative is high and more detailed study should be given to this transit mode if it is considered further in the alternative development and evaluation process.

Table 2 – Belief values associated with attributes in a reasoning map for different transit mode alternatives

Performances and Consequences	Transit Mode Alternatives											
	Personal Rapid Transit (PRT)				Bus				Streetcar			
	Low	Med	High	IDK	Low	Med	High	IDK	Low	Med	High	IDK
Fleet size requirement	0.00	0.09	0.50	0.41	0.65	0.24	0.01	0.10	0.73	0.16	0.01	0.10
Travel time saving	0.08	0.28	0.33	0.31	0.15	0.65	0.18	0.02	0.15	0.71	0.12	0.02
Land acquisition	0.31	0.28	0.20	0.21	0.44	0.28	0.25	0.03	0.27	0.28	0.41	0.04
Service reliability	0.01	0.11	0.44	0.44	0.35	0.50	0.05	0.10	0.30	0.53	0.08	0.09
Capital costs	0.04	0.11	0.73	0.13	0.84	0.15	0.01	0.00	0.15	0.43	0.41	0.01
Operating costs	0.39	0.20	0.13	0.28	0.08	0.27	0.61	0.04	0.22	0.34	0.40	0.04
Possibility of TOD	0.22	0.23	0.34	0.22	0.19	0.29	0.49	0.03	0.19	0.27	0.50	0.03
Availability	0.12	0.16	0.21	0.51	0.22	0.20	0.49	0.09	0.22	0.20	0.49	0.09
Mobility	0.08	0.19	0.21	0.52	0.20	0.53	0.20	0.07	0.20	0.56	0.17	0.07
Capacity	0.51	0.17	0.07	0.25	0.20	0.37	0.40	0.03	0.16	0.32	0.49	0.03
Comfort	0.27	0.20	0.07	0.46	0.18	0.42	0.30	0.10	0.26	0.38	0.24	0.12
Safety	0.00	0.01	0.89	0.10	0.24	0.55	0.18	0.02	0.00	0.00	0.99	0.01
Accessibility	0.16	0.13	0.42	0.29	0.00	0.12	0.87	0.01	0.01	0.10	0.84	0.05
Transit riders	0.19	0.36	0.32	0.12	0.09	0.59	0.31	0.01	0.07	0.60	0.32	0.01
Fare revenues	0.16	0.27	0.18	0.38	0.16	0.40	0.34	0.10	0.14	0.41	0.35	0.10
Automobile users	0.14	0.25	0.23	0.38	0.21	0.37	0.27	0.15	0.22	0.38	0.26	0.15
Traffic congestion	0.09	0.12	0.22	0.57	0.18	0.24	0.36	0.22	0.18	0.25	0.354	0.22
Quality of life	0.17	0.07	0.06	0.70	0.38	0.16	0.17	0.29	0.37	0.17	0.17	0.29
Gasoline use	0.10	0.10	0.21	0.58	0.20	0.19	0.37	0.24	0.21	0.19	0.36	0.24
Air quality	0.09	0.13	0.21	0.57	0.18	0.22	0.35	0.25	0.18	0.23	0.34	0.26
Environmental quality	0.11	0.10	0.27	0.52	0.49	0.17	0.20	0.14	0.49	0.16	0.22	0.13
Aesthetic quality	0.10	0.14	0.58	0.18	0.59	0.21	0.17	0.04	0.01	0.05	0.93	0.01
Economic development	0.19	0.20	0.16	0.45	0.35	0.31	0.19	0.16	0.28	0.22	0.35	0.15
Planners' satisfaction	0.31	0.40	0.20	0.09	0.01	0.45	0.54	0.00	0.19	0.62	0.16	0.02
Users' satisfaction	0.10	0.21	0.57	0.12	0.10	0.43	0.45	0.03	0.07	0.38	0.52	0.03
Community's satisfaction	0.23	0.25	0.33	0.19	0.43	0.30	0.22	0.05	0.30	0.21	0.44	0.05
Overall satisfaction	0.20	0.31	0.38	0.12	0.10	0.31	0.52	0.07	0.14	0.46	0.32	0.08

