

Combinatorial Design Optimization of Automotive Systems by Connecting System Architecture Models with Parts Catalog

Hongman Kim, David Fried, and Grant Soremekun
Phoenix Integration Inc.

ABSTRACT

Performing system-level trade studies during the design of complex systems has many benefits in terms of performance, reliability, and cost. However, current engineering practices often do not facilitate system-level trade studies because system specifications and requirements are not connected to analytical models that are used to predict performance and cost. To bridge the gap, authors have created a bridge between system architecture models and engineering analyses. This work extends the bridge between the system modeling language (SysML) and engineering analyses to support the use of parts catalogs from system architecture models. Complex systems such as automobiles are seldom created from scratch. Rather, there are many off-the-shelf parts and subsystems available. Combined with the bridge between SysML and engineering analyses, parts catalog data available from system models enables evaluating many different configurations of a system and identifying best designs. The technical approach is demonstrated using an automobile brake design example. The integrated approach allowed generating a large number of design configurations and evaluating those using engineering analyses. Multidimensional point cloud visualization techniques were applied to identify trade-offs between cost and system performance. It is discussed how the interactive point cloud visualization technique can be used to perform requirements change impact analysis

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INTRODUCTION

Performing system-level trade studies during the design of complex systems has many benefits in terms of performance, reliability, and cost. However, current engineering practices often do not facilitate system-level trade studies because system specifications and requirements are not connected to analytical models that are used to predict performance and cost. A comprehensive model-based engineering (MBE) toolset can help engineers quickly evaluate a given system architecture, understand design trade-offs, and optimize performance. For example, previous works [1], [2] by the authors created a bridge between system architecture models and engineering analysis models by connecting the system modeling language (SysML) and an engineering analysis work flow framework called ModelCenter [3]. The bridge allows engineers to evaluate system performance based on specifications defined in SysML models, and perform trade-off studies when system requirements are changed. The capability was applied to a number of system development projects in industry, including a ground-based radar system [4].

The work presented here extends the bridge between SysML and engineering analyses to support the use of parts catalogs from system architecture models. Complex systems such as automobiles are seldom created from scratch. Rather, there

are many off-the-shelf parts and subsystems available. A key element of system design process is to choose the best combination of parts from available options. Combined with the aforementioned bridge between SysML and engineering analyses, parts catalogs available from system models enable evaluating many different configurations of a system and identifying best designs.

Using parts catalogs, system trade-off becomes a discrete combinatorial problem. One useful concept to this type of problem is the design by shopping paradigm [5], where design process is approached as a shopping experience. Using the technique discussed in this work, cost and performance metrics can be calculated for a large number of system configurations based on parts catalogs. When comparing different configuration options, a truly multi-objective decision making process is going on inside the designer's mind. Multidimensional design space visualization techniques are useful for multi-objective decision making. For example, a design point cloud visualization technique developed by authors in a previous work [6] can be used to understand design space and graphically identify designs that satisfy requirements. The discrete nature of the catalog-based design poses challenges to traditional gradient based optimization

techniques. Instead, genetic algorithms are more natural choices when applying a formal optimization to design problems involving discrete choices.

In the following sections, the technical approach of connecting SysML models, engineering analyses, and parts catalogs is discussed using an automobile brake design problem. The integrated approach allowed generating a large number of design configurations and evaluating those using engineering analyses. Multi-dimensional point cloud visualization techniques were applied to identify trade-offs between cost and system performance. It is discussed how the interactive point cloud visualization technique can be used to perform requirements change impact analysis.

TECHNICAL APPROACH

Model-based systems engineering (MBSE) is an approach to improve the traditional document-based systems engineering process through the use of system models [7]. System Modeling Language (SysML) [8], [9] is a graphical modeling language that was created as an international standard to support MBSE. To achieve the full benefit of MBSE, there is a critical need to create links between systems engineering and disciplinary/domain engineering. Systems engineering models defined in SysML are descriptive in nature and do not directly produce analytical results. Because systems engineers and engineering analysts are using different models, tools, and terminology, they have to rely on ad-hoc communications and manual translation of design specifications and data. The gap between systems engineering and engineering analysis results in inefficiencies and quality issues that can be very expensive to fix.

To close the gap, authors developed a bridge between system architecture models and engineering analyses, called MBSE Analyzer. The bridge integrates SysML modeling tools, such as Rhapsody® or MagicDraw®, and an engineering analysis workflow framework called ModelCenter®. The capability is based on a few general principles. First, the capability needs to support models of different levels of abstraction. Second, distinctive perspectives of systems engineers and domain experts must be supported. Third, engineering analyses needs to be performed in the context of a system model. Fourth, both top-down and bottom-up approaches must be supported in the creation of models.

