# A Model Driven Development approach to supporting System Engineering Trade Studies

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**Abstract.** It is very common in manufacturing organizations for the organization to build its new products using the same or similar technology as the previous versions of the product. This means that the organization is not making the best use of new technology or components that could potentially improve their products and/or profitability. This presentation demonstrates an objective approach to evaluate and select complex physical architectures, i.e. doing a Trade Study. It is based upon SysML and it uses a modeling toolset (ref 1) to demonstrate the technique. The approach is based upon the definition of assessment criteria and target values for the product under consideration. Various means of physically realizing the architecture are proposed and the combined effect of the various components evaluated against the target values for the product. The results of this are used as the basis for final selection of the architecture. A practical worked example is provided throughout the paper to further demonstrate the techniques involved.

**Introduction.** Trade studies are part and parcel of the System Engineering process. It's important to fully explore the design space to ensure that a proposed solution best meets conflicting performance and cost requirements. The intent of this paper is to show how systems engineering trade studies can be carried out in a structured way using a model driven approach. To best demonstrate the approach, the paper will describe a multi variable decision problem based upon the selection of a power source for a vehicle to be built in the very near future for the European/UK market. It should be noted that this has an impact on the costs associated with the variables used in the analysis which will be quoted in UK Pounds (£). The vehicle is intended to have green credentials and low fuel cost as its primary considerations. These and other requirements are captured in the requirements diagram (Figure 1) below.

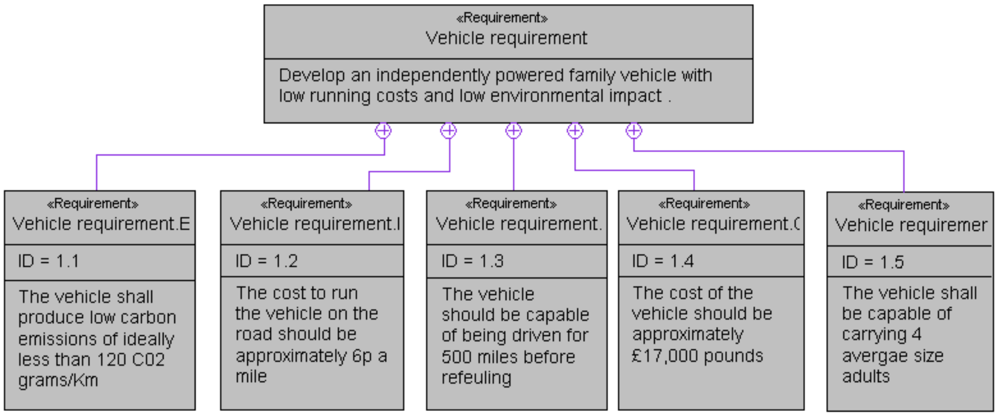


Figure 1 High Level Requirements Diagram

The process followed is based upon the workflow described in the 3 rd Version of the IBM Rational Harmony Deskbook (ref 2), which this author also contributed to), see figure 2. To evaluate the various potential solutions a technique known as the *Weighted Objectives Method* (ref 3) is employed. Each stage of the process, apart from the task "Merge Solutions to Form System Architecture" will be detailed in the worked example and a brief description of how the supporting toolset supports it. The final stage in figure 2 will be left out because the example will only focus on one Key System Function, so this stage is unnecessary.

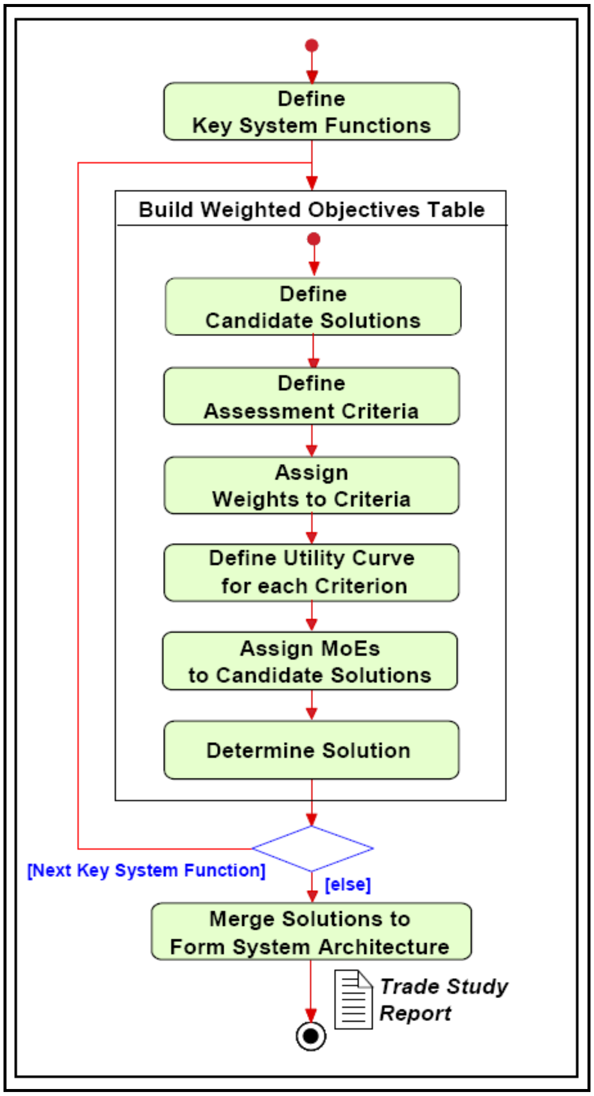


Figure 2 Trade Study Workflow

It should be noted that although the figures used in this example are sourced from published information the final results should not be taken as definitive. The intent of the paper is to provide an example of the method and the usage of the supporting toolset rather than an explicit proof that electric vehicles will save the world.

**Identify key system Functions** The first stage of the analysis is to identify key system functions. These are derived from the activity diagram that describes the functional flow within the system. In this instance we are interested in the functional flow that causes the vehicle to move (based upon the Use Case "Drive Vehicle" shown in figure 3).

