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Modular Design Approach for Development of Electrical, Electronic, and Software System Architectures for Multiple Product Platforms

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ABSTRACT

Modular systems provide the ability to achieve product variety through the combination and standardization of components. Modular design approaches used in the development of electrical, electronic, and software (EES) systems allow sharing of architectures/modules between different product lines. Modular products provide economies of scale, reduced development time, reduced order lead-time, and easier product diagnostics, maintenance and repair. In this paper, new optimization algorithms and software tools are presented that allow EES system design engineers to develop architectures/modules that can be shared across product platforms (for OEMs) and across OEMs (for suppliers). Approaches presented in this paper use matrix clustering and graph based techniques. The application of the approach is illustrated with an example from the automotive industry on the development of a modular EES system that can be shared across multiple vehicle platforms.

INTRODUCTION

Modularity arises from the way a product is physically divided into components and refers to the use of interchangeable components to create product variants. Two major benefits associated with modular products are the standardization of components and the ability to achieve product variety through the combination of components. Ulrich and Tung (1991) describe five different ways modularity is used in the industry to exploit component standardization and to achieve product variety, i.e., component swapping, component sharing, fabricate-to-fit, bus, and sectional modularity. Ulrich and Tung (1991) also defined product modularity and explored the benefits and costs associated with modular products. O'Grady (1999) provides an in-depth description of modularity and showed how companies can use modularity to reduce product development time, costs, and capital investments. Pimmler and Eppinger (1994) used product decomposition to address the integration problems in development of modular products. Kusiak and Huang (1996) presented a methodology for development of modular products while considering product cost and performance. The product modularity problem was represented with a graph, while the module components of a product set were determined by a heuristic approach. Huang and Kusiak (1998) also presented a matrix representation of the modularity problem. A decomposition approach was used to determine modules for different products. Zakarian and Rushton (2001) presented a methodology that combines the system modeling, integration analysis, and optimization techniques for development of modular electrical, electronic, and software (EES) systems. A new clustering technique was developed to identify clusters in the incidence matrix, group the functions, and create EES system modules. The ability to produce a variety of systems through the combination of modular components is a meaningful benefit of modularity. Other potential benefits of modularity include economies of scale, reduced order lead-time, easier product diagnostics, maintenance and repair, and decoupling of tasks. In this paper, new approaches are presented that allow vehicle system design engineers to develop modular architectures/modules that can be shared across product platforms (for OEMs) and across OEMs (for suppliers). The methodology presented in this paper uses matrix clustering and graph based techniques. The **S**ystem **A**rchitecture (**SA**) Builder software tool presented in this paper allows system design experts to identify multiple product configurations in the generic system requirements model and build a low cost EES architecture that can support multiple configurations. **SA** Builder identifies an optimal system architecture for given product/system features and feature take rates by grouping (integrating) system functions into physical modules and determining the best possible tradeoffs between system overhead, give away, and wiring costs. **SA** Builder is written in C++ and can support development of EES system architectures with up to 20,000 functions. Also in this paper, a new approach is presented that allows system developers to identify common modules in EES architectures that can be shared across multiple vehicle platforms.

DEVELOPMENT OF COMMON SYSTEM ARCHITECTURES

In this section, we present the approach that allows system design engineers to determine low cost EES architectures in multi option product development environments using modular design concepts. The overall design approach is shown in Figure 1 (Zakarian and Rushton 2001).

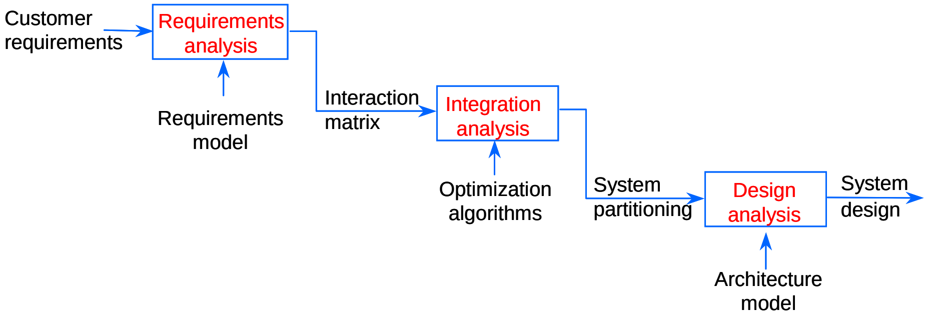


Figure 1 - System Design Process

System modeling is used to develop a functional requirements model for a system. The system requirements model defines the interfaces (interactions) between system functional elements (primitives) to support functions of various product configurations. From this functional requirements model, the system design engineer may capture the requirements of multiple product configurations (see Figures 2 and 3). For example, three different configurations could be as follows: 1) four-door body style, automatic transmission, and diesel engine; 2) two-door body style, automatic transmission and hybrid engine and 3) convertible body style, automatic transmission and gas engine. It is clear that some of the functions of the EES architectures that support the above configurations are mutually exclusive. For example, the EES architecture that supports a two-door body style configuration may not have some of the functions that are required for the EES architectures that support a four door or convertible body style configuration. Once the requirements of various vehicle configurations are captured and the interfaces among the functional elements that support all these different configurations are identified, a function-function interaction (incidence) matrix of the interfaces is developed (see Figure 4). Each row (column) in the interaction matrix corresponds to a function (primitive process or PSPEC), and each non-zero entry in the matrix represents an interaction (data flow) between the functions (PSPEC's). Clustering techniques and optimization algorithms can then be used to identify a low cost EES architecture that supports all three vehicle configurations. The objective of the clustering algorithm is to determine an optimal (low cost) common EES system architecture for given features and feature take rates by grouping (integrating) system functions into physical modules and determining the best possible tradeoffs between system overhead, give away, and wiring costs.

