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Smarter system development: a systems engineering trade study to support green initiatives with model-driven development.

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Introduction

We know they're an essential part of the systems engineering process. Trade studies help us fully explore the design space to ensure that a proposed solution best meets conflicting performance and cost requirements. But many of us don't know that you can analytically and objectively conduct your trade studies well before you engineer anything. Using a model-driven approach with IBM Rational® Rhapsody® software, you can determine which solution will best capture stakeholder requirements while also justifying your engineering decisions.

This paper describes a multivariable decision problem based upon the selection of a power source for an environmentally conscious but cost-effective family-size vehicle for the European/United Kingdom (U.K.) marketplace. Stakeholders' primary requirements for the vehicle are green credentials and low fuel costs, which are shown in U.K. pounds (£). Figure 1 captures the two primary requirements, as well as several others.
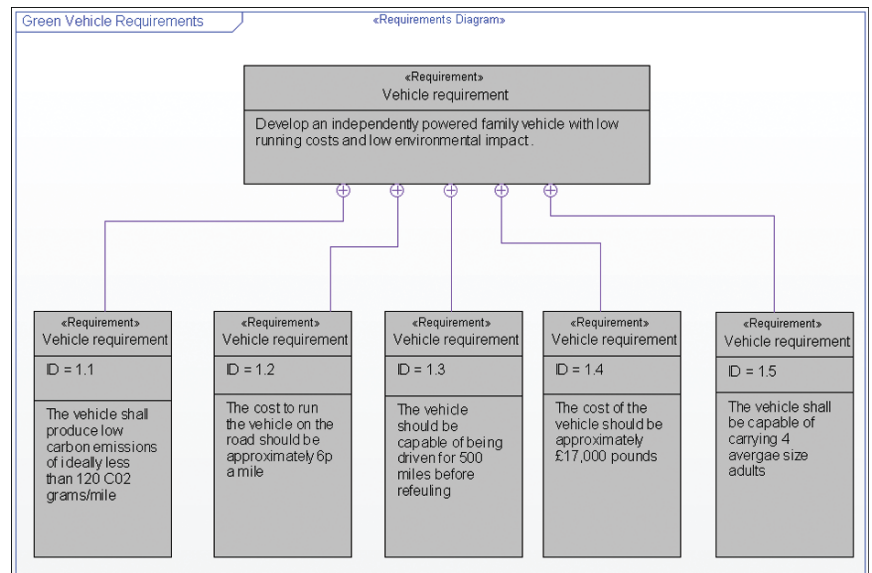

Figure 1: High-level requirements diagram

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Highlights

Weighted objectives method: A means of rationally evaluating a number of potential solutions to a problem.

In this paper, we'll work through each stage of the weighted objectives method and use Rational Rhapsody software to determine which vehicle type best fits our requirements.

The process we're going to follow is based on the workflow described in the third version of *The Harmony Deskbook*[1] (a helpful guidebook to which this author also contributed). To evaluate the potential solutions, we'll employ a technique known as the *weighted objectives method*,[2] and we'll automate the process using Rational Rhapsody software (as implemented by A. Lapping, a colleague to whom this author owes great thanks). Each stage of the process, apart from the task "merge solutions to form system architecture," will be detailed in a worked example, and we'll briefly discuss the implementation in Rational Rhapsody software. Our green vehicle example only focuses on one key system function, so the final stage in figure 2 will not be discussed.
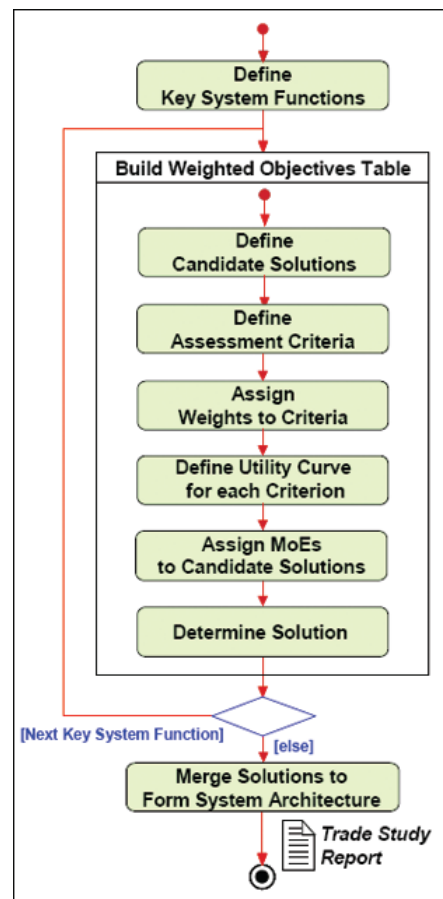

Figure 2: Trade study workflow

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Key system functions: A grouping of system functions.

We employ use-case diagrams and activity diagrams to identify key system functions.

It's worth noting that, although the figures used in this example are sourced from published information, the final results should not be taken as definitive. Our intent is to provide an example of how to use the modeling method and the Rational Rhapsody tool; we're not implying that electric vehicles will save the world in the very near future.

Identify key system functions

The first step in our trade study analysis is to identify *key system functions*, which are derived from the activity diagram that describes the functional flow within the system. In our example, we're interested in the functional flow that causes the vehicle to move (based upon the use-case diagram "drive vehicle," which is shown in figure 3).
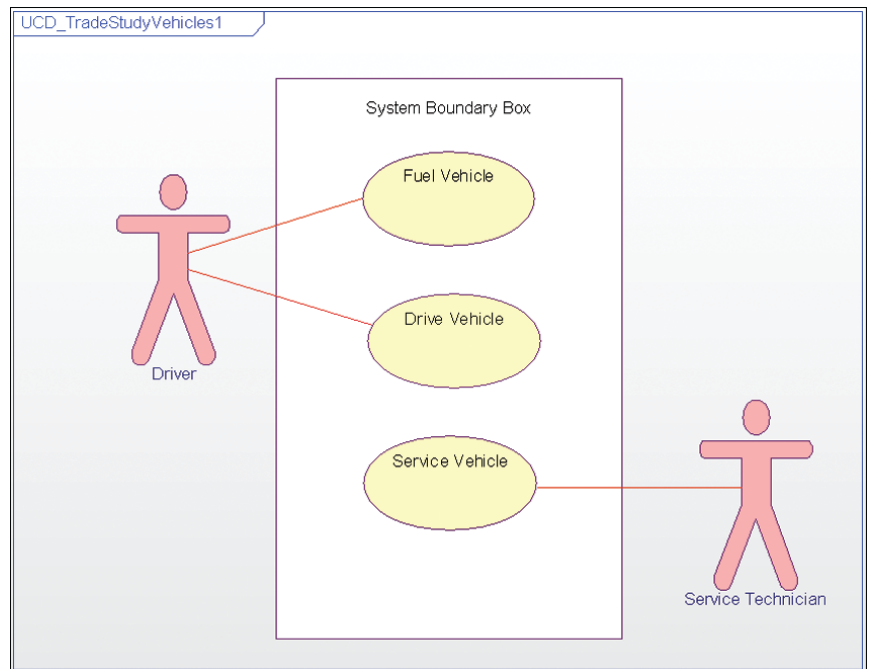

