Application of Multiattribute Utility Theory to Public Transit System Design

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Advanced Public Transportation Systems (APTSs) represent a promising concept that applies existing and emerging technologies and techniques to enhance and expand transit services. However the rapid emergence of a large variety of technologies and techniques might increase the possibility that new designs for transit systems will focus heavily on available products, neglect functional issues, and thus lead to partial and fragmented systems. Transit authorities need a mechanism they can use to avoid this negative situation and to develop transit systems that are as comprehensive, effective, and efficient as possible. Multiattribute Utility Theory (MAUT) is a normative model of decision making. Transit system design is a context in which the application of MAUT may be useful. Specifically MAUT provides tools for systematically evaluating, priority ranking, and integrating desired transit functionalities and APTS capabilities. The application of a MAUT-based framework for the process of transit system design is described and illustrated. It is hoped that the framework will both aid transit authorities in systems-design efforts and stimulate discussions that might influence the development of a nationwide specification for APTSs and lead to a standard, open transit system design.

Public transit faces a simultaneous decline in customer base and a rise in costs (*1–3*). As a result transit authorities are more than ever faced with the unenviable task of developing means of increasing the share of the market held by transit and at the same time reducing costs and increasing revenues. Along with these systems-design objectives transit authorities must respond to numerous legislative mandates, for example, the Clean Air Act Amendments of 1990, the Americans with Disabilities Act, and acts related to energy use and must improve transit safety and security (*4*).

The recent growth of Advanced Public Transportation Systems (APTSs), a promising concept that applies existing and emerging technologies and techniques to enhance and expand transit services, would appear to provide a means of attaining the aforementioned systems-design objectives. However the rapid emergence of a large variety of technologies and techniques might increase the possibility that new designs for transit systems will focus heavily on available products, neglect functional issues, and thus lead to partial and fragmented systems.

Furthermore integration of available resources into a single unified system is difficult because of the involved and interrelated nature of the subsystems and the social and political issues that the designer must accommodate. Moreover forecasts of effects of interventions are speculative by nature, and there is no all-encompassing evaluative framework by which to judge the efficacy, justice, and cost of any action. The complexity inherent in this situation often overwhelms designers and promotes retreat to simplistic solutions.

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Therefore there is a pressing need to approach the design of transit systems in a more organized manner. Designers need a clarifying mechanism that increases the quality of the design process through avoiding potential piecemeal and haphazard designs while developing comprehensive and coherent transit systems that are effective and efficient at meeting transit objectives.

METHODOLOGY

The cognitive psychology literature shows that unaided decision makers perform poorly in comparison with decision makers who use normative models (*5*). This is true for the quantitative fit between actual decision-making behavior and optimal behavior, that is, rational behavior as prescribed by a normative model, and for the qualitative character of decision makers' actions, evidenced by persistent violation of fundamental and self-evident axioms of rational behavior.

Studies have shown that decision makers are potentially amenable to support. In many problem-solving situations an aided decision maker can outperform an unaided decision maker. For example a study comparing the diagnostic capabilities of aided engineering graduate students against the baseline capabilities of unaided general practitioners found that, in diagnosing common ambulatory care complaints, the students were able to reduce diagnostic costs by 32 percent and the number of major diagnostic errors by a factor of 4 (*6*).

As implied earlier the difficulty of decision making in situations analogous to a systems-design process is intuitively largely because of the number, complexity, and interrelated nature of the issues faced. Research supports this intuition by demonstrating that people can maintain only a finite and relatively small number of issues in mind at any one time. Specifically studies have shown that people can adequately identify only 7 ± 2 levels of any unidimensional stimulus such as sound or sight (*7*). People are more adept at distinguishing multidimensional stimuli and, for example, can recognize hundreds or more categories when judging between faces or phonemes of human speech. Unfortunately the level of experience that leads to this capability appears to be lacking in most other decision-making environments. The implication of this human inadequacy is that issues need to be "chunked" or put into higher-level terms if far-reaching or intricate processes are to be handled with any degree of sophistication.

Multiattribute Utility Theory (MAUT) is a normative model of decision making (*8,9*) that designers can use to code the enormous amount of disparate information necessary for systems design into manageable chunks. In other words problem-solving methodologies based on MAUT can provide decision-making support for the task of selecting a single alternative or a set of alternatives in a risky or uncertain environment involving multiple, noncommensurate, and conflicting objectives. Such methods are also useful for inverse decision aiding or policy capture, which can provide insight into the reasons why a decision maker might prefer an alternative. Simply stated, MAUT-based methods provide a framework for decomposing a highly complex problem-solving or design task into a collection of simpler issues that, when resolved and recomposed, leads to a solution of the original problem.