Note: IDK = "I don't know"

Comparison of the Results

Table 3 compares the final results obtained from the weighting and scoring AHP method and the proposed Belief Reasoning method. The results show that, again keeping in mind that this is a hypothetical case to illustrate the method, both the Belief Reasoning and the Scoring Method recommend the same transit mode alternative, although this need not be the case in general. For the Scoring Method, the Bus alternative is rated the highest composite score among three transit modes (3.5 out of 5).

With the Belief Reasoning method, the Bus alternative is believed to achieve the best 'High' level overall satisfaction, although the degrees of belief in achievement of 'High' for all three are not particularly high, *m*("Bus is High" = 0.52), *m*("PRT is High" = 0.38, and *m*("Streetcar is High" = 0.32). It is interesting that from the Community's view the Streetcar gives highest satisfaction. The results suggest that none of the alternatives as designed for the experiment achieves the goals of the project. In the planners' view, the Bus alternative is superior over PRT and Streetcar, The degrees of the planning experts' uncertainty, shown by the values of "I don't know", $m(IDK)$, regarding the Bus alternative's performances and goal achievement are the lowest and much lower than that of PRT.

Table 3 – Comparison of the results between the traditional and proposed methods

Transit Mode Alternatives	**Decision-Making Methods**	
	Weighting and Scoring Method	**Belief Reasoning Method**
Personal Rapid Transit (PRT)	Medium (Score = 3.0)	Degree of belief: "PRT is High" = 0.38 Degree of belief: "PRT is Med" = 0.31 Degree of belief: "PRT is Low" = 0.20
Circulator Bus (BUS)	High (Score = 3.5)	Degree of belief: "BUS is High" = 0.52 Degree of belief: "BUS is Med" = 0.31 Degree of belief: "BUS is Low" = 0.10
Streetcar (SCR)	Medium (Score 3.3)	Degree of belief: "SCR is High" = 0.32 Degree of belief: "SCR is Med" = 0.46 Degree of belief: "SCR is Low" = 0.14

5. DISCUSSION

Benefits of Reasoning Map Structure

The proposed reasoning method provides benefits over the traditional method, although the final recommendation may be, but need not be, similar with both methods.

Using the reasoning map structure, the decision-makers can justify and explain the reasons for supporting a transport alternative through a mapping structure. The public is informed broadly and can debate in a logical way the benefits and consequences and express their degrees of belief through a mapping structure. The critical (most important) reasons can also be traced in the reasoning map, shown in red in Figure 7 through Figure 9, for supporting PRT, Bus, and Streetcar alternatives, respectively. An evaluation of these paths will guide additional data collection and analyses to reduce uncertainty in the results.

PRT alternative does not achieve the 'High' level of satisfaction for overall goal achievement because it is regarded 'Low' by planners. PRT is especially weak in cost recovery compared to the other transit modes. The predicted PRT ridership is rather low to yield satisfactory fare revenue, and the capital costs are high, mostly due to the capital costs of the elevated guideway system and the large fleet size. The planners could cut down the fleet size and reduce the investment cost; but with a smaller fleet size the capacity would be less and that would make PRT less comfortable and less accessible, and most likely yielding low ridership. Consequently, the system has low cost recovery and lower satisfaction than Bus shadowed with a high degree of uncertainty.

With the available information the planners would recommend Bus alternative in this case because, in their opinion, it provides the most benefits. Bus has low capital costs because it operates on the existing shared lane. Street improvements and land acquisition are not required. However, the community seems to value the benefits of the Streetcar. Bus does not meet the community's goals because it is not expected to improve environmental quality and reduce traffic congestion; however, these are not the only purposes of the project and (with the assigned values) the community does not have a strong opinion against the bus. Nonetheless, the community's willingness to pay for the higher costs should be investigated.