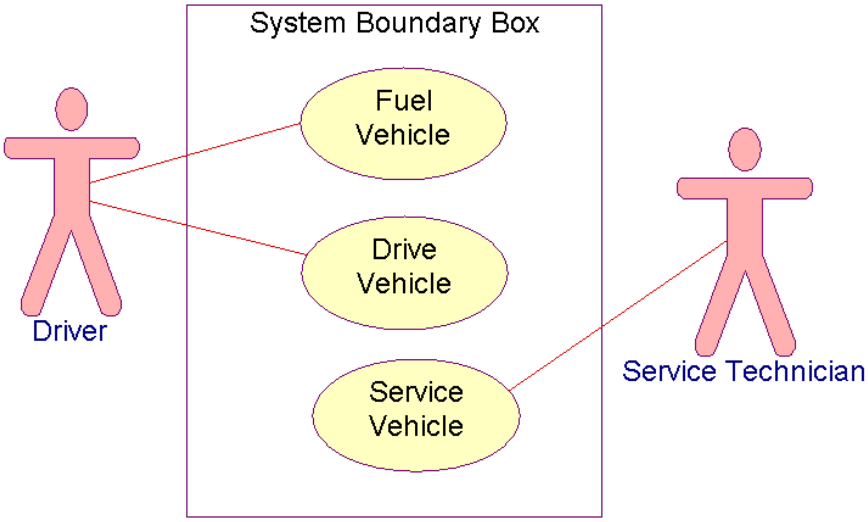


Figure 3 Use Case Diagram for a Green Vehicle

The "Drive Vehicle" use case is broken down into the simple functional flow shown in the activity diagram in Figure 4.

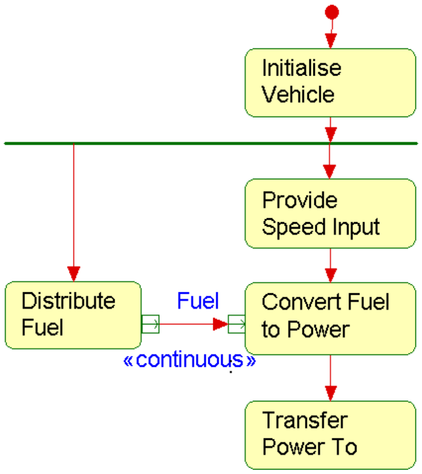


Figure 4 Drive Vehicle Activity Diagram

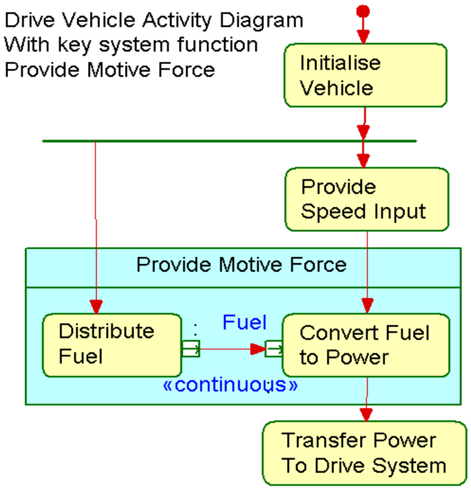


Figure 5 Activity Diagram with Key System Function Identified

Where the driver provides a speed input (normally via the accelerator) the vehicle power system draws fuel to itself from the fuel distribution system where it converts the fuel to power and then transfers the power to the drive system. The key system function here is encapsulated in the actions

“Distribute Fuel” and “Convert Fuel To Power”. These can be combined into the Key System Function “Provide Motive Force” (shown for diagrammatic purposes only) see Figure 5.

The reason why Key System Functions are created is because if separate trade studies were done on “Distribute Fuel” and “Convert Fuel to Power” it is possible that

A) Incompatible solutions could be found (i.e. combining an electrical power network with a clean diesel engine)
B) Potential solutions to the key System Function could be ignored due to the lower granularity of the functions that need to be realised. If you take this approach can only consider part solutions and not take a holistic approach to the problem.

The Key System Function named here as “Provide Motive Force” is named in this way to provide what is know as a Neutral Solution problem definition, i.e. a definition that does not identify a solution and restrict the solution space. A bad key system function would be “Provide a Diesel Engine” .

**Define Candidate Solutions** Once the Key System Function has been identified the user needs to find potential solutions that could possibly fulfil it. In this instance we will investigate three potential solutions, Liquefied Petroleum Gas (or LPG as it is known), Hybrid Electric Vehicle Systems and finally Electric Powered Vehicle systems.  In our toolset this is captured in a Block Definition Diagram with a single block representing the Key System Function and the three potential solutions connected to it via generalizations. See figure 6.

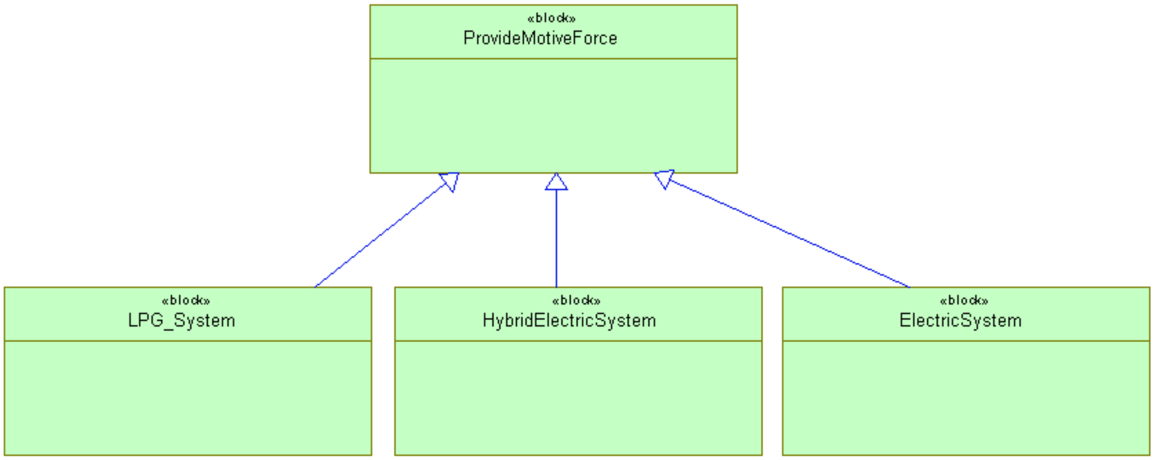


Figure 6 Key System Function and potential Solutions

**Define Assessment Criteria** The next stage is to identify the assessment criteria; the assessment criteria are the factors against which you will be measuring each candidate solution. Typically there will be a large number of criteria which the potential solutions will be assessed against, normally in the order of 10s. This will give a much more accurate result but will also take more time to do as the methodology requires reliable information for the analysis to work successfully. As this is an example there are only 4 assessment criteria. In this instance the assessment criteria are derived from the requirements, although they can be generated from techniques such as brainstorming, focus groups, analysis of customers needs, Quality Function Deployment analysis etc. The assessment criteria selected are:

Low Emissions from requirement 1.1
Low Fuelling Cost from requirement 1.2
Long Range from requirement 1.3
Predicted Vehicle Cost from requirement 1.4

The “low fuelling cost” assessment criterion is a derived figure based upon the cost of energy source to charge or fill an average tank of fuel and the range the vehicle travels on the full charge or tank. An example of how a Parametric Diagram can be used to help in the derivation of an assessment value for these criteria will be described later in the paper. Requirement 1.5 (figure 1) helps define vehicle size. Typically most practical electric system vehicles are two seaters. To make one a four seater requires a larger power source and more powerful drive system, and this will be reflected in the price. Once the assessment criteria have been identified they are added as an attribute stereotyped as <<moe>>, to the Key System Function, see figure 7. The term MoE will be described later.