As a result MAUT-based methods are useful for improving the capability of a decision maker or designer through aiding in the identification of contradictory facts and preferences and through enhancing the quality of the alternatives selected. These methods are also useful in improving the acceptability of decisions. This is possible because the basis of decisions is material provided by the user, not the method or a consultant. This user perspective also facilitates data acquisition because the information needed is often readily accessible to the designer, who sometimes is the knowledge source. Furthermore a common and major impediment to project evaluation is lack of clear objectives. MAUT-based methods avoid this by requiring a priori explication of design objectives. Such explication also provides a clear basis for arguing the merits of a project before and justifying project expenditures in the eyes of the relevant agencies and the general public.

Transit system design is a context in which the application of MAUT may be useful. Specifically MAUT provides tools for systematically evaluating, priority ranking, and integrating desired transit functionalities and APTS capabilities. MAUT can thus facilitate a comprehensive approach to the process of transit system design, in sharp contrast to a design approach based solely on implementation of technologies and techniques individually available in the marketplace. The work reported here framed a methodology as the 10-step process illustrated in Figure 1. Note that the designer can iterate the process if needed. Figure 1 shows only the most significant iterative loop; however, the process permits a return to any previous step at any point.

Step 1 in Figure 1 requires the determination of a hierarchy of objectives such as that shown in Figure 2. The objectives, which represent considerations that the designer thinks necessary and sufficient for a satisfactory system design, are instrumental in guiding and evaluating the design process. In developing the objectives the designer must remember that a good transit design will appeal to a number of potential target audiences, including transit personnel (general managers, operations managers, maintenance managers, motor coach operators, and maintenance and office personnel), suppliers, governmental authorities, and customers and taxpayers.

As illustrated in Figure 2, a given objective in a hierarchy, O_j, is often associated with several levels of subordinate or superordinate objectives. In many cases different objectives are associated with different numbers of levels as well. The design process can focus on any level of objectives or can even include objectives from a combination of levels, subject to the prerequisite that the analysis must include one and only one objective between the highest and lowest levels of each branch of the hierarchy, as illustrated by the shading in Figure 2. Use of the lowest-level objective for each branch would provide the greatest specificity; however, in actual practice, uncertainty and resource constraints often force the analysis to higher levels in the hierarchy. This is not a great hindrance.

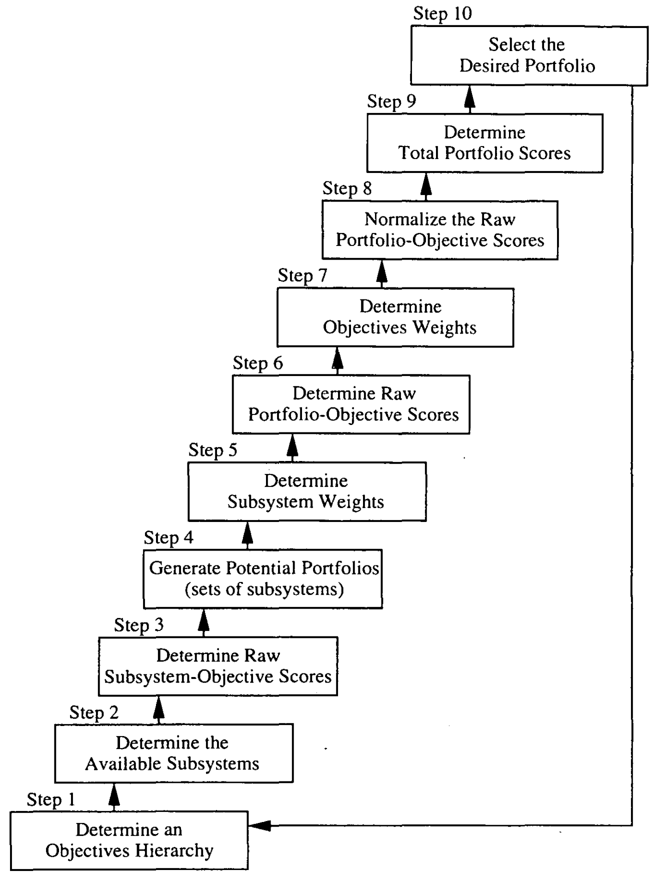

FIGURE 1 Transit system design methodology.