Streetcar alternative does not achieve the 'High' level for overall goal achievement, although the capacity cost is moderate compared to that of PRT. The Streetcar supports the community's goals more than Bus. According to the experts' values Streetcar's benefits to the community are the strongest of all the modes, because it will bring higher aesthetic quality to the development through the permanency of a rail-based system. However, the quality of life, while best among the transit alternatives, is not improved, in part because the area is automobile-oriented. The investment cost of Streetcar receives the 'Low' rating from the planners.

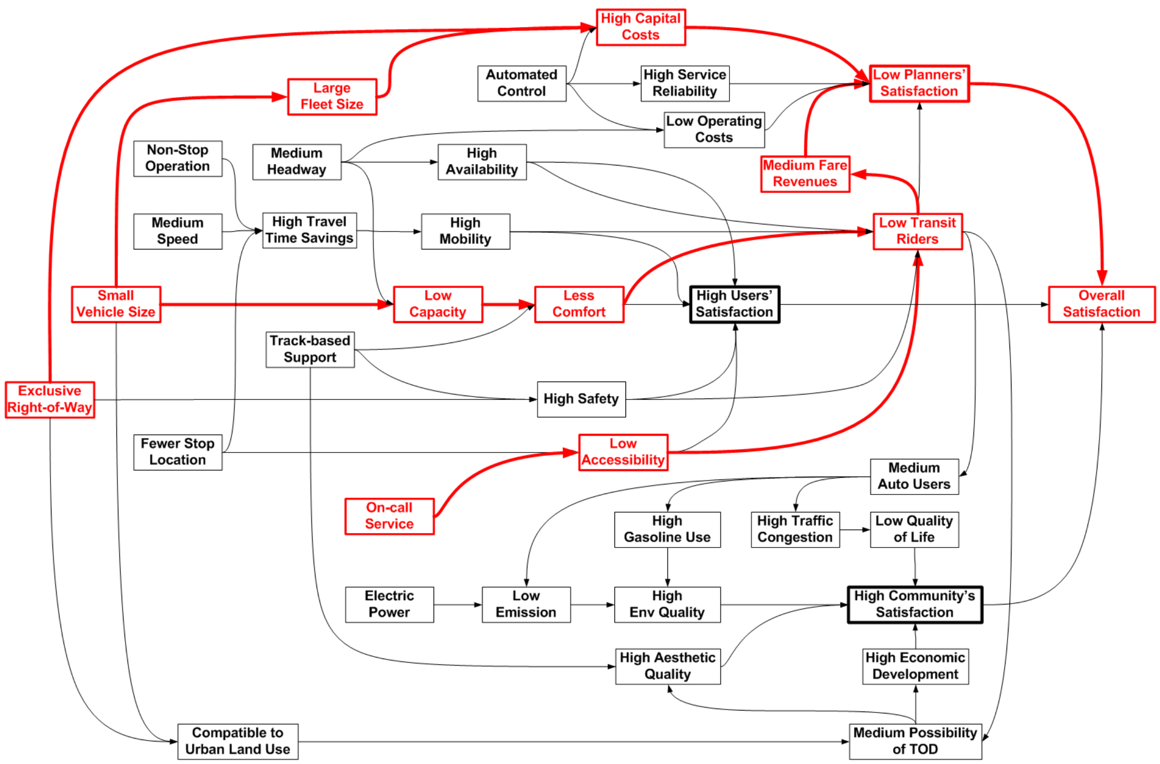

Figure 7 – Critical reasoning path for PRT alternative

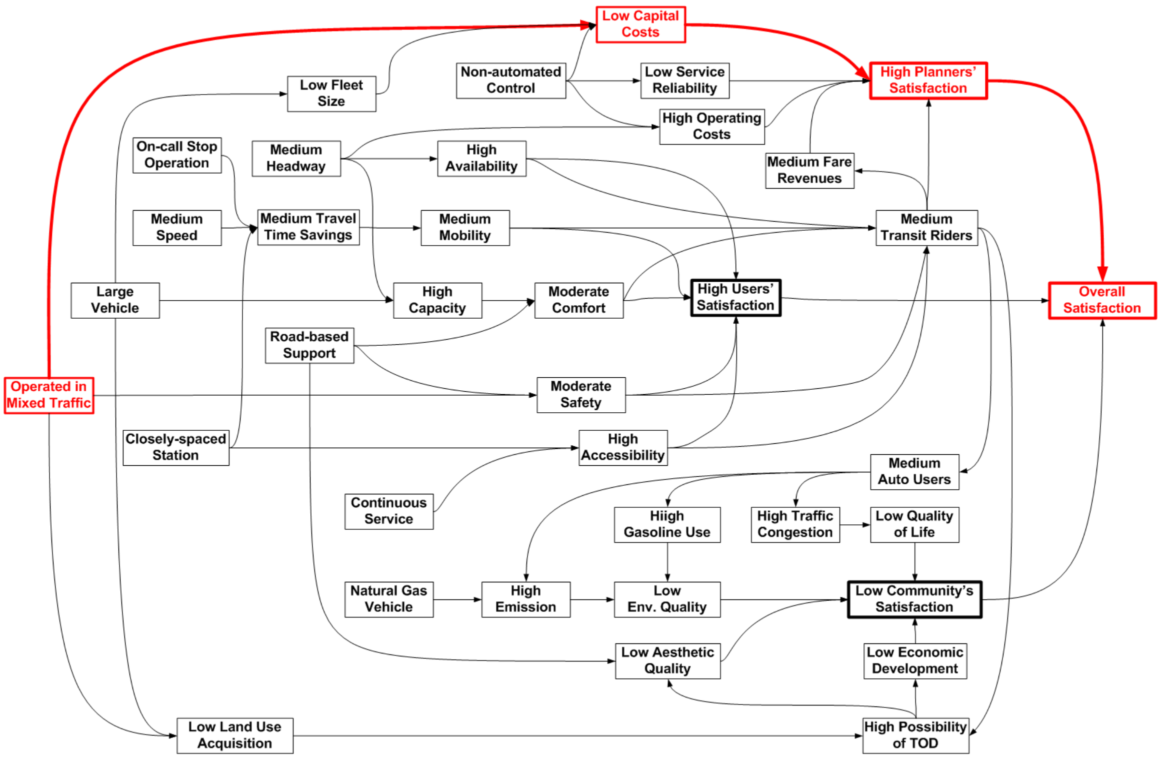

Figure 8 – Critical reasoning path for Bus alternative

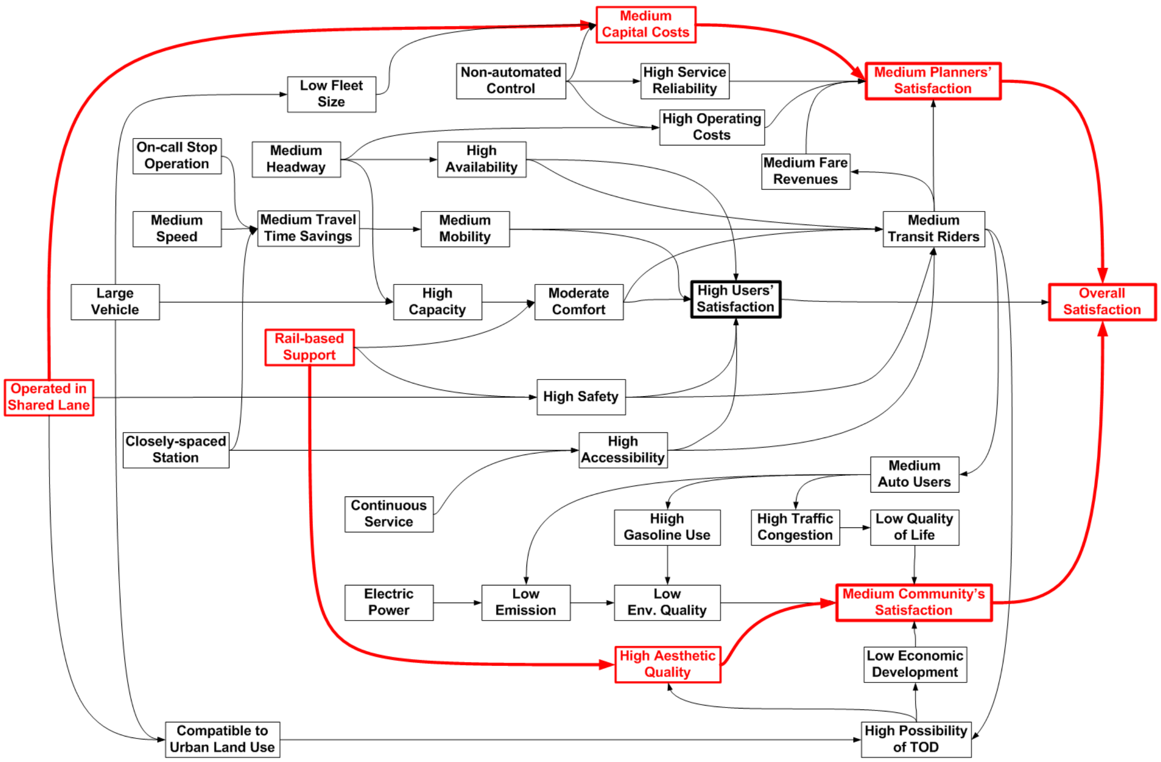

Figure 9 – Critical reasoning path for Streetcar alternative

Measuring the degrees of belief in reasoning allows recognizing the uncertainty of the evaluation process. This relatively simple case study—but with complex decision variables—shows the strengths and value of the Belief Reasoning method. It provides useful information to planners, decision-makers and citizens; it suggest reasons and issues for