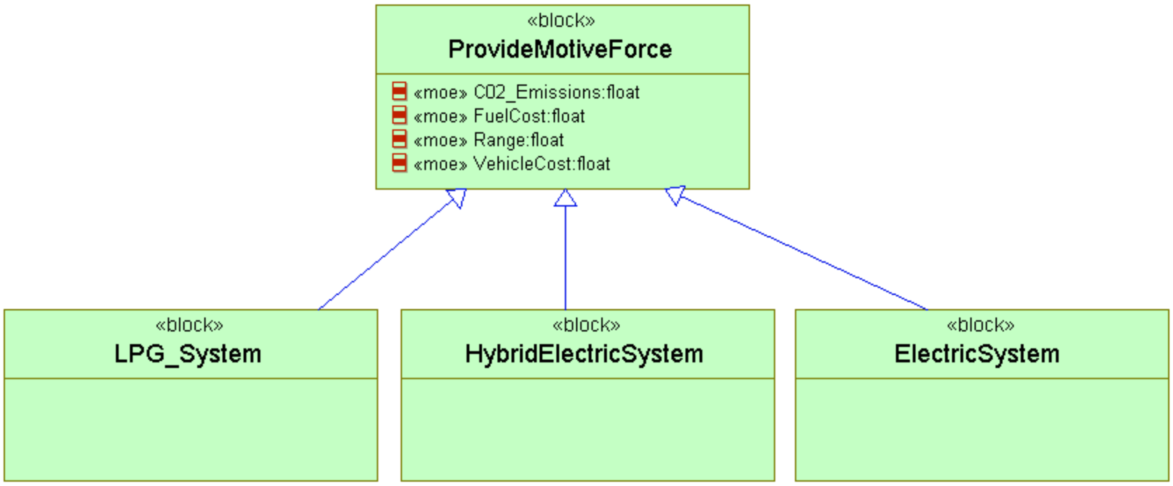


Figure 7 Key System Function with MOEs

**Assign weights to Criteria** Weight assignment is very influential, it is an indicator of how important a particular assessment criterion, is to the stakeholder. The more important a feature is to a stakeholder the higher the weight. The sum total of the weights should not exceed 1. In this instance the most important assessment criteria are low “$CO_2$ emissions” and low “fuel cost”. The “range” and “predicted vehicle cost” are less important. Given these criteria, weights will be assigned as follows.

| | |
|---|---|
| $CO_2$ Emissions | 0.3 |
| Fuelling Cost | 0.3 |
| Range | 0.2 |
| Predicted Vehicle Cost | 0.2 |

It is important that these weights are analysed properly before any calculation takes place as they have a very large impact on the solution. Normally this is done in conjunction with stakeholders and subject matter experts. In our toolset the weights are assigned directly to the <<moe>>s using their “weight” tag, see figure 8.

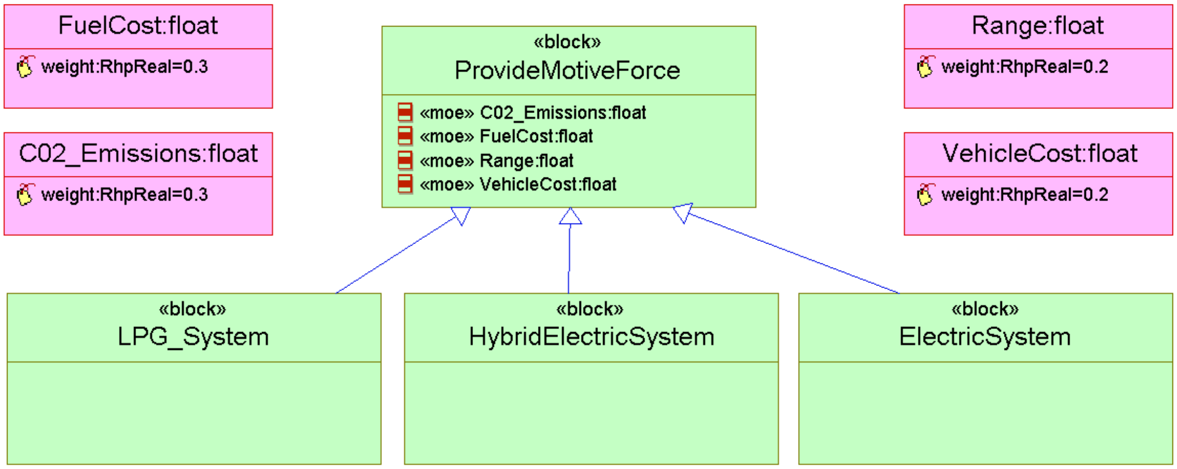


Figure 8 MoEs with weights assigned

The next stage is to employ a feature of the System Engineering Toolkit which copies the <<moe>>s down into the possible solutions. This gives the Block Definition Diagram seen in Figure 9.