The results of the objectives-determination process are inherently subjective. However the process outlined in Figure 1 enjoins the designer to explicate intentions, seek out necessary data, and then make decisions in a rational manner.

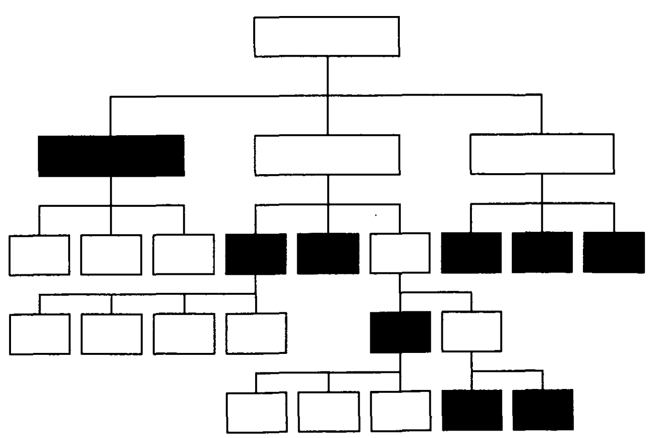

FIGURE 2 Format of objectives hierarchy.

After the designer has determined the objectives hierarchy, Step 2 requires determination of the available subsystems S_k. A subsystem can be either a technology (such as Automatic Vehicle Location) or technique (such as traffic regulation) that might enable attainment of the objectives.

At this point, Step 3, the designer must evaluate the ability of each subsystem to meet each of the objectives through determination of a raw (nonnormalized) score, called S_kO_j, for each subsystem-objective pairing, that is, for each (S_k, O_j) pair. The process of determining these raw subsystem-objective scores is equivalent to putting an S_kO_j score into each of the (S_k, O_j) cells of a matrix composed of J objectives in the columns and K subsystems in the rows. The designer can express the raw subsystem-objective scores in absolute terms. However in many designs it may be more helpful to express scores as changes from current conditions. Explicating each subsystem in this way will often highlight key subsystems and show the benefit of eliminating other subsystems because of the inability to meet design objectives or excessive cost.

Ideally each score or measure of effectiveness would be quantitative, such as fuel efficiency in kilometers per liter, service reliability in percentage of on-time operation, customer service in time to respond to telephone inquiries in seconds, or subsystem setup and maintenance costs in dollars per vehicle. Unfortunately many of the most important measures of effectiveness, such as customer perception of the quantitative measures and customer satisfaction, are qualitative and are thus somewhat more difficult to evaluate. However the designer may assign a utility to each level of a qualitative measure, utility being a method of subjectively valuing individual preference (*8,9*). In some cases the designer might wish to assign a utility to the quantitative measures as well. Other than possibly being preferentially inaccurate, the use of utility has no effect on the MAUT methodology. The designer will also have to use subjective judgment if the process includes evaluation of emerging technologies and concepts, because these offer little if any actual data and the designer will likely need to assign subjective values, even for quantitative measures.

After identifying and scoring the subsystems, then, as Step 4, the designer generates a number of portfolios, P_i. Each portfolio represents a different combination of the essential subsystems that constitute a system. The simplest method of generating portfolios is to arrange the K available subsystems in each of the possible 2^K include or exclude combinations to arrive at a total of I portfolios. Take, for example, a design problem in which two subsystems, S_1 and S_2, are available; that is, K is equal to 2. S_1 and S_2 can form four portfolios ($I = 4$), P_4 (both S_1 and S_2), P_3 (only S_1), P_2 (only S_2), and P_1 (neither S_1 nor S_2). Note the inclusion of P_1, the "do-nothing" option, that is, a portfolio with no (new) subsystems, which represents the status quo. Although P_1 could conceivably be a competitor for the best system design, the designer need not explicitly include it in the analysis.