Figure 3: Use-case diagram for a green vehicle

The "drive vehicle" use case is broken down into the simple functional flow shown in the activity diagram in figure 4.

The "drive vehicle" use case illustrates the details involved in the "provide motive force" key system function.
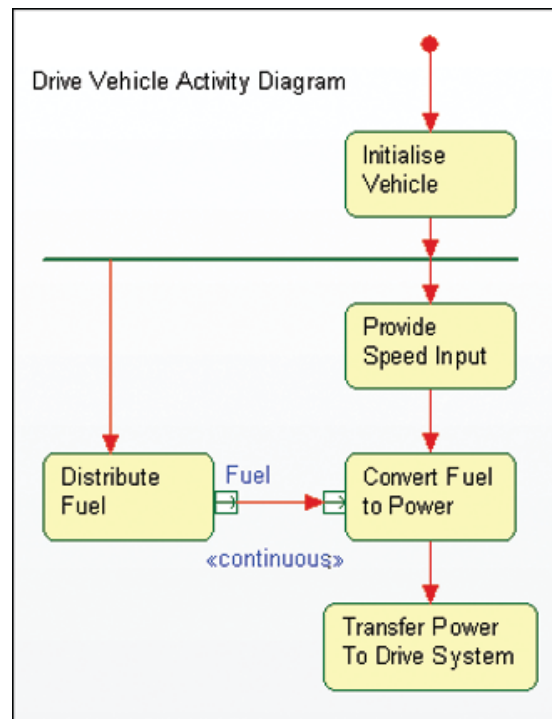

Figure 4: "Drive vehicle" activity diagram

When the driver provides a speed input—that is, when he or she accelerates—the vehicle's power system draws fuel to itself from the fuel distribution system. From there, it converts the fuel to power and transfers it to the drive system. The key system function here is captured in the actions "distribute fuel" and "convert fuel to power," which can be combined to form the key system function "provide motive force" (figure 5).

In figure 5, we add the key system function "provide motive force" to the "drive vehicle" activity diagram.
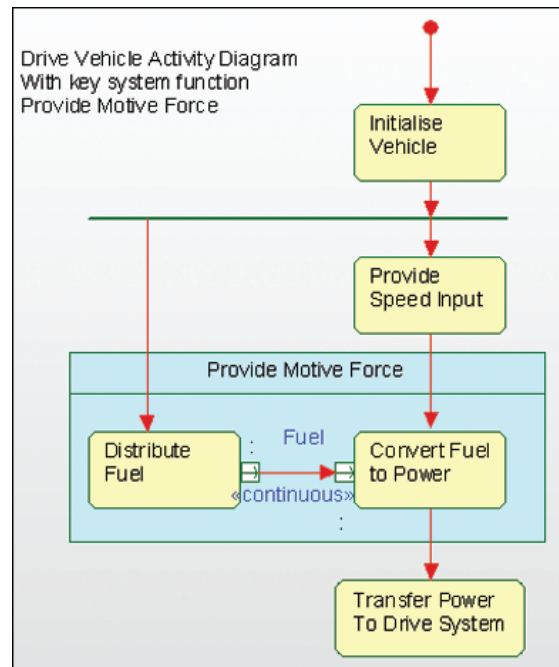

Figure 5: Activity diagram with key system function identified
(Note: Normally, you would not show the grouping on the activity diagram. This is for display purposes only.)

We're creating key system functions because, if separate trade studies were performed on "distribute fuel" and "convert fuel to power," it's possible that:

- *Incompatible solutions could be found (e.g., combining an electrical power network with a clean diesel engine).*
- *Potential solutions to the key system function could be ignored because the functions that need to be realized are too granular. If you take this approach, you'll end up studying partial solutions.*

Neutral solution problem definition: A way of describing a problem so that potential solutions are not indicated in the definition.

We've named the key system function "provide motive force" so that we get what is known as a *neutral solution problem definition*, a definition of the problem that does not identify a solution and thereby restrict the solution space. A bad key system function would be, for example, "provide a diesel engine."

Define candidate solutions

Once the key system function has been identified, we need to find potential solutions to fulfill it. In this instance, we'll investigate the following three possible solutions:

- *Liquefied petroleum gas (LPG) system*
- *Hybrid electric vehicle system*
- *Electric-powered vehicle system*

Block definition diagram: A SysML diagram that displays SysML blocks and their structural and communication relationships to one another.

In Rational Rhapsody, these solutions are shown in a *block definition diagram*, where a single block represents the key system function and the three potential solutions are connected to it via generalization relationships (figure 6).
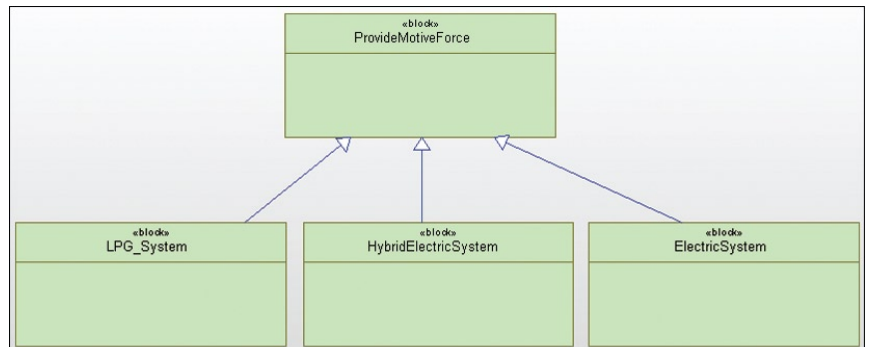

Figure 6: Key system function and potential solutions

Define assessment criteria

Assessment criteria: Characteristics of the required system against which the potential solutions are assessed.