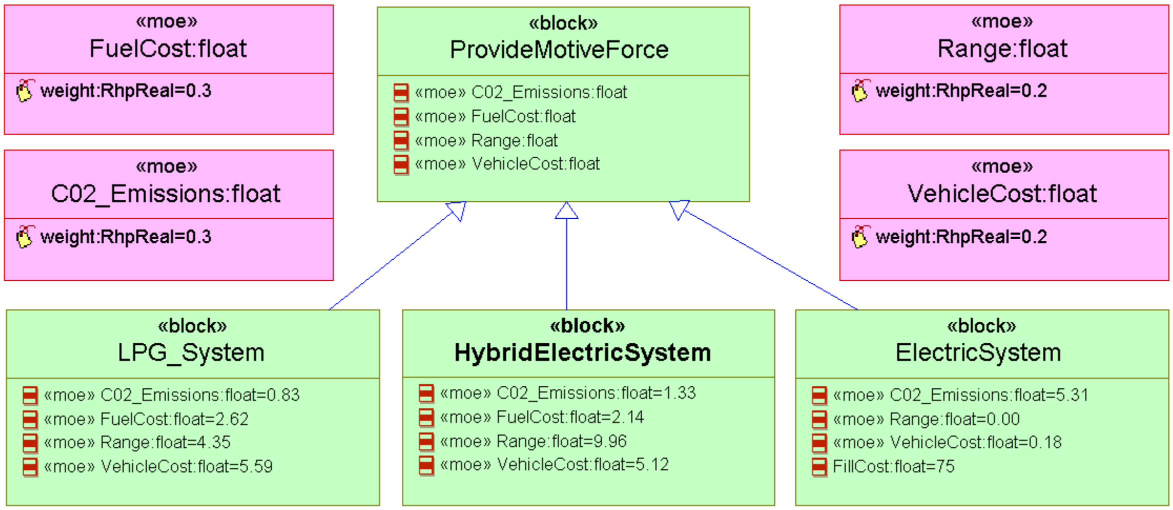


Figure 9 Solutions with MOEs

## Defining Utility Curves

A utility curve defines the relationship between the value of a specific assessment criteria for a solution and what is know as the Measure of Effectivenes or MoE, the MoE provides a means of rating the specific assessment criteria values. The value of the assessment criteria for a specific solution is input into a graph, or mathematical function, that represents the utility curve and from this the MoE is obtained. The MoE is normally ranked between 0 and 10 (where 0 shows a low MoE and 10 a high MoE).

There are a number of ways to determine the form of a utility curve. These are just a few possible examples, they can be determined, by for example.

A/ The optimum value for the assessment criteria is given an MoE value of 5. A tolerance of, for instance, +/- 50% around the optimum value is then selected as the assessment criteria range. The upper and lower values are then given an MoE score of 10 or 0, and a straight line drawn through all three points to give a straight line utility curve. This technique was used for the Fuel Cost, Range and Vehicle Cost utility curves.

B/ Identify the best expected value of the assessment criteria to give an MoE of 10. Then determine the worst case value of the assessment criteria to give an MoE of 0. Draw a straight line between the points and this gives the utility curve. See Figure 10 which demonstrates the ideal purchase cost for a component (in this instance) being \$0 giving an MoE of 10 and worst case of \$400 in which case an MoE of 0 is given. This technique was used for the Emissions utility curve.

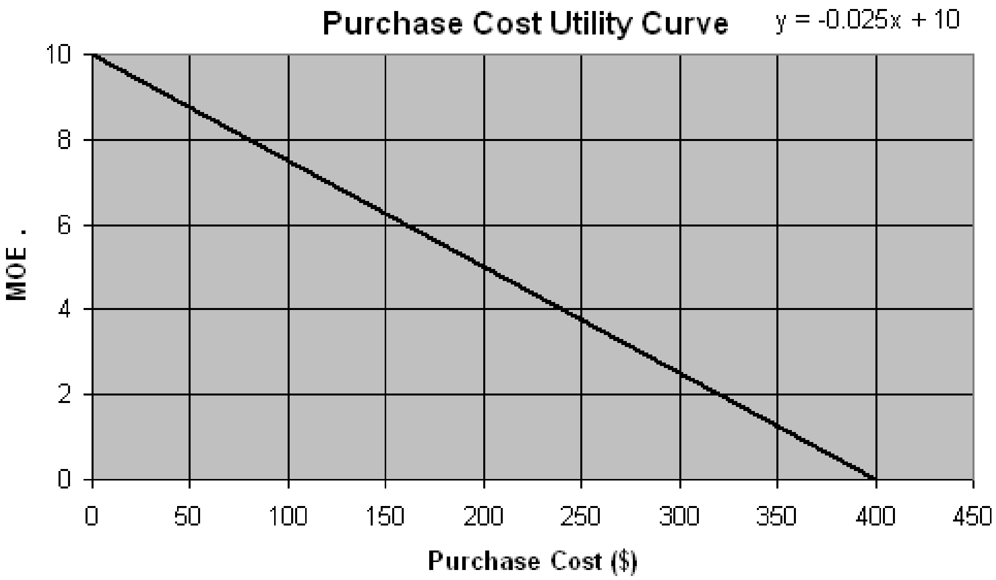


Figure 10 Straight Line Purchase Cost Utility Curve

C/ Determine an optimum point to give an MoE of 10 and select a range such that if the actual criteria is less than or more than the optimum the MoE trails off to 0 (this will generally give an arc of some description), indicating that the solution being considered is either under or over specified. See figure 11 where the mechanism under consideration is required to lift a mass through an optimum distance of 1.1 Metres.

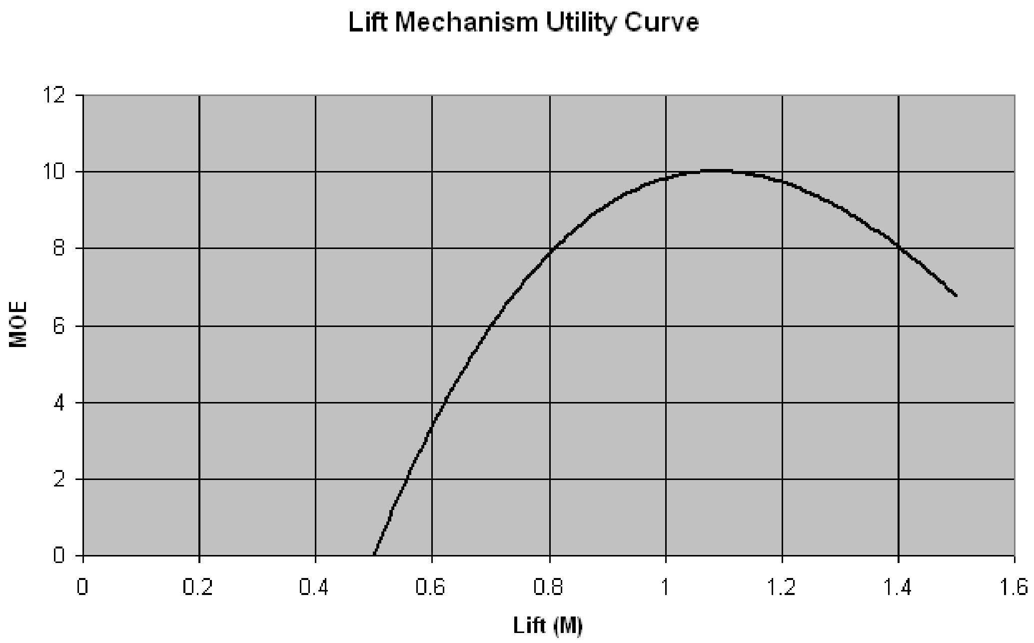


Figure 11 Non Linear Utility Curve

D/ Stakeholders and subject matter experts define a curve in a subjective manner e.g. as a step function or non linear curve and use this as the utility curve.