This method quickly becomes impractical as the number of subsystems increases. A modest system with only 12 subsystems, for example, would have 2^{12} (4,096) possible portfolios. For a large or detailed study the number of portfolios could easily exceed this number by several orders of magnitude. Three means of handling this situation are available. The designer could make an early move to cull subsystems from consideration through review or revision of the results of Steps 1 to 3. Such action narrows the analysis. Alternatively the designer could concede to grouping the subsystems into supersubsystems, $S_{k'}$, and perform the analysis on these. Doing so limits the depth of the analysis in a manner analogous to performing the analysis at a higher level in the objectives hierarchy. Finally the designer could separately analyze the supersubsystems in detail and then treat the best subportfolios as inputs to a second analysis. This method does not reduce the size of the analysis as much as the former two methods do, but it does not constrain the level of detail as much either.

Often many of the possible combinations that make up portfolios are infeasible. This might be because, say, S_1 also requires the presence of S_3 if it is implemented in conjunction with S_2, and so portfolios with S_1 but not S_3 are infeasible. Similarly S_2 might not be workable in the presence of S_4. When designers know this in advance they can save some effort by excluding such combinations from the portfolio generation process. If not noted ahead of time, however, the designer can eliminate infeasible portfolios from consideration at this point.

During Step 5 the designer ascertains the subsystem weights, SW_{ijk}. The subsystem weights represent the relative importance of each subsystem to each portfolio-objective combination and need to be as objective as possible to avoid introducing ambiguity. Differences in weights might arise from different levels of importance of the subsystems, might be due to synergy or dissonance among the chosen subsystems, and so on. The weights must sum to 1 across subsystems for each portfolio-objective pairing, with the exception of the cost objective, for which the designer commonly simply adds the scores, that is, gives a weight of 1.0 to each subsystem. If economies of scale or economies owing to synergisms are possible, then the designer can reduce the cost weights accordingly.

During Step 6 the designer must determine raw (nonnormalized) scores, called P_iO_j, to evaluate the ability of the remaining feasible portfolios to meet each of the design objectives, that is, for each portfolio-objective or (P_i, O_j) pair. The process of determining these raw portfolio-objective scores is equivalent to putting a P_iO_j score into each of the (P_i, O_j) cells of a matrix composed of J objectives in the columns and I portfolios in the rows. The designer calculates each raw portfolio-objective score as a weighted sum of the raw subsystem-objective scores, S_kO_j, from Step 3. The appropriate weights are the subsystem weights, SW_{ijk}, from Step 5, with a factor termed PS_k, which reflects the composition of the portfolio under consideration; that is, PS_k is 1 if the portfolio has subsystem S_k and zero if not. In short the designer uses Equation 1 to determine P_iO_j. The designer should eliminate portfolios that fall short of, or exceed in the case of cost, design requirements.

$$P_iO_j = \Sigma(SW_{ijk})(S_kO_j)(PS_k) \quad (1)$$

In Step 7 the designer must determine the weights of the objectives, OW_j. It would be best if the designer were able to assign absolute weights. However in many situations decisions about the relative importance of the objectives are difficult to make either because the designer has no basis for such decisions or because it is easier to attain consensus if the designer does not specify detailed weights. To circumvent the need for absolute weights the designer may determine the weights of the objectives on the basis of the difference in relative importance of the portfolios for the various objectives. If the designer views the difference in raw portfolio-objective scores between portfolios for a specific objective as negligible; that is, if the designer thinks all portfolios have essentially the same impact on the given objective, then the weight for that objective should be low. That is, because all portfolios are roughly equally fitted for meeting this objective, then with respect to this objective it does not matter which portfolio is selected and so the objective should not be considered in the decision-making process. If the portfolios have substantially different impacts on the objective under consideration, the designer should assign a high weight to the objective. The weights of the objectives, including cost, should sum to 1. If the designer uses this method, then the weights of the objectives are also known as *trade-off weights*, because the method involves "trading" the difference in portfolio-objective scores associated with one objective for the difference in scores associated with another.

In Step 8 the designer normalizes the raw portfolio-objective scores to make the comparison of totals meaningful. The normalization process results in a standardized distribution for each set of portfolio-objective scores. Each distribution ranges from a low score of zero to a high score of 1, 10, 100, and so on, if desired. If the designer uses expected value in decision making, calculation of the normalized portfolio-objective scores, called NP_iO_j, is by a linear function, such as Equation 2. Note that the normalization of cost scores requires subtraction of the NP_iQ_j calculated by using Equation 2 from the maximum normalized score, which is 10 in this case. This is because for cost less is better.

$$NP_iO_j = \frac{(10)[P_iO_j - \min(P_1O_j{:}P_IO_j)]}{[\max(P_1O_j{:}P_IO_j) - \min(P_1O_j{:}P_IO_j)]} \quad (2)$$