The next stage is to identify the *assessment criteria*, or the factors against which we'll be measuring each candidate solution. Much more accurate results are produced when you assess potential solutions against a large number of criteria, but this approach also takes more time, since it requires reliable information for the analysis to work successfully. Our example has four assessment criteria.

Assessment criteria can be derived from the requirements or generated from techniques such as brainstorming, focus groups, customer needs analyses, quality function deployment analyses or others. Our criteria are based on our requirements (as identified in figure 1), and they include:

- *Low emissions (from requirement 1.1).*
- *Low fueling cost (from requirement 1.2).*
- *Long range (from requirement 1.3).*
- *Predicted vehicle cost (from requirement 1.4).*

The assessment criterion for low fueling cost is a derived figure based upon the cost to fully charge a battery or to fill an average tank with fuel, combined with the range the vehicle travels on the full charge or tank. Later in this paper we'll show how a parametric diagram can be used to determine an assessment value for these criteria.

Incidentally, although requirement 1.5 (figure 1), which helps define vehicle size, isn't as important to us as requirements 1.1 through 1.4, it weighs in heavily for the electric vehicle. Our vehicle design must accommodate a family of four, but typical electric-system vehicles are two-seaters. To make one a four-seater requires a larger power source and a more powerful drive system—and these factors will be reflected in the price.

Once we identify the assessment criteria, we add them as attributes—stereotyped as <<*moe*>>s—to the key system function (figure 7). The term *MoE* will be described later.
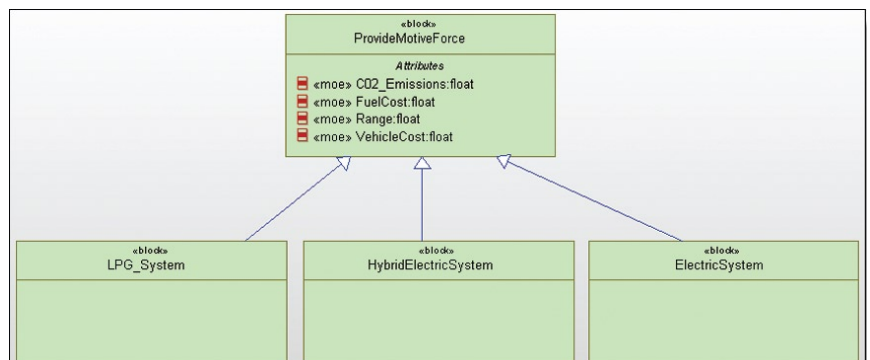
Figure 7: Key system function with MoEs

At the heart of the weighted objectives method are the weights of assessment criteria.

Rational Rhapsody software assigns weights for you, which facilitates a more careful analysis.

Assign weights to the criteria

Before we can effectively employ the weighted objectives method, we need to assign a weight to each assessment criterion. Weights indicate the importance of a particular criterion; the more important a feature is to a stakeholder, the higher the weight. The sum total of the weights should not exceed 1. In our example, we know that the most important assessment criteria to our stakeholders are low CO_2 emissions and low fuel cost. The range and predicted vehicle cost are less important. Given these criteria, we'll assign the following weights:

Low emissions	0.3
Low fueling cost	0.3
Long range	0.2
Predicted vehicle cost	0.2
Total	**1.0**

Given that they have a heavy impact on the solution, these weights should be analyzed properly before any calculation takes place. Ordinarily, stakeholders and subject-matter experts would get together to determine the appropriate weights, but in Rational Rhapsody, weights are assigned directly to the *<<moe>>*s using weight tags (figure 8).
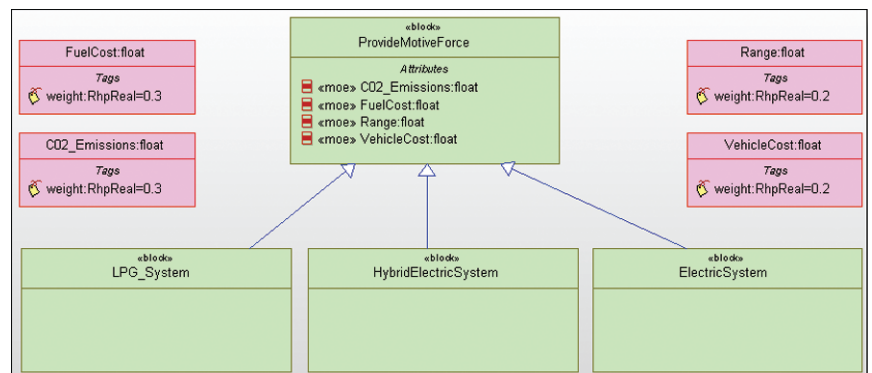

Figure 8: MoEs with weight tags assigned

Next, we're going to employ a feature of the Rational Rhapsody system engineering toolkit that copies the *<<moe>>*s into the possible solutions. This gives the block definition diagram shown in figure 9.
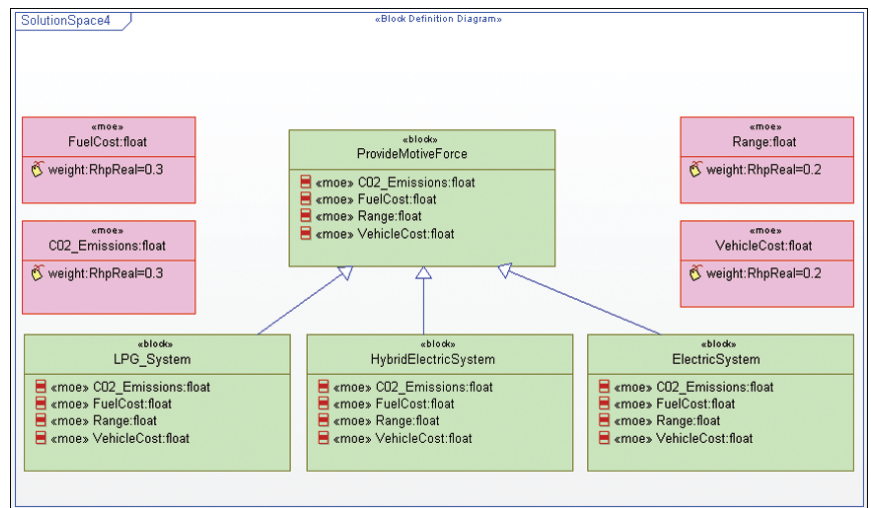

Figure 9: Solutions with MoEs

Defining utility curves

Utility curve: A means of relating the assessment criteria to the measure of effectiveness (MoE).