The utility curve for all the assessment criteria in the green vehicle example will use upon a negative straight line curve based upon the equation Y=MX+C where

Y is the output MoE
X is the value of the assessment criteria
M is the range of the measure (this gives a -ve value for a negative slope, +ve value for a positive slope)
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/Km, and because an electric vehicle has zero emissions this give a range of 0 to 120 $CO_2$ grams/Km. This gives the following utility curve for

$$\text{Emissions MoE} = (10/(0-120))*(X-0)+10$$

The fuel cost requirement indicates a target value of 6p a mile, +/- 70% gives a range of between 1.8 and 10.2 p a mile. This gives the following utility curve for

$$\text{Emissions MoE} = (10/(1.8-10.2))*(X-1.8)+10$$

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

$$\text{Vehicle Range MoE} = (10/(900-100))*(X-100)+10$$

Predicted Vehicle cost requirement indicates a target value of £17000, +/- 50% gives £ £8500 to £25500. This gives the following utility curve for

$$\text{Predicted vehicle cost MoE} = (10/(8500-25500))*(X-8500)+10$$

**Determine Measures of effectiveness** To define how well the candidate solution meets the median value it is necessary to find the actual value of the candidate solution for each assessment criteria. This value is then input into the relevant utility curve, determined in the previous section to give the MoE.

**$C0_2$ Emissions** Research has indicated that LPG Systems give the same performance as light duty diesel cars, giving an average $C0_2$ measure of approximately 110 grams/Km. For Electric Systems the effective $C0_2$ is 0 grams/Km. For Hybrid Electric Systems the figure for $C0_2$ approximates to 104 grams/Km.

| Emissions | Actual Value grams $CO_2$/Km | MoE |
|---|---|---|
| LPG System | 110 | 0.83 |
| Electric System | 0 | 10.00 |
| Hybrid Electric System | 104 | 1.33 |

**Vehicle Cost** A standard new small family petrol vehicle in this field is averagely priced at £ 14000, Most of the solutions we will be investigating will be higher than this hence the target cost being approximately £ 17000**.** From doing research it was found that an LPG System costs an extra £ 2000 for the compressed gas tank, compressor pump and other changes to the vehicle, this gives a value of £ 16000 for the LPG vehicle. For the electric vehicle system, typical electric vehicles at present are based upon small 2 seaters, research has indicated that an equivalent Electric vehicle to give the same power for a 4 seater would be approximately 80% more expensive, this gives a cost of £ 25200 for the Electric vehicle. It should be noted that some electric systems are significantly more expensive than this. For the Hybrid Electric System research indicates it would be 20% more expensive than a standard vehicle, giving a cost of £ 16800.

| Vehicle cost | Actual Value £s | MoE |
|---|---|---|
| LPG System | 16000 | 5.59 |
| Electric System | 25200 | 0.18 |
| Hybrid Electric System | 16800 | 5.12 |

**Vehicle Range** LPG systems are typically fitted with a 90 litre tank, this provides 16 Gallons of fuel (the tank can only be filled to 80% of its capacity for safety reasons). LPG has also been found to be 30% less efficient than petrol so assuming a petrol mileage of 40 miles per gallon this gives 28 miles per gallon for LPG and a range of 448 miles for a 90 Litre Tank. Electric vehicle systems at the moment tend to have very low mileage typically in the order of 100 miles. This is due to the capacity of the batteries, size and the cost. Hybrid electric systems are not dependant upon electric charges as they store electricity from regenerative braking and the motion of the vehicle. A typical hybrid electric vehicle can give around 56 miles to the gallon, giving it range of 896 miles for a 16 gallon tank.

| Range | Actual Value miles | MoE |
|---|---|---|
| LPG System | 448 | 4.35 |
| Electric System | 100 | 0.00 |
| Hybrid Electric System | 896 | 9.95 |

**Fuel Cost per mile** The fuel cost per mile MoE calculation is a derived calculation based upon, in this instance, the simplistic approach of taking the average cost to fill or charge a vehicle and how far the vehicle will travel. Because it is derived, the relationships between the filling cost and the mileage could be detailed in a SysML Parametric diagram. This is a graphical means of showing mathematical relationships, they can be used to understand the interaction between these relationships and therefore help engineers understand how to derive the calculations that give the actual assessment value for specific criteria. Although this is a simple example and would not normally considered for this form of analysis the basic concepts will be presented here for educational reasons The building blocks of Parametric Diagrams are ConstraintBlocks, they detail the mathematical relationships that exist in a system. They can either be very primitive(i.e. Divide or Mutliply) or more complex (i.e. a set constraints to give a straightline curve). If the Constraint Blocks are primitive they give more scope for reuse in other applications. The ConstraintBlock is then employed on a Parametric Diagram as a ConstraintProperty, this defines a specific application of the ConstraintBlock. To calculate the Fuel Cost per mile it is required take the cost to charge or fill the tank of the system under consideration and divide it by the Range in miles. So in this example to give the FuelCost a ConstraintBlock (figure 12) representing the Divide function is created in a Block Definition Diagram, this will be used to determine the Cost per Mile. The ParameterConstraints (the pins either side of the ConstraintBlock) provide the binding to the variables in the Constraint itself.

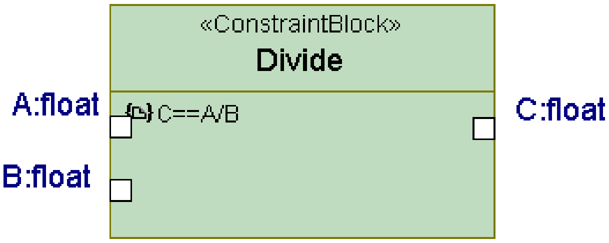


Figure 12 "Divide" ConstraintBlock

The ParametricDiagram that shows the usage of the “Divide” ConstraintBlock is shown in Figure 13. It takes the values of FillCost and MileageRange and based upon the ParametricCosntraint C==A/B it gives the FuelCostPerMile.