Many large organizations judge decisions by expected value; that is, they are risk neutral toward any single project. This is possible because diversification enables the organization to spread the risk over a number of projects. In contrast the designer might be risk averse or risk seeking (*8,9*). For example the designer might be risk averse in system design if there is no fallback position; the designer might play it safe and keep sufficient funds in reserve to counteract any potential large-scale failure. On the other hand the designer might be risk seeking in system design if the goal is exploratory research and the budget is relatively unrestricted; the designer might take risks in seeking a potential breakthrough in system design. Regardless of the reason, if the designer is not risk neutral, some form of nonlinear function must replace Equation 2.

In Step 9 the designer determines a total score, called TP_i, for each portfolio. The designer calculates each TP_i as a weighted sum of the normalized portfolio-objective scores, NP_iO_j, from Step 8. The appropriate weights are the trade-off weights of the objectives, OW_j, from Step 7. In short the designer uses Equation 3 to determine TP_i.

$$TP_i = \Sigma(OW_j)(NP_iO_j) \quad (3)$$

At Step 10 the designer selects a single portfolio for implementation. If no portfolio is clearly superior or no portfolio meets expectations, the designer can iterate the design process. Iteration could include obtaining more information about the subsystems, better elicitation of the designer's preferences, and perhaps better explication or even modification of the objectives.

A final word on the method is appropriate. If it is difficult to generate raw scores or weights, the designer can substitute natural language statements such as "approach *Q* is preferable to approach *R*." This type of substitution greatly complicates the analysis, however, because the designer must use inequalities in the analysis. Therefore the design process should handle only a very few items in this way.

ILLUSTRATION

Any method composed of 10 steps may understandably be difficult to grasp at first. This section illustrates the process to enable the reader to better understand the details. A fictional designer is followed through the process of planning an upgrade for a transit (bus) fleet of 100 vehicles. While reading through the illustration the reader may find it useful to occasionally refer to the preceding section.

Step 1, determination of an objectives hierarchy, is crucial to the ultimate usefulness of the design. After careful consideration the designer concluded that the hierarchy must incorporate three questions basic to transit system design. First, does the system as designed satisfy transit customers? That is, is the system "satisfying"? Second, does the transit authority have, or have access to through subcontract, the technical, systems integration, business, and management skills required to successfully implement and maintain the system as designed? That is, is the system "doable"? Third, does the transit authority have the financial resources to implement the system as designed? That is, is the system affordable?

Other objectives are also possible. For example a fourth question is important to transit system design. Does the system as designed adequately address policy issues such as mobility equity, energy conservation, and so on? For simplicity this question was left out of the illustration. Moreover political issues are important. However many designers might conclude, as in this example, that it is not politic to explicitly include politics as an objective. After further thinking the designer drew the rudimentary objectives hierarchy of Figure 3. If resources had been available the designer clearly could develop the hierarchy and carry out the design in greater detail.

In Step 2, determination of available subsystems, the designer included 13 subsystems. They were vehicle area network, vehicle self-diagnostics, automatic vehicle location, pacing, collision warning, smart card fare payment, digital voice and data radio, telephone-based itinerary selection assistance, information kiosks at major locations, computer integration of operations, transfer coordination, flexible routing, and automatic operator check-in.

Table 1 shows the matrix resulting from the designer's efforts in Step 3, determination of raw scores for the subsystem-objective pairings. Because the scores shown are for illustrative purposes only, the reader should not interpret any score as representing an actual or estimated value. Moreover inasmuch as the analysis is taking place at a high level in the objectives hierarchy, the designer had to score qualitatively.

Note that the designer focused on the objectives called *doable*, *satisfying*, and *affordable*. However in evaluating the affordability objective, the designer focused on set-up cost to the exclusion of operating cost and resources. The designer needs to consider these other objectives for the design to be complete; recall that the analysis must include one and only one objective between the highest and lowest levels of each branch of the hierarchy. However the designer estimated that future operating costs would be no greater than, and it is hoped would be significantly less than, current operating costs, and so continuation of the existing fare revenue