acquiring additional information for reducing ambiguity; adding new features to the plans or alternatives, or dropping alternatives from further work. These kinds of information and reasoning cannot be deduced from the traditional weighting and scoring methods. The method leaves behind a concrete paper trail for retrospective evaluation of beliefs about costs and benefits and other impacts; accuracy of planning methods; differences of stakeholder values; and degrees of 'I don't know'. Over time these kinds of information will add to scientific knowledge about planning.

Reflections about the Hierarchical Tree Structure and Belief Reasoning Methods

The hierarchical tree structure multi-criteria decision-making (MCDM) methods are currently very popular means of evaluating alternatives (FTA 2009). However, MCDM does not explain the dependent relationships between elements. In the hierarchical tree structure, each attribute in the same group must be independent of each other and belong only to one group (as shown in Figure 1). There is no redundancy (interrelationship) among the elements. This assumption makes it difficult for analysts to classify the attributes when they, in fact, belong to several groups.

Two typical issues are present when developing a hierarchical structure in the transportation planning process. The first issue is interdependency. As shown by the example, improvement in mobility and accessibility not only benefits users but also gains benefits to the community through enhancing the quality of life and changing environmental quality. Hence, 'mobility' should be classified under both 'Benefits to users' and 'Benefits to the community.'

The second issue is the correlation among attributes. For example, 'Accessibility' and 'Mobility' are often regarded as two independent attributes. 'Accessibility' can be measured by service area while 'Mobility' can be measured by (transit) ridership. However, service area and transit ridership are highly correlated. The correlation among attributes makes it difficult to compare the relative importance between two attributes.

Determining the weight values in a hierarchical tree structure is burdensome for experts and analysts. The values of weights are subjective, but additive and relative. The weight values represent the degree of contribution of individual elements in their category, but at the same time, they represent the relative importance of one element to the others in the same category. The weight determination requires a normalization process which may bias the real meaning of the weight values.