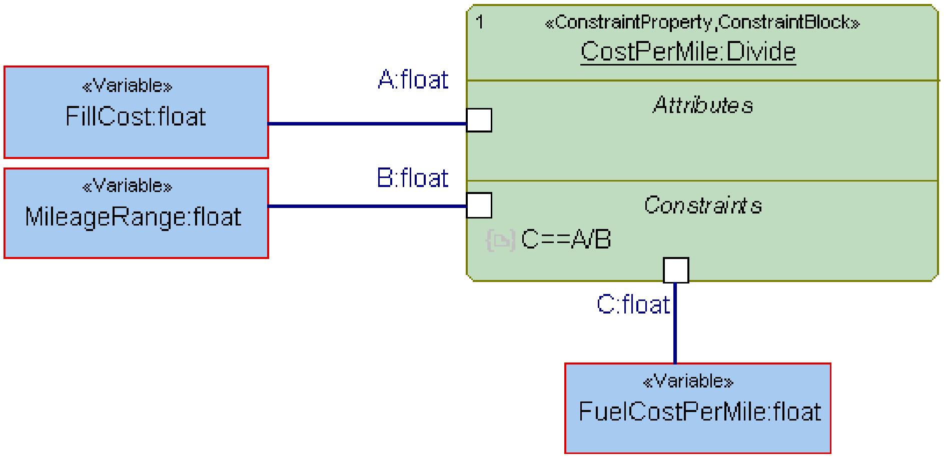


Figure 13 Fuel Cost per Mile Parametric Diagram

Although ParametricDiagrams are not currently executable they do provide a useful way of graphically showing the mathematical relationships that exist between various abstract concepts and can be considerably more complex shown than the examples described in this paper. The above parametric Diagram was used as the basis for understanding and carrying out the calculations below. LPG systems have a low fuel cost due to the lack of duty which they currently incur. To fill a 90 litre tank of an LPG system costs, £36.00, divided by the 448 miles it would cover, this gives a cost of 8p a mile The cost of charging electric vehicle systems varies, dependant upon the tariff but research has shown that to charge a typical battery would cost approximately £ 2., divide this by the 100 mile range and it gives a cost of 2 p a mile. Although hybrid systems use batteries (there is no charge cost involved) they also use a diesel or petrol, the cost of filling a 90 litre tank is approximately £ 75 pounds, divided by the range of 896, this gives a cost of 8.4 p a mile.

| FuelCost/Mile | Actual Value p/miles | MoE |
|---|---|---|
| LPG System | 8 | |
| Electric System | 2 | |
| Hybrid Electric System | 8.4 | |

To show the relationship between the FuelCostPerMile and the final MoE a second constraint block can be defined (Figure 15), this will represent a StraightLineCurve, it is based upon the utility curve equations described earlier, C is a constant set at 10. It is a good candidate for a ConstraintBlock because it can be used in several different ways. There are three other potential usages detailed in this paper!

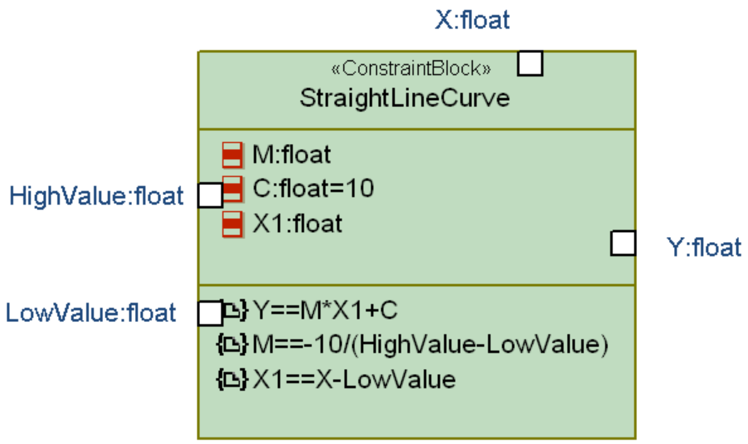


Figure 14 Straight Line Curve ConstraintBlock

A usage of this ConstraintBlock (StraighLineCurve) can be combined with CostPerMile ConstraintProperty to define the relationship between the MoE and the assessment value. This is shown in Figure 16.

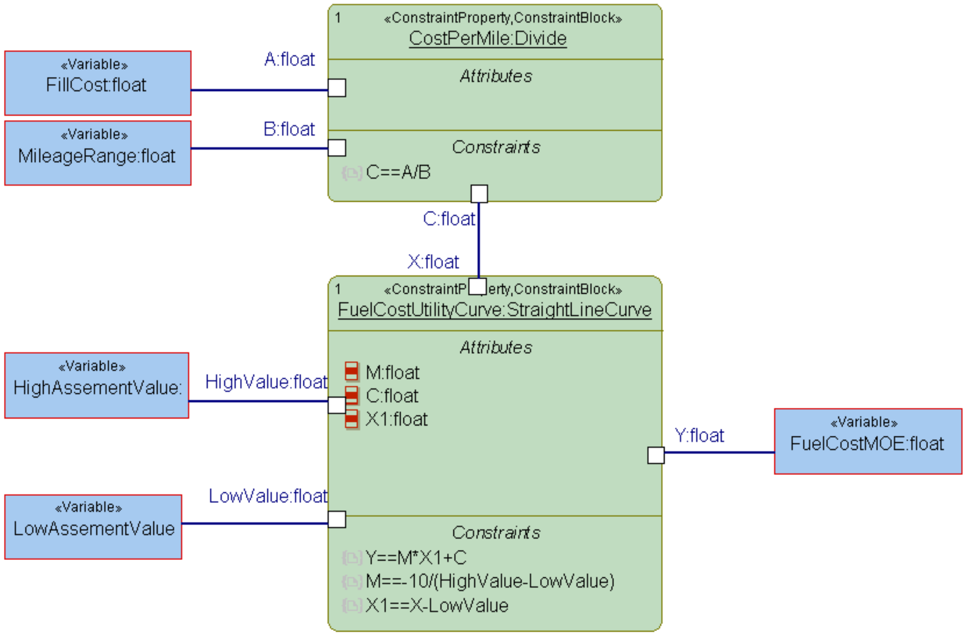


Figure 15 Fuel Cost MOE Parametric Diagram

The following values for the FuelCostPerMile were calculated based upon these parametric diagrams.

| FuelCost/Mile | Actual Value pence/miles | MoE |
|---|---|---|
| LPG System | 8 | 2.62 |
| Electric System | 2 | 9.79 |
| Hybrid Electric System | 8.4 | 2.14 |

**Determine Solution** To determine the solution the Weighted Objectives Table which combines the MoEs and the weights for the various assessment criteria is calculated. A summary of the MoE results can be seen below.

| MoEs for Provide Motive Force | Emissions | Fuel Cost/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 |

Where the MoE is less than 0, or greater than 10 this indicates that the actual assessment value is outside the expected range for that particular assessment. If many of the MoEs exceed the 0-10 range it indicates that the range and/or utility curve should be adjusted. In this instance the analysis is very analytical and hence *objective*. It should be noted that an MoE can also be *subjective*, in which case it is determined from the views of stakeholders, subject matter experts, focus groups etc. The intent here being to obtain a consensus view on how well the proposed solution meets the assessment criteria. The weighted objectives table is then calculated by first adding the MoES to the blocks representing the various solutions, figure 16.