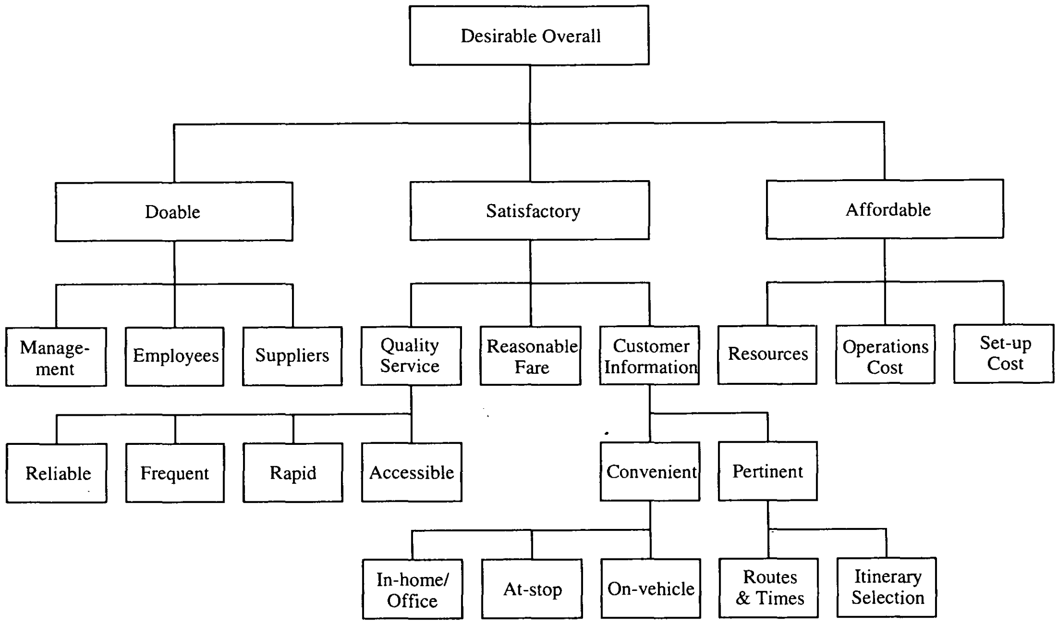

FIGURE 3 Example objectives hierarchy for transit system design.

and government subsidy could cover foreseeable needs. Therefore the designer temporarily set the issue of operating costs aside. The designer knew that the capital improvement budget was already available and fixed at $2,250,000, and so the resources were not included in the table either.

At this point the designer excluded the collision warning subsystem from consideration because of excessive cost. After elimination of collision warning, 12 subsystems were available, and so 2^{12} (4,096) portfolios resulted from the designer's initial attempt at Step 4. To circumvent this untenable situation the designer grouped the subsystems into three super subsystems, $S_{k'}$, of four subsystems each and continued with the design process. The first supersubsystem, which the designer called the vehicle-based supersubsystem, consisted of the vehicle area network, vehicle self-diagnostics, automatic vehicle location, and pacing subsystems. The second, or interface-based (vehicle-to-operations or customer-to-system), supersubsystem consisted of the subsystems providing smart card fare payment, digital voice and data radio, telephone-based itinerary selection assistance, and information kiosks at major locations. The third, or operations-based, supersubsystem, consisted of the subsystems providing computer integration of operations, transfer coordination, flexible routing, and automatic operator check-in.

Because three supersubsystems were available for inclusion in a portfolio, 2^3 (8) portfolios were possible, as shown in Table 2. The designer assumed that implementing the interface-based supersubsystem without the operations-based supersubsystem would seriously degrade the effectiveness of the former. Therefore the designer eliminated those portfolios with the interface-based supersubsystem but not the operations-based supersubsystem, that is, Portfolios 3 and 7. The designer also put Portfolio 1, the status quo, in the background.

In Step 5 the designer used knowledge of the system and the design environment to determine an appropriate set of supersubsystem weights. The designer thought that the interface-based supersubsystem would influence the success of implementation of the system design more than the vehicle-based and operations-based supersubsystems and believed that the latter were of equal importance to this objective. Therefore the weights given to the

TABLE 1 Raw Subsystem-Objective Scores (S_kO_j)[a]