Connecting SysML Parametric Diagrams with Engineering Analyses

In SysML, parametric diagrams are used to specify quantitative relationships among system properties. The bridge between SysML and engineering analyses automatically translates parametric diagrams to executable analysis models. Parametric diagrams use analysis blocks (called constraint blocks) that represent physical or logical relationships between system properties in the model. Typically, analytical relationships of constraint blocks are limited to simple algebraic equations. To overcome this limitation, constraint blocks are

extended using SysML stereotypes so that they point to wrapped analyses that will be executed by ModelCenter. Each wrapped analysis is identified by a URL (Uniform Resource Locator) that is specified in a SysML tag.

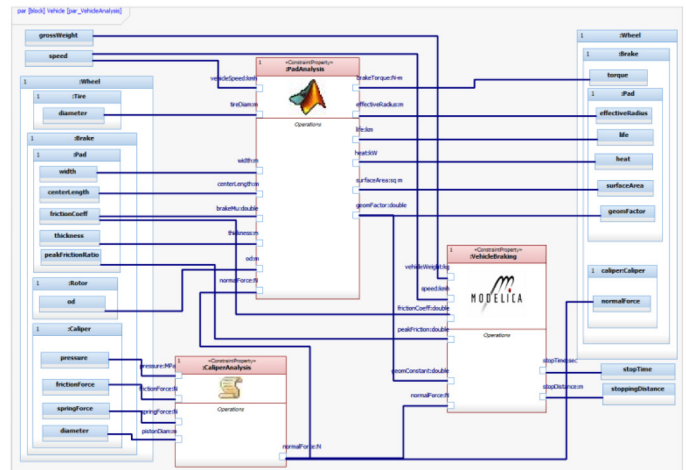


Figure 1. SysML parametric diagram that is using wrapped analyses.

Figure 1 shows an example of a SysML parametric diagram that calculates performance of a brake system. The diagram has three constraint blocks that are based on a Matlab code, an Open Modelica model, and a Visual Basic script, respectively. When domain specific analysis models are needed, they are first wrapped using ModelCenter, and the wrapped models are imported as SysML constraint blocks. For the parametric diagram in Figure 1, the constraint blocks of Matlab and Open Modelica were created by importing wrapped analysis models.

On the other hand, it is more convenient to define simple algebraic equations directly in a SysML model without having to create wrappers and import them. For the parametric diagram in Figure 1, Visual Basic script was directly defined in the constraint block. MBSE Analyzer provides a graphical way to define scripts for constraint blocks.

Binding connectors in parametric diagrams represent equality relationships between system properties. When a parametric diagram is translated to a ModelCenter model, constraint blocks will be converted to wrappers, and binding connectors will be converted to variable links as shown in Figure 3. The Matlab and Open Modelica wrappers were automatically instantiated. Note that the constraint block based on scripts was translated to a script plug-in component in ModelCenter.

The generated model can be executed from MBSE Analyzer, which is available within the SysML tool environment, to evaluate performance of the given system configuration. The user can change design property values and perform what-if analyses. Results of engineering analysis are presented in MBSE Analyzer as seen in Figure 4. New values are compared with the original values defined in the SysML model. If system

properties are related to requirements in the SysML model, analyses results are used to check the requirements. When desired, SysML model can be updated using analyses results.

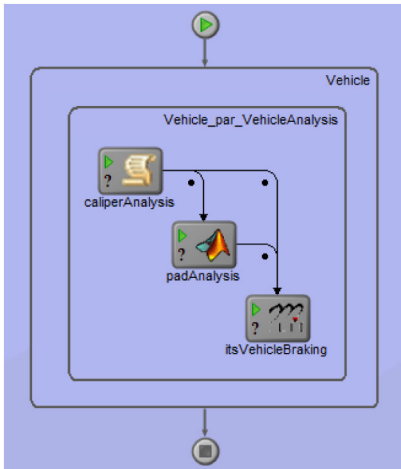


Figure 2. ModelCenter model generated from a parametric diagram.