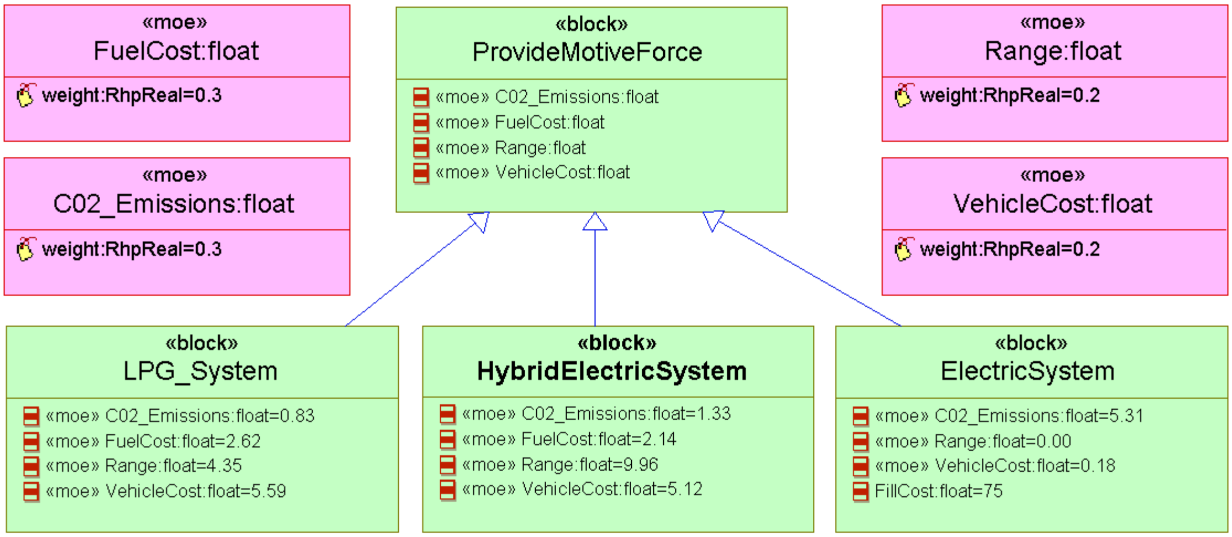


Figure 16 Solutions with MoE values added

Once the MoEs have been added to the block representing the solutions, a second block definition diagram is required. This 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. Here we are only dealing with one set of solution architectures so this diagram will show a block for each potential solution. In this instance we will create 3 blocks, FamilyElectricVehicle, FamilyLPGVehicle, FamilyHybridVehicle and join them with a composition connector to their respective Solutions. See figure 17.

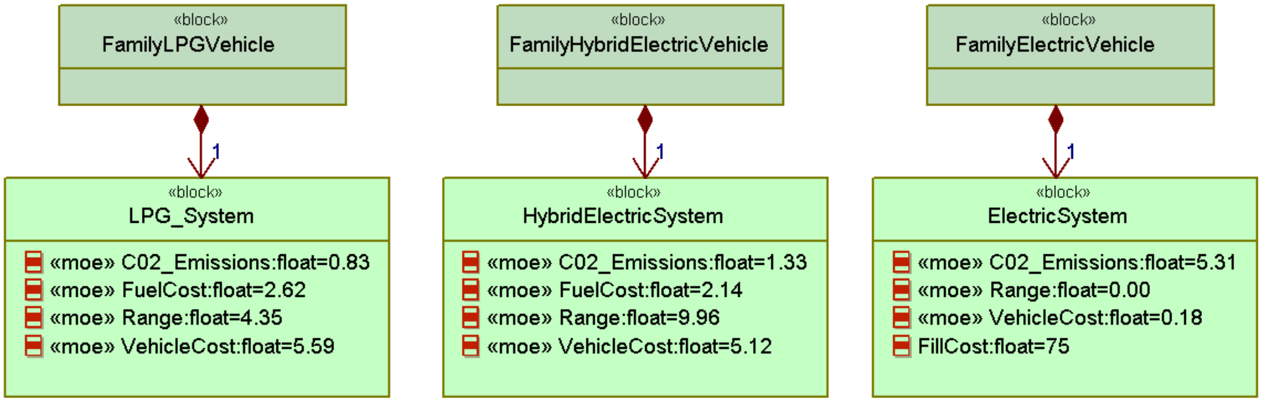


Figure 17 Solution Architectures

The final stage is to create a third block definition diagram that collects the three solutions together this is the CalculationSpace diagram and it just consists of the three candidate solutions. See figure 18.

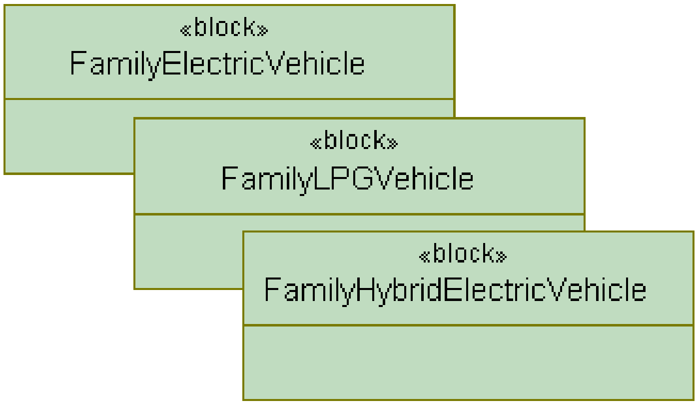


Figure 18 Calculation Space

The actual trade study calculation is carried out via a feature (“Perform Trade Analysis”) of the System Engineering Toolkit, see figure 19. An Excel spreadsheet is produced that contains the Weighted Objectives Table results, see Figure 20.