Ranking of alternatives through a hierarchical structure can be easily manipulated by the assignment of the weights. These weight values are always debatable and require policy makers to select their preferred weight values; the 'secret agenda' of a preferred transit mode can be advanced by selecting the "right" weight values.

In reality the elements of the transportation decision-making system interact in a complicated manner. The oversimplified weighting schemes will not truly replicate the decision-making. Hierarchical structures leave no paper trail about the reasoning process and the beliefs embedded in it. In addition, the planners and experts have some knowledge beyond the relative importance between elements, and this can be represented in a Belief Reasoning map.

Not unlike MCDM, Benefit-Cost Analysis, and AHP, the Belief Reasoning Map method is also complex and laborious. But having gone through several exercises both complexity and laboriousness are less than with the other methods. Many of the shortcomings and objections to MCDM methods are overcome. But, there is an additional difficulty of no small magnitude: how to judge the results and recommend an alternative. How to make a choice? The reasoning maps themselves and amount of information can be bewilderingly complex and large (Table 2, Figures 7-9) and time-consuming to develop. Several reasoning maps may emerge for the same problem depending on the affected interests' vantage points. And, the reasoning maps may not be stable as the process evolves and show severe conflicts and disagreements that are hidden in the other methods.

The Reasoning Map method will also add to the complexity and time requirements of public participation events. The authors do attach much importance to participatory planning process which enables the planners (reflecting the views of the policy-makers), consultants, stakeholders and affected interests clarify their chain of reasoning and assess reasonableness of the plans to achieve or support the accepted (regional) goals. It is unclear what value the Reasoning Map Method would add to public participation. Theoretically, however, the proposed framework will promote informed discourse among the planners and citizens as it can identify the weak and strong links in the reasoning process.

The proposed approach has similarities to Forrester's system dynamics. (Forrester, 1969) Both use complex cause-and-effect chains. The Reasoning Map method can use both quantitative and qualitative, and "I don't know" information, which the systems dynamics cannot.

In brief, while the proposed approach is useful and promising, it requires more research in practical settings. Among the most critical issues are: (i) how to develop reasoning maps quickly and incorporate only the important factors: (ii) are the reasoning chains and the belief assignments stable during the planning process; (iii) how serious is the danger of "group think" in belief assignments (all planners think alike); and, (iv) especially, how to incorporate explicitly the consideration of costs and willingness to pay in the reasoning chains.

And finally an App should be developed to systematize the use of the method and make its application user-friendly.

6. CONCLUSIONS

This paper proposes a reasoning map structure for decision-makers, planners and citizens to evaluate and express preferences about alternatives for (public) transportation system. The capabilities of the proposed reasoning map structure are compared with the hierarchical tree structure through an alternatives analysis for a proposed circulator transit system in a large commercial development in the U.S. The paper examines the characteristics of the methods and discusses benefits and limitations of the proposed reasoning map.

The proposed method, with a reasoning map structure as its basic frame, has several advantages over other methods of evaluation and assessment. We enumerate the most apparent ones. First, the proposed method allows all stakeholders—decision-makers, planners, citizen groups—to evaluate ex-ante the performances of transportation alternatives, measure the validity of their reasoning chains and the degrees of belief of the project's goal achievement. Second, the proposed reasoning method can handle non-deterministic characteristic of values of performance measures (e.g. operating costs can be low or medium or high, depending on the design), as well as the nature of uncertainty of (experts') judgments (e.g. "I don't know" notion). Third, the reasoning map attempts to model the decision problem and human thinking processes. It allows modelling the interdependency, conflicts and redundancy among elements of the system and decision processes. And fourth, the method leaves behind a paper trail of the stakeholders' thinking and reasoning chains during project or plan development and evaluation process. This paper trail in itself is likely to encourage 'truth' in project or plan evaluation and support ex-post analyses of the planning processes, enable learning and improve their scientific basis. These advantages are not available from the traditional multi-criteria decision-making or benefit-cost analysis methods. On the contrary, the proposed reasoning method has greater flexibility to model the decision issues in transportation project and systems planning and provides a learning environment for the benefit of the profession and citizens.