Measure of effectiveness (MoE): A measure of how well a potential solution meets a particular assessment criterion.

A *utility curve* defines the relationship between the value of a specific assessment criterion for a solution and what is known as the *measure of effectiveness* (or *MoE*). To determine the MoE, you input the value of specific assessment criteria to a graph, or mathematical function, that represents the utility curve. From this, the MoE is obtained. It's ranked between 0 and 10 (where 0 shows a low MoE and 10 shows a high MoE).

There are a number of ways to determine the form of a utility curve. But it's important to note that, for each utility curve, the units (e.g., grams, pence, miles) used to describe the X-axis range reflect the particular characteristics in a certain domain. They aren't necessarily international standard units.

Used to relate assessment criteria to the measure of effectiveness, utility curves can be determined using a variety of methods.

Example A

Give the optimal value for the assessment criteria an MoE value of 5. Then, select the assessment criteria range. In this example, let's use plus or minus 50 percent around the optimal value. Give the upper and lower values an MoE score of 10 and 0, respectively, and draw a straight line through all three points to give a straight-line utility curve. We used this technique for the fuel cost, range and vehicle cost utility curves.

Example B

First, identify which assessment criterion you believe will provide the best expected value, and give it an MoE of 10. Then, determine the worst-case value of the assessment criteria, and give it an MoE of 0. To get the utility curve, draw a straight line between the points. Figure 10 shows an example where the ideal purchase cost for a component is US$0. This criterion gets an MoE of 10. The least-ideal purchase cost is US$400; it gets an MoE of 0.
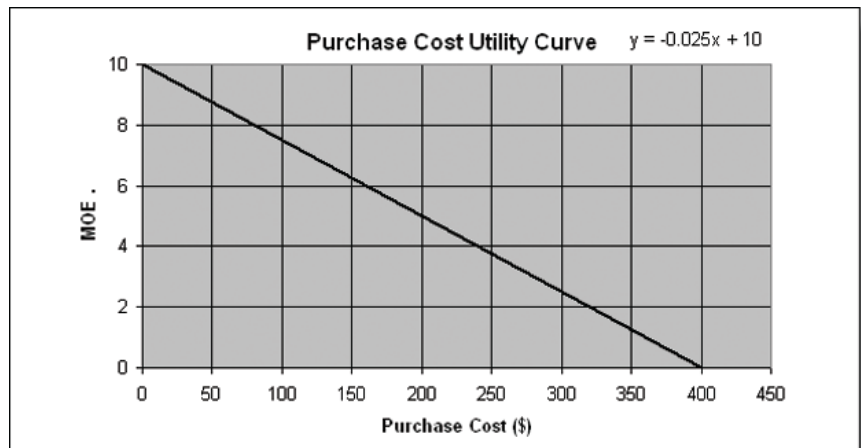

Figure 10: Straight-line purchase cost utility curve

Example C

Determine an optimal point to give an MoE of 10, and select a range such that if the actual criterion is less than or more than the optimum, the MoE trails off to 0 (this will generally give an arc of some description). This indicates that the solution being considered is either under- or overspecified. In figure 11, the mechanism under consideration is required to lift a mass through an optimal distance of 1.1 meters.
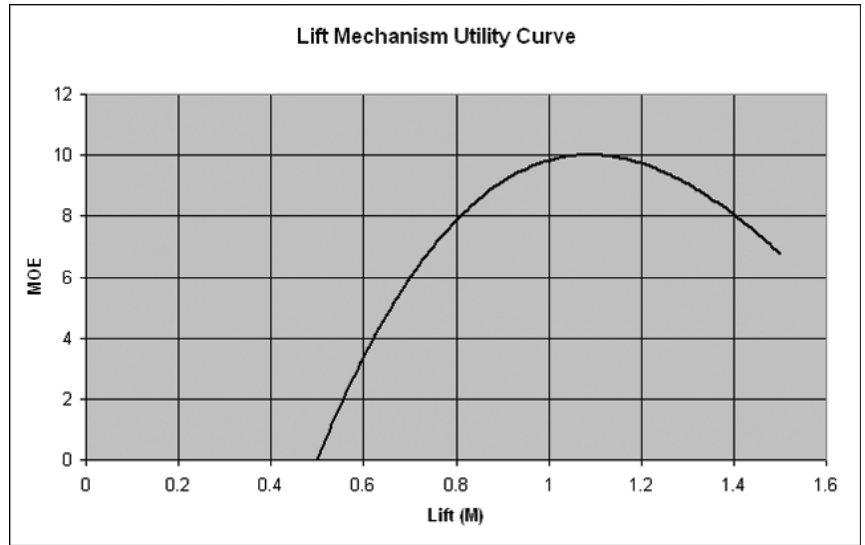
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Figure 11: Nonlinear utility curve

Example D

Some stakeholders and subject-matter experts define a curve in a subjective manner—for example, as a step function or nonlinear curve—and use this as the utility curve.

The next step in our process is to determine utility curves for each of our assessment criteria.