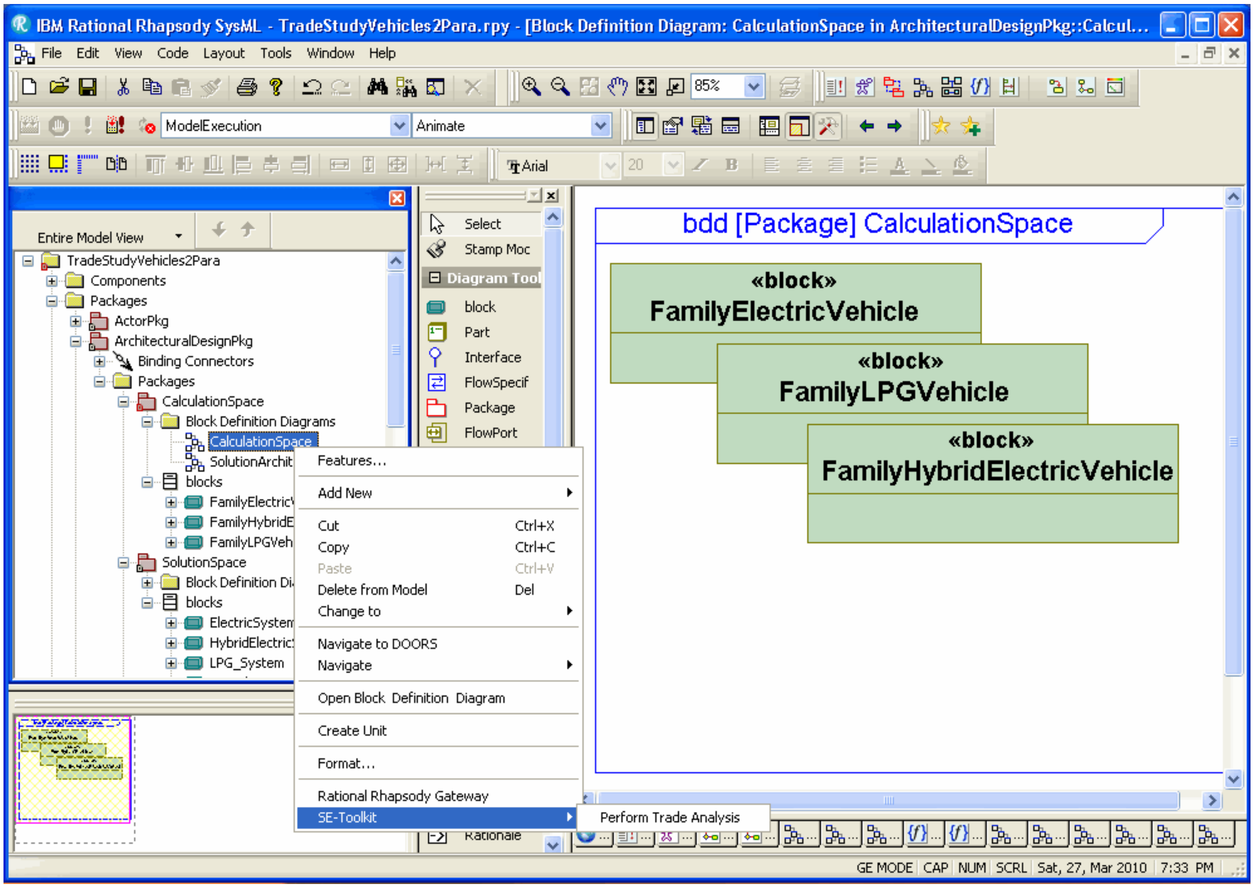
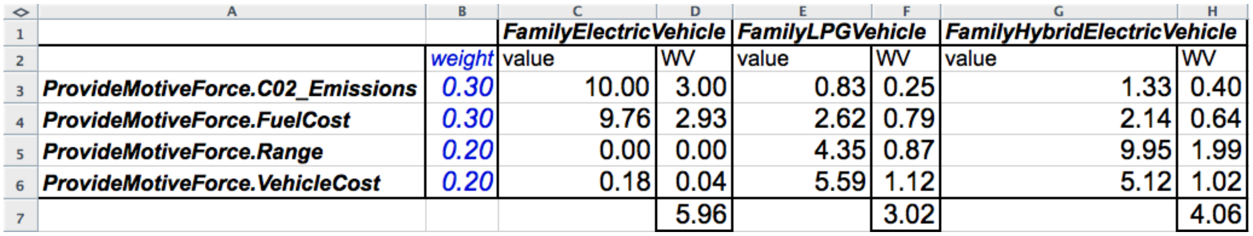


Figure 19 Perform Trade Analysis

The weighted Objectives Table is calculated by taking the weight of each assessment criteria and multiplying the relevant MoEs by this value, the resulting values are then summed for each 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*** | *0.30* | 10.00 | 3.00 | 0.83 | 0.25 | 1.33 | 0.40 |
| 4 | ***ProvideMotiveForce.FuelCost*** | *0.30* | 9.76 | 2.93 | 2.62 | 0.79 | 2.14 | 0.64 |
| 5 | ***ProvideMotiveForce.Range*** | *0.20* | 0.00 | 0.00 | 4.35 | 0.87 | 9.95 | 1.99 |
| 6 | ***ProvideMotiveForce.VehicleCost*** | *0.20* | 0.18 | 0.04 | 5.59 | 1.12 | 5.12 | 1.02 |
| 7 | | | | 5.96 | | 3.02 | | 4.06 |

Figure 20 Weighted Objectives Analysis Results

From Figure 20 it becomes clear that the FamilyElectricVehicle from the ElectricSystem solution, given the basis for good economy and green credentials should be the proposed power source for the new product line as it has the highest score of 5.96 compared to 4.07 and 3.02. It should be mentioned that the ElectricSystem did not really meet the requirement for a range of 500 miles so in this case the HybridElectricSystem power source of the FamilyHybridElectricVehicle which scored 4.07 could well be the best choice for the power source.

**Conclusion** This paper describes a model driven approach for carrying out trade study analysis. To demonstrate the techniques, a modeling toolset was used with screenshots to show how the information would be represented. It proposed the problem of determining a power source for a green family vehicle, with low emission and fuel cost. Based upon the steps outlined in using a rigourous model driven process, a analytical method called the *Weighted Objectives Method* and a modeling toolset it showed how trade studies could be carried out in an analytical and objective manner.

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3. Engineering Design Methods, N.Cross, Wiley 1989.

## BIOGRAPHY

Graham Bleakley originally studied Mechanical Engineering  at Southbank University, this was followed by a PhD in Model Based Systems Engineering and Process for Safety Critical Systems at City University. After going back to Southbank University for 2 years to run and teach the Computer Aided Engineering degree, he left and joined I-Logix in 2000, working as an Application Engineer/Consultant with companies such as BAE, Thales,Selex, MBDA and Alcatel. He has written and presented a number of technical papers at INCOSE as well for other publications on the themes of Model Based Systems Engineering. He is currently a principal consultant in IBM Rational where, when not consulting, he works on Model Based System Engineering Process definition and Architectural Frameworks, being one of the lead architects on the OMG UPDM submission.