		Objective j		
		O_1	O_2	O_3
Subsystem k		Doable [b]	Satisfying [c]	Affordable [d]
S_1	Vehicle Area Network	3	1	350,000
S_2	Vehicle Self-Diagnostics	3	3	400,000
S_3	Vehicle Location	4	4	200,000
S_4	Pacing	4	5	50,000
S_5	Collision Warning	1	1	Unknown; high
S_6	Smart Card Fare Payment	3	5	450,000
S_7	Digital Voice/Data Radio	4	2	400,000
S_8	Customer Telephone Aid	3	4	100,000
S_9	Information Kiosks	3	4	250,000
S_{10}	Integrated Operations	3	2	50,000
S_{11}	Transfer Coordination	3	4	10,000
S_{12}	Flexible Routing	1	5	100,000
S_{13}	Operator Auto-Check-in	4	0	10,000

[a] Scores given are for illustrative purposes only.
[b] Score represents designer-perceived probability of successful system implementation (scaled 1 to 5).
[c] Score represents customer-perceived service quality (scaled 1 to 5).
[d] Score represents dollars needed to equip a transit system of 100 vehicles.

TABLE 2 Portfolio Descriptions

	Super-Subsystem k'		
Portfolio i	$S_{1'}$	$S_{2'}$	$S_{3'}$
(System i)	Vehicle	Interface	Operations
P_1	no	no	no
P_2	no	no	yes
P_3	no	yes	no
P_4	no	yes	yes
P_5	yes	no	no
P_6	yes	no	yes
P_7	yes	yes	no
P_8	yes	yes	yes

three components for the doable objective were 0.4, 0.3, and 0.3, respectively. Furthermore the designer thought that the interface-based component was the most important to travelers; this was followed first by the vehicle-based component and then by the operations-based component. Thus the weights given to the three components for the satisfying objective were 0.5, 0.3, and 0.2, respectively. Finally the designer thought the three super-subsystems were relatively independent from the vantage point of implementation; that is, the designer did not foresee any cost break for joint implementation of the various components. As a result the designer did not reduce any of the weights for the cost objective from the initial values of 1.0, 1.0, and 1.0, respectively.

Note that in this illustration the subsystem weights did not vary across portfolios. However for analyses done at a greater level of detail the weights might well vary across portfolios because of synergism among the subsystems for example. Furthermore many designers might find it difficult to provide weights of the form given in the illustration if the analysis requires more than a few weights. However most designers are able to rate each subsystem on a scale of, say, 1 to 100. These intermediate ratings are easy to normalize into the desired form.

The results from Step 6, determination of the raw portfolio-objective scores, are shown in Table 3. The designer calculated these scores using Equation 1, the subsystem weights from Step 5, and the raw subsystem-objective scores from Table 1. To get the supersubsystem scores from Table 1 the designer averaged the appropriate subsystem scores for the doable and satisfying objectives and summed the values for the affordable objective. Portfolio 8 clearly cost too much and the designer eliminated it.

In Step 7, determination of the objectives trade-off weights, the designer calculated the low/high difference in raw portfolio-objective scores for the doable, satisfying, and affordable objectives to be 1.3, 1.875, and $1,200,000, respectively. According to the perceived relative significance of these differences, the designer assigned weights of 0.3, 0.3, and 0.4, respectively, to these objectives.

In Step 8 the designer normalized the raw portfolio-objective scores from Table 3 using Equation 2. The result of such action is shown in Table 4, along with the total portfolio scores, which are described next.

To calculate the total portfolio scores, Step 9, the designer combined the normalized portfolio-objective scores from Step 8 using Equation 3 and the associated weights of the objectives from Step 7. Table 4 contains the weighted sums, which represent each total portfolio score, in addition to the normalized portfolio-objective scores from Step 8.

At this point the designer found Step 10, selecting the desired portfolio, to be straightforward. Portfolio 4, composed of the interface- and operations-based supersubsystems and costing $1,370,000, had the highest total score, so the designer chose it as the systems design.

TABLE 3 Raw Portfolio-Objective Scores (P_iO_j)[a]

Portfolio i (System i)	Objective j: O_1 Doable [b]	O_2 Satisfying [c]	O_3 Affordable [d]
P_2	0.825	0.550	170,000
P_4	2.125	2.425	1,370,000
P_5	1.050	0.975	1,000,000
P_6	1.875	1.525	1,170,000
P_8	3.175	3.400	2,370,000

[a] $P_iO_j = \Sigma\,(SW_{ijk'})\,(S_{k'}O_j)\,(PS_{k'})$; the $SW_{ijk'}$ are from Step 5 (SW_{i11}=0.3, SW_{i12}=0.4, SW_{i13}=0.3; SW_{i21}=0.3, SW_{i22}=0.5, SW_{i23}=0.2; SW_{i31}=1.0, SW_{i32}=1.0, SW_{i33}=1.0), the $S_{k'}O_j$ are derived from Table 1 by averaging the appropriate subsystem scores, S_kO_j, for the doable and satisfying objectives and summing the scores for the affordable objective, and $PS_{k'}$ is 1 if the portfolio has super-subsystem $S_{k'}$ and 0 if not.
[b] Score represents designer-perceived probability of successful system implementation (scaled 1 to 5).
[c] Score represents customer-perceived service quality (scaled 1 to 5).
[d] Score represents dollars needed to equip a transit system of 100 vehicles.