The utility curve for all the assessment criteria in our green vehicle example is a straight-line curve based upon the equation $Y = MX + C$ where:

- *Y is the output MoE.*
- *M is the range of the measure (this gives a -ve value for a negative slope and a +ve value for a positive slope).*
- *X is the value of the assessment criteria.*
- *C is the maximum permissible value of the MoE, assuming 0 is the lowest permissible value.*

The emissions requirement indicates a maximum target value of 120 CO_2 grams per kilometer (g/km). Because an electric vehicle has no emissions, this gives a range of 0 to 120 CO_2 g/km, which provides the following utility curve for the emissions MoE:

$$[10 \div (0 - 120)] \times (X - 0) + 10$$

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The fuel cost requirement indicates a target value of 6 pence per mile (ppm). Plus or minus 70 percent gives a range between 1.8 and 10.2 ppm. This gives the following utility curve for the fuel cost MoE:

$$[10 \div (1.8 - 10.2)] \times (X - 1.8) + 10$$

The range requirement indicates a median value of 500 miles. Because electric vehicles have a low range of approximately 100 miles, we will make this assessment between 100 and 900 miles. This gives the following utility curve for the vehicle range MoE:

$$[10 \div (900 - 100)] \times (X - 100) + 0$$

The predicted vehicle cost requirement indicates a target value of £17,000. Plus or minus 50 percent gives £8,500 to £25,500. This gives the following utility curve for the predicted vehicle cost MoE:

$$[10 \div (8,500 - 25,500)] \times (X - 8,500) + 10$$

After we arrive at our utility curves, we determine measures of effectiveness for each of our criteria.

Determine measures of effectiveness

To define how well the candidate solution meets the median value, we need to find the actual value of the candidate solution for each assessment criterion. Then we'll input this value to the relevant utility curve—which we determined in the previous section—to give the MoE.

CO_2 emissions

Research has indicated that LPG systems perform similarly to light-duty diesel vehicles. This would give us an average CO_2 measure of approximately 110 g/km. For electric systems, the effective CO_2 is 0 g/km. For hybrid electric systems, the figure for CO_2 approximates to 104 g/km.

The electric vehicle has the best MoE in terms of CO_2 emissions.

Emissions	Actual value in CO_2 g/km	MoE
LPG system	110	0.83
Electric system	0	10.00
Hybrid electric system	104	1.33

In terms of vehicle cost, the electric system has the best MoE.

Vehicle cost

A typical small, gasoline-powered vehicle is averagely priced at £14,000. Most of the solutions we'll be investigating are more expensive, so our target cost is closer to £17,000.

Due to the expenses for the compressed gas tank, compressor pump and other changes to the vehicle, an LPG system costs an extra £2,000. This gives us a value of £16,000 for this vehicle type.

As we mentioned before, the price for an electric vehicle is typically based on the cost of a two-seater. Since we need to consider a four-seater for a family model, we've extrapolated an additional expense of 80 percent, resulting in a cost of £25,200.

Compared to a standard gasoline/diesel-based vehicle, hybrid electric vehicles are 20 percent more expensive. This gives a total cost of £16,800.

Vehicle cost	Actual value in pounds	MoE
LPG system	16,000	5.59
Electric system	25,200	0.18
Hybrid electric system	16,800	5.12

Vehicle range

LPG systems are typically fitted with a 90-liter tank, approximately equivalent to 20 imperial gallons. Since, for safety reasons, the tank can only be filled to 80 percent of its capacity, the final volume of the tank is 16 gallons. LPG has also been found to be 30 percent less efficient than gasoline. This means that if we assume a gasoline mileage of 40 miles per gallon, we get 28 miles per gallon for LPG and a range of 448 miles for a 90-liter tank.

Due to the size, cost and capacity of the batteries, electric vehicle systems tend to have very low range, typically around 100 miles.

Hybrid electric systems are not dependent upon electric charges, as they store electricity from regenerative braking and the motion of the vehicle. A typical hybrid electric vehicle can get around 56 miles to the gallon, giving it a range of 896 miles for a 16-gallon tank.

Range	Actual value in miles	MoE
LPG system	448	4.35
Electric system	100	0.00
Hybrid electric system	896	9.95

Fuel cost per mile

The MoE calculation for fuel cost per mile is achieved by taking the average cost to fill or charge a vehicle and dividing it by how far the vehicle will travel. Because it is derived, the relationships between the filling cost and the mileage could be detailed in a Systems Modeling Language (SysML) parametric diagram. A graphical means of showing mathematical relationships, *parametric diagrams* can be used to understand the interaction between relationships, thereby helping us understand how to derive the calculations that give the actual assessment value for specific criteria.

The building blocks of parametric diagrams are *constraint blocks*, which detail the mathematical relationships in a system. They can either be very primitive (e.g., divide or multiply) or more complex (e.g., give a straight-line curve). If the constraint blocks are primitive, they give more scope for reuse in other applications. The constraint block is then employed on a parametric diagram as a constraint property.

To calculate the fuel cost per mile, we'll take the cost to charge or fill the tank of the system and divide it by the range in miles. This equation is shown in the constraint block in figure 12, where the divide function is created in a block definition diagram. The *parameter constraints* (the pins on either side of the constraint block) provide the binding to the variables in the constraint itself.
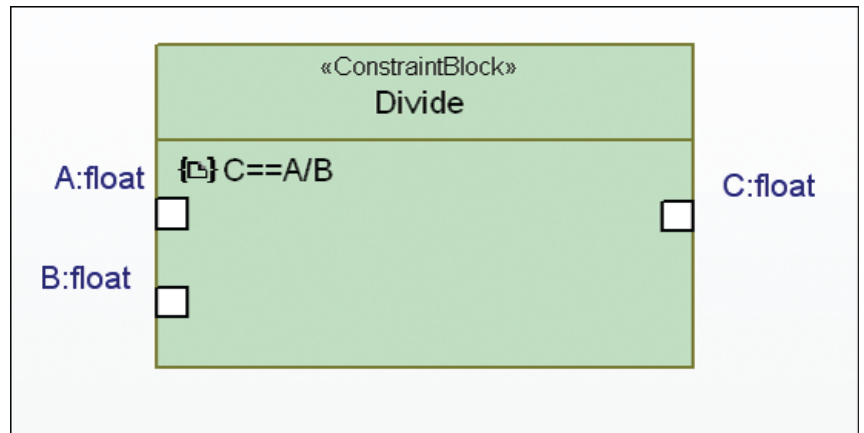
Figure 12: A divide constraint block