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ANNEX

This Annex presents the mechanism to compute the degrees of belief in Dempster-Shafer theory and determine the critical reasoning path in the reasoning map.

Consider there are two strands of arguments (pieces of evidence) about transit-oriented development (TOD) as shown in Figure A-1. One (group) argues that transit-oriented development is likely to satisfy local community because it will enhance economic development, and as a result, will achieve 'High' satisfaction to the community. The other (group) argues that transit-oriented development will create inconvenience to people, especially to those who live near a transit station due to parking, traffic and overall higher rents in the corridor, and as a result gives low satisfaction to the community. For the first (economic development), the degrees of belief for "Satisfaction to Community" are $m_1(High) = 0.5$, $m_1(Med) = 0.2$, $m_1(Low) = 0.05$, and $m_1(I\ don't\ know) = 0.25$, and for the second (inconvenience) $m_2(High) = 0.0$, $m_2(Med) = 0.05$, $m_2(Low) = 0.85$, and $m_2(I\ don't\ know) = 0.10$.

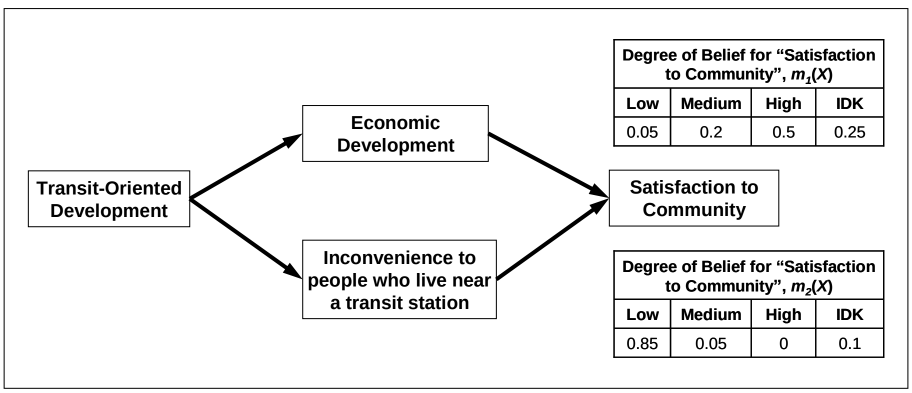

Figure A-1 – An example of two conflicting reasons

The degrees of belief from two views ($m_1(X)$ and $m_2(X)$) can be combined by the Dempster's Rule of Combination in Dempster-Shafer theory. Figure A-2 shows the distribution of belief values of Evidence 1, 2, and their combination.