TABLE 4 Normalized Portfolio-Objective Scores (NP_iO_j) and Total Portfolio Scores (TP_i)

Portfolio i (System i)	Normalized Portfolio-Objective Scores [a]: O_1 Doable	O_2 Satisfying	O_3 Affordable	Total Portfolio Scores [b]
P_2	0.0	0.0	10.0	4.0
P_4	10.0	10.0	0.0	6.0
P_5	1.7	2.3	3.1	2.4
P_6	8.1	5.2	1.7	4.6

[a] $NP_iO_j = (10)[P_iO_j - \min(P_1O_j{:}P_IO_j)] / [\max(P_1O_j{:}P_IO_j) - \min(P_1O_j{:}P_IO_j)]$.
[b] $TP_i = \Sigma\,(OW_j)\,(NP_iO_j)$; the OW_j are from Step 7 (OW_1=0.3, OW_2=0.3, OW_3=0.4).

DISCUSSION OF RESULTS

In the illustration a set amount of money was available and the designer needed to determine what level of sophistication the transit authority could implement. The reverse case is also possible; the designer can use the method both to determine the budget needed for capital improvement and to justify the inevitable appeal to governmental authorities (through a request for capital improvement funds), to the private sector (through issue of bonds or stocks), or to the general public (through proposal of a tax to support transit) to attain the funds necessary to implement the design. In other words the designer can develop a shopping list to show the community that at certain levels of funding, certain transit system functions are available.

The designer can also use the analysis to determine what percentage of the transit fleet the transit authority can afford to equip and how much less a given subsystem would have to cost to become feasible. For example if the designer had kept Portfolio 8 in the illustration and maintained the same objective weights, further analysis would show that reducing the cost of the vehicle-based supersubsystem by 15 percent, or equipping only 85 percent of the fleet, would have brought Portfolio 8 within budget and made it the best choice. The same would be true if the designer could increase the budget slightly.

The MAUT approach is also quite useful as a tool for developing requests for proposals to upgrade capital and operations and for evaluating systems designs submitted in response to those requests. The Ann Arbor Transportation Authority (AATA) in Ann Arbor, Michigan, is applying the method in this manner. Note that in systems evaluation, as opposed to systems design, relatively few portfolios exist because the number of portfolios equals the number of systems submitted in the competition, and the number of bids is commonly low. This greatly simplifies the evaluation at the expense of reducing the potential options.

Because the MAUT framework presented here represents an explicit and rational process, it is a good mechanism for drawing out needs, identifying solutions, and justifying decisions. Therefore the method should prove useful whether it is used to design systems or evaluate proposals.

The authors hope that this paper and the AATA experience (the results of which will be available soon) will stimulate discussion that might influence the development of a nationwide specification for APTSs. It is hoped that such a specification will detail a standard, open transit system design that addresses issues concerning systems architecture, technologies, and services from functional as well as product aspects. An appropriate APTS specification will also incorporate the current system and yet be highly amenable to modular expansion and upgrades in the future. For universal appeal any specification must be applicable in both large and small transit systems.

To develop a transit system capable of achieving desired transit objectives it will likely prove to be necessary to coordinate the entire transportation system by means of the process known as *mobility management.* Intermodal transportation linked by intermodal information may prove to be essential to future tansit competitiveness. Furthermore expansion of the system design process to encompass the larger community will be essential. Specifically the transit authority will need to gain the collaboration of authorities responsible for planning and oversight of roadways, land use zoning, and travel and parking regulations (*4*) as well as the cooperation of numerous community and special interest groups. Implicit in any transit growth scheme are cooperation and coordination regarding multijurisdictional, multiparty issues. Management of this larger problem might require broader methodologies such as social decision analysis (*10*) or policy exercise (*11*).

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