The parametric diagram that shows the usage of the divide constraint block is shown in figure 13. It takes the values of fill cost and mileage range and, based upon the parametric constraint $C = A \div B$, gives the fuel cost per mile.
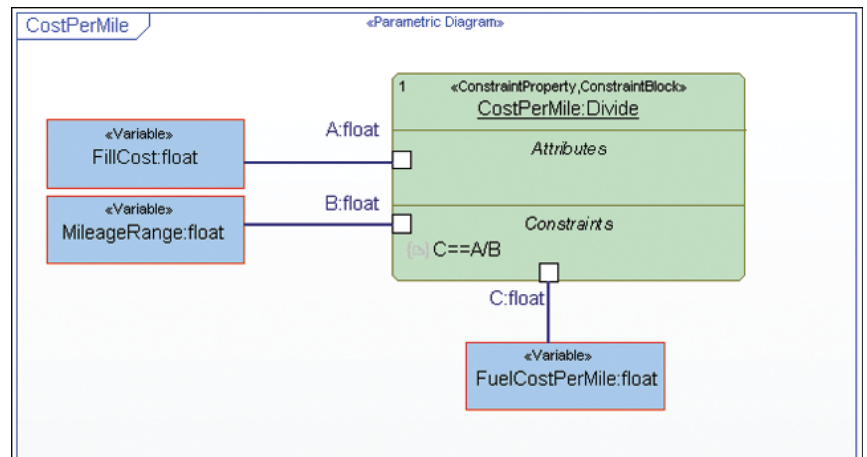

Figure 13: Fuel cost per mile parametric diagram

Parametric diagrams are useful for showing the mathematical relationships between abstract concepts.

Although parametric diagrams are not currently executable, they do provide a useful way of graphically showing the mathematical relationships between various abstract concepts. The parametric diagram in figure 12 was used as the basis for understanding and carrying out the calculations that follow.

The electric system vehicle has an extremely low fuel cost of £2 per battery charge.

LPG systems have a low fuel cost because they perform light-duty work. To fill a 90-liter tank of an LPG system costs £36. If we divide this by the 448 miles the vehicle could cover on this full tank, we get a fuel cost of 8 ppm.

Although the cost of charging an electric vehicle is greatly affected by taxes, research has shown that charging a typical battery costs approximately £2. If we divide this by the 100 miles the vehicle could cover on the full charge, we get a fuel cost of 2 ppm.

Hybrid systems use batteries (even though no charging costs are involved), and they also use diesel or regular gasoline. To fill the 90-liter tank in one of these vehicles costs approximately £75. If we divide this by the 896 miles the vehicle could cover on the full tank, we get a fuel cost of 8.4 ppm.

Fuel cost per mile	Actual value in ppm	MoE
LPG system	8.0	
Electric system	2.0	
Hybrid electric system	8.4	

To show the relationship between the fuel cost per mile and the final MoE, a second constraint block can be defined (figure 14). Representing a straight-line curve, this constraint is based upon the utility curve equations described earlier, where C is a constant set at 10. It's a good candidate for a constraint block because it can be used in several ways—three of which we'll discuss next.

Highlights

Combining the straight-line curve constraint block with the cost-per-mile constraint property, we can determine the relationship between the MoE and the assessment value.
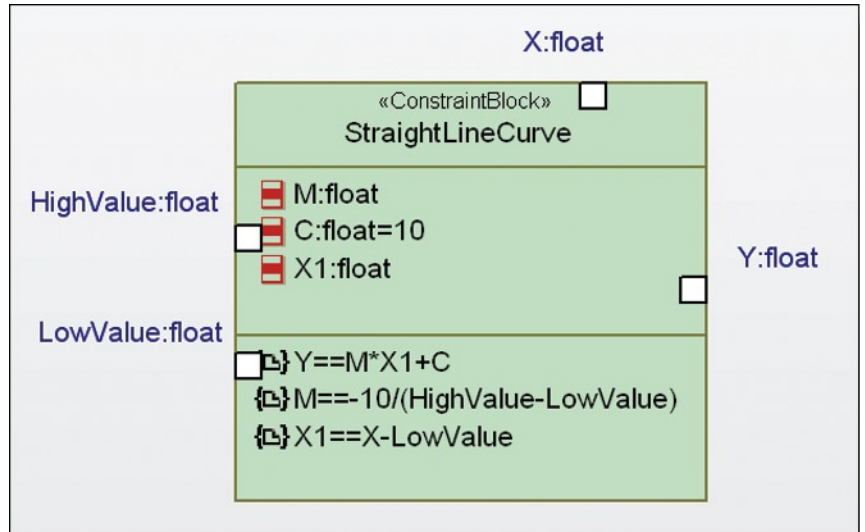

Figure 14: Straight-line curve constraint block

If we use the straight-line curve constraint block and combine it with the cost-per-mile constraint property, we can define the relationship between the MoE and the assessment value (figure 15).
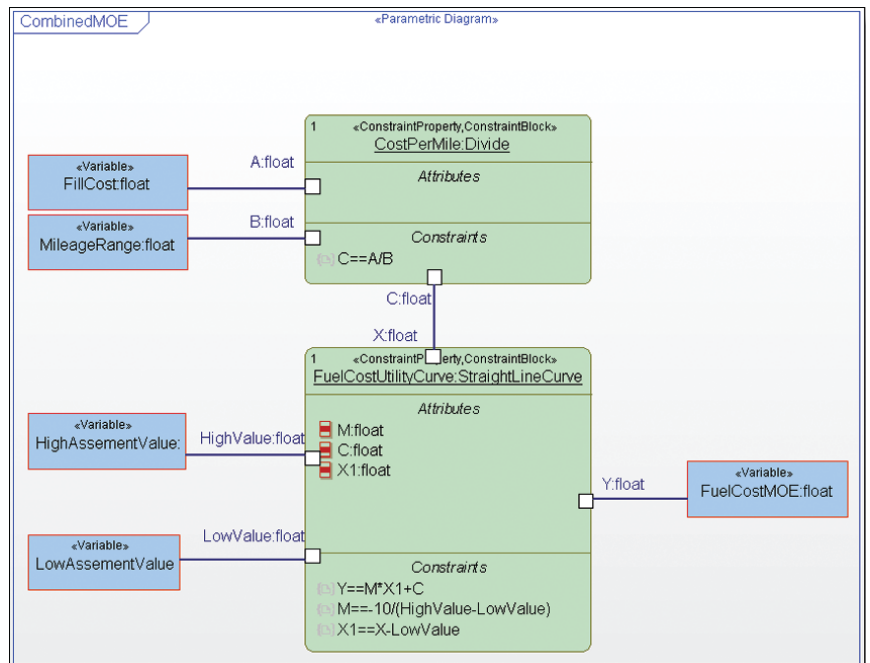

Figure 15: Fuel cost MoE parametric diagram

Based upon these parametric diagrams, we can then calculate the values for the fuel cost per mile.