Property	Units	Original	New	Margin
Vehicle				
wheel				
brake				
caliper				
pad				
centerLength	m	0.076	0.076	
frictionCoeff	Real	0.58591116334167	0.58591116334167	
peakFrictionRatio	Real	1.2	1.2	
thickness	m	0.00836024909199673	0.00836024909199673	
width	m	0.038	0.05	
effectiveRadius	m	0.105	0.1	
geomFactor	double	0.654676403801532	0.624858951745608	
heat	kW	31.5441940414119	29.7586736236678	✓ 5.2413 kW
life	km	60041.4211646333	83741.9821515332	✓ 23,742 km
surfaceArea	m²	0.002888	0.0038	
rotor				
od	m	0.25	0.25	
torque	N·m	390.359401262472	368.263586092889	
tire				
diameter	m	0.55	0.55	
grossWeight	kg	1500.0	1500.0	
speed	km/h	100.0	100.0	
stoppingDistance	m	59.6454429641072	62.8692385288436	✗ 2.8692 m
stopTime	s	4.29447189343124	4.52658517409318	

Figure 3. Results of engineering analysis are compared with original values in the system model and used to check requirements.

Connecting Parts Catalog with System Models

A SysML block represents an abstraction of a physical entity in a system, such as a part. Therefore, it is natural to relate SysML blocks to parts catalog. When a block is connected to a parts catalog, the block represents a generic part, whereas entries in the catalog represent possible realization of the part. In this work, SysML blocks are connected to parts catalogs that are available as spreadsheets or databases.

MBSE Analyzer provides a graphical tool that helps connect blocks to parts catalogs. There are two ways to do this. An existing block can be connected to a catalog by defining mapping between SysML properties and part properties in the catalog. Alternatively, a new block can be created by importing a catalog. Figure 4 shows how mapping is defined. Part numbers are used as the key to identify parts in a catalog. If there is no SysML property that represents part number, it will be automatically created. The mapping information will be

saved as SysML tags in the block. Once a parts catalog is connected to a block, its content can be browsed in MBSE Analyzer. Figure 5 shows available options in a catalog for a brake pad. The catalog data is pulled from an Excel spreadsheet. The user can select a part number to update property values of the corresponding SysML block.

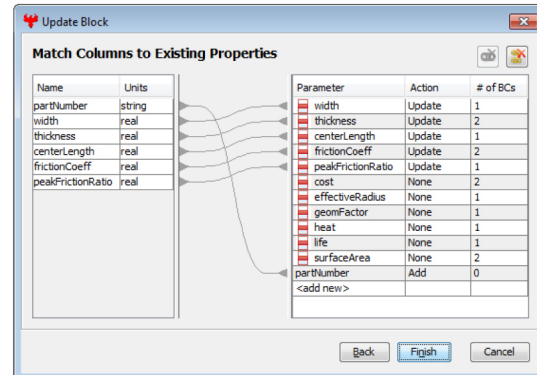


Figure 4. Parts catalog is connected to a block by defining a mapping between catalog properties and block properties.


View Part Catalog

SysML Block: Structure::Pad

Catalog: |solutions|applications|SysML|examples|Rhapsody|CarBrakePartCatalogModelica|BrakePartCatalog.xlsx

partNumber	frictionCoeff	width	centerLength	thickness	peakFrictionRatio
Titan P20	0.586	0.038	0.076	0.0080	1.2
Titan P30	0.586	0.038	0.076	0.0084	1.2
Titan P40	0.586	0.05	0.076	0.0090	1.2
Titan P50	0.586	0.06	0.076	0.01	1.2
Titan P20S	0.6	0.038	0.076	0.0080	1.3
Titan P30S	0.6	0.038	0.076	0.00836	1.3
Titan P40S	0.6	0.05	0.076	0.0090	1.3
Titan P50S	0.6	0.06	0.076	0.01	1.3
Proto C5	0.5	0.042	0.076	0.00836	1.1
Proto C7	0.5	0.042	0.08	0.00836	1.1
Proto C9	0.5	0.042	0.09	0.00836	1.1
Proto C10	0.5	0.042	0.1	0.00836	1.1
Proto C5F	0.52	0.038	0.076	0.01	1.2
Proto C7F	0.55	0.04	0.076	0.01	1.2
Proto C9F	0.6	0.038	0.076	0.0112	1.2
Proto C10F	0.6	0.04	0.076	0.0115	1.2

Select Part
Close

Figure 5. Parts catalog can be browsed for a given SysML block.

Connecting system architecture models to external parts catalog has several benefits. The system model provides a clear context of each parts catalog, allowing system engineers to easily navigate parts catalog. Using external catalogs also prevents the system architecture model from being cluttered with catalog data that may not be essential for the purpose of the model. The approach also makes it possible for subject matter experts to maintain parts catalog independently from the system model.

EXAMPLE: CAR BRAKE DESIGN

The integrated modeling and analysis technique is demonstrated using a brake design example. The design goal is to find a brake design with a lowest cost while satisfying requirements of stopping distance, projected life of brake pad, and heat generated during braking.