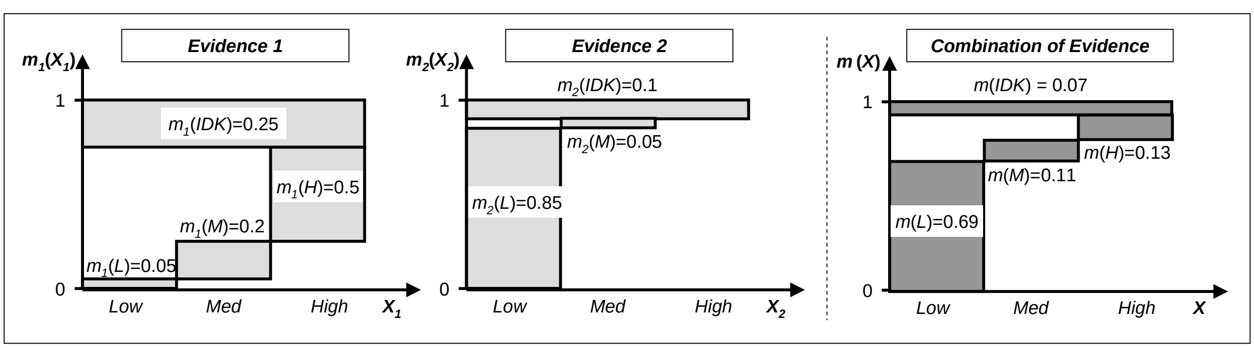

Figure A-2 – Illustration of belief distributions in Dempster-Shafer theory

The combined degree of belief $m(X)$ is calculated as:

$$m(X) = m_1(X_1) \oplus m_2(X_2) = \frac{\sum_{X_1, X_2 | X_1 \cap X_2 = X} m_1(X_1) \cdot m_2(X_2)}{1 - K}$$

where $K = \sum_{X_1, X_2 | X_1 \cap X_2 = \varnothing} m_1(X_1) \cdot m_2(X_2)$

$X_1, X_2, X \subseteq \{Low, Med, High\}$

The numerator is the sum of the product of the belief values associated with outcomes of evidence that supports set *X*. The denominator is a normalizing factor which is the sum of the product of the belief values associated with all the possible combinations of evidence that are not in conflict. *K* is the sum of the product of the belief values for evidence that are in conflict.

$$K = m_1(L) \cdot m_2(M) + m_1(L) \cdot m_2(H) + m_1(M) \cdot m_2(L) + m_1(M) \cdot m_2(H) + m_1(H) \cdot m_2(L) + m_1(H) \cdot m_2(M)$$
$$= 0.05 \times 0.05 + 0.06 \times 0 + 0.2 \times 0.85 + 0.2 \times 0 + 0.5 \times 0.85 + 0.5 \times 0.05 = 0.623$$

$$m(L) = \frac{m_1(L) \cdot m_2(L) + m_1(L) \cdot m_2(L \cup M \cup H) + m_1(L \cup M \cup H) \cdot m_2(L)}{1 - K}$$

$$m(L) = \frac{0.05 \cdot 0.85 + 0.05 \cdot 0.1 + 0.25 \cdot 0.85}{1 - 0.623} = 0.69$$

$$m(M) = \frac{m_1(M) \cdot m_2(M) + m_1(M) \cdot m_2(L \cup M \cup H) + m_1(L \cup M \cup H) \cdot m_2(M)}{1 - K}$$

$$m(M) = \frac{0.2 \cdot 0.05 + 0.2 \cdot 0.1 + 0.25 \cdot 0.05}{1 - 0.623} = 0.11$$

$$m(H) = \frac{m_1(H) \cdot m_2(H) + m_1(H) \cdot m_2(L \cup M \cup H) + m_1(L \cup M \cup H) \cdot m_2(H)}{1 - K}$$

$$m(H) = \frac{0.5 \cdot 0 + 0.5 \cdot 0.1 + 0.25 \cdot 0}{1 - 0.623} = 0.13$$

$$m(IDK) = \frac{m_1(L \cup M \cup H) \cdot m_2(L \cup M \cup H)}{1 - K} = \frac{0.25 \cdot 0.1}{1 - 0.623} = 0.07$$

In this example the belief value of reasoning for 'High' community satisfaction from economic development is less than the belief for 'Low' community satisfaction from inconvenience: $m_1(High) < m_2(Low)$, and the combined result from the two reasoning favors 'Low' community satisfaction. Thus, a high degree of belief (strong opinion) would have priority over the weak opinion. This is a characteristic of the belief value in Dempster-Shafer theory—and, incidentally, not in conflict with common perception. If two consistent opinions are combined, the combined opinion is even stronger, while with two conflicting opinions the mechanism will indicate support for the strong opinion but with less strength of opinion. Of course, the result does not mean that those who howl the loudest should get their way, but simply that the "weak opinion" may indicate a need for deeper study about its truth value.