Fuel cost per mile	Actual value in ppm	MoE
LPG system	8.0	2.62
Electric system	2.0	9.76
Hybrid electric system	8.4	2.14

Determine solution

Weighted objectives table: A summary of the results of the weighted objectives calculation.

Now that we have all this essential information, we're ready to calculate the *weighted objectives table*. It combines the MoEs and the weights for the various assessment criteria. A summary of the MoE results is shown below.

MoEs for "provide motive force"	Emissions	Fuel cost per mile	Range	Vehicle cost
LPG system	0.83	2.62	4.35	5.59
Electric system	10.00	9.76	0.00	0.18
Hybrid electric system	1.33	2.14	9.95	5.12

When the MoE is less than 0 or greater than 10, we know that the actual assessment value is outside the expected range for that particular assessment. If any of the MoEs exceed the 0–10 range, we need to adjust the range and/or the utility curve.

We've gone to some length to show how analytical and objective MoE determinations can be. But they can also be subjective when they're determined from the views of stakeholders, subject-matter experts, focus groups and so on. Subjective determinations are often conducted to obtain a consensus on how well the proposed solution meets the assessment criteria.

The weighted objectives table is calculated by first adding the MoEs to the blocks representing the various solutions (figure 16).

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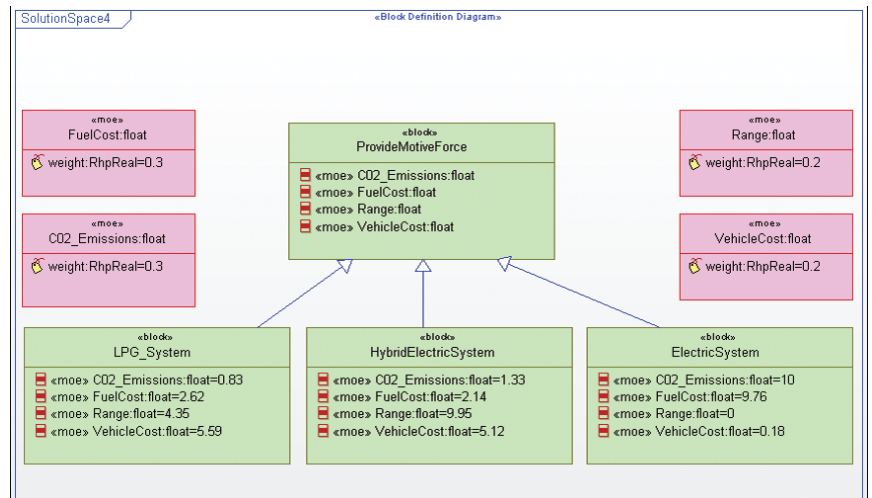
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Figure 16: Solutions with MoE values added

Solution block diagrams allow us to build combinations of candidate architectures that can help us find solutions to several key system functions at once.

Once we've added the MoEs to the blocks representing the solutions, we need to add a second block definition diagram. This diagram contains solution architectures and allows us to build combinations of several candidate architectures that we may want to investigate, thus allowing engineers to find solutions to several key system functions at one time. For more complex solution architectures, we would create a separate block definition diagram for each potential architecture. Our example only has one set of solution architectures, so we're creating three blocks for our three solutions—family LPG vehicle, family electric vehicle and family hybrid vehicle. And we'll join the solutions with a composition connector to the MoE blocks (figure 17).

Highlights
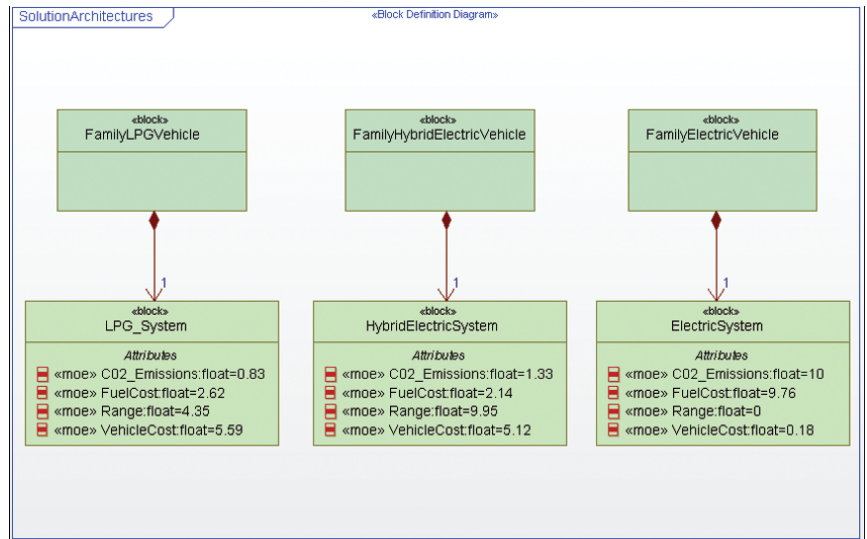
Figure 17: Solution architectures

The final block definition diagram brings the candidate solutions together to be analyzed.

The final stage is to create a third block definition diagram that brings the three candidate solutions together so that they can be analyzed (figure 18).
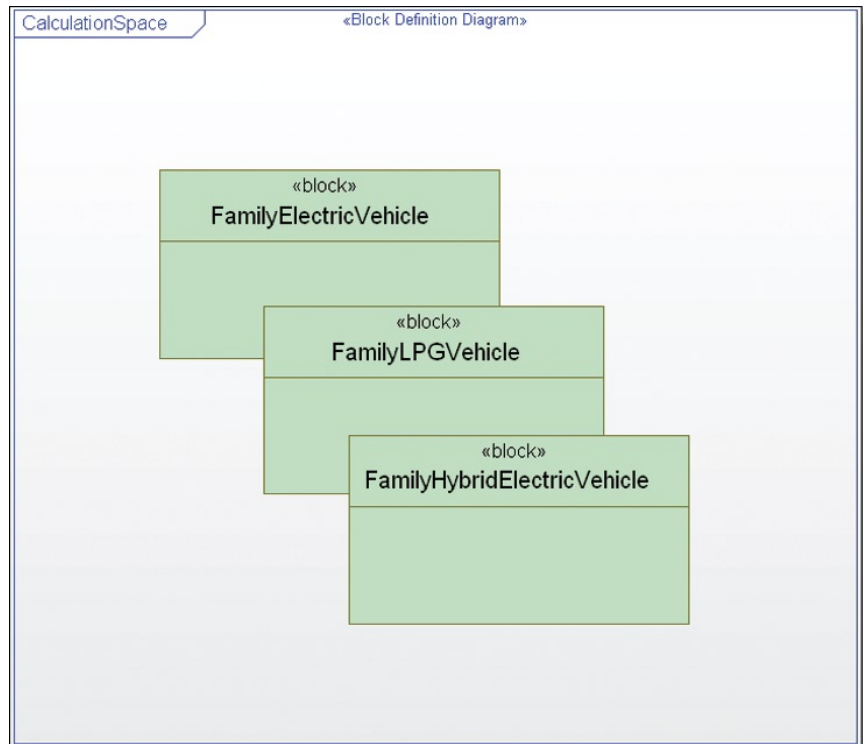

Figure 18: Solutions to be analyzed

Highlights

Rational Rhapsody enables us to calculate the trade study via the "perform trade analysis" feature.

The actual trade study calculation is carried out via the "perform trade analysis" feature of the Rational Rhapsody system engineering toolkit. After we apply this command to the block definition diagram that contains the solutions to be analyzed (figure 19), the Rational Rhapsody software produces a Microsoft® Excel spreadsheet that contains the results of the weighted objectives table (figure 20).
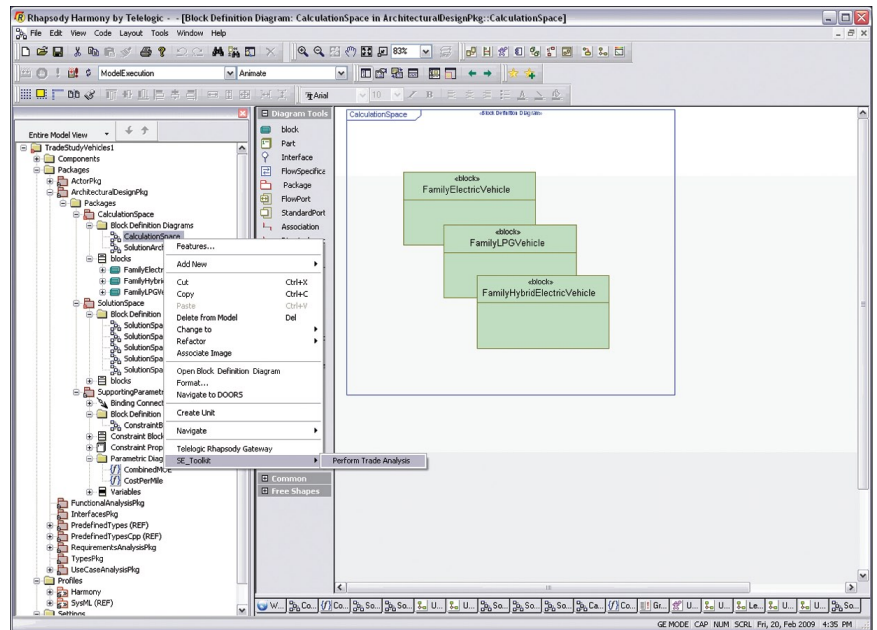
Figure 19: Perform trade analysis

To complete the weighted objectives table, we multiply the assessment criteria by their respective MoEs.

We calculate the weighted objectives table by taking the weight of each assessment criterion and multiplying it by the relevant MoEs. Then, we take those results and add them up to get an overall value for each of our three potential solutions. The system architecture with the highest score is the best potential solution.

	A	B	C	D	E	F	G	H
1			*FamilyElectricVehicle*		*FamilyLPGVehicle*		*FamilyHybridElectricVehicle*	
2		*weight*	value	WV	value	WV	value	WV
3	*ProvideMotiveForce.C02_Emissions*	*0.3*	10	3	0.83	0.249	1.33	0.4
4	*ProvideMotiveForce.FuelCost*	*0.3*	9.76	2.928	2.62	0.786	2.14	0.64
5	*ProvideMotiveForce.Range*	*0.2*	0	0	4.35	0.87	9.95	1.99
6	*ProvideMotiveForce.VehicleCost*	*0.2*	0.18	0.036	5.59	1.118	5.12	1.02
7				5.964		3.023		4.06

Figure 20: Weighted objectives analysis results

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Highlights

Our analysis indicates that the electric vehicle best meets our stakeholders' requirements.

Using model-driven development and Rational Rhapsody software, we were able to perform a trade study analysis during the systems engineering process—saving time and money in the development lifecyle.

A look at figure 20 shows us that the electric system should be the proposed power source for our new green vehicle because it has the highest score at 5.96. We need to take into account, however, that our electric vehicle didn't meet the requirement for a range of 500 miles per charge. If we exclude this solution based on this factor, the hybrid electric system power source of the family hybrid electric vehicle—with a score of 4.07—becomes the best choice.

Conclusion

Trade study analysis should be used as a means to determine the most appropriate solution to a given problem prior to implementation or development. Using a model-driven approach, you can perform these analyses up front during your systems engineering process.

In this paper, we used the weighted objectives method and the Rational Rhapsody toolkit from IBM to analytically and objectively conduct a trade study analysis during the systems engineering process. Our goal was to determine which power source would give us the lowest CO_2 emissions and fuel costs for a green family vehicle. Using the Rational Rhapsody tool, we not only accomplished this objective, we did so through modeling, which saves time, energy and—of course—money.

For more information

To learn more about conducting trade study analyses with model-driven development techniques and Rational Rhapsody software from IBM, contact your IBM sales representative or IBM Business Partner, or visit:

ibm.com/software/rational

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1 *The Harmony Deskbook*, 3rd edition, P. Hoffman
PhD, Rational software, IBM Software Group, 2009.

2 *Engineering Design Methods*, N. Cross, Wiley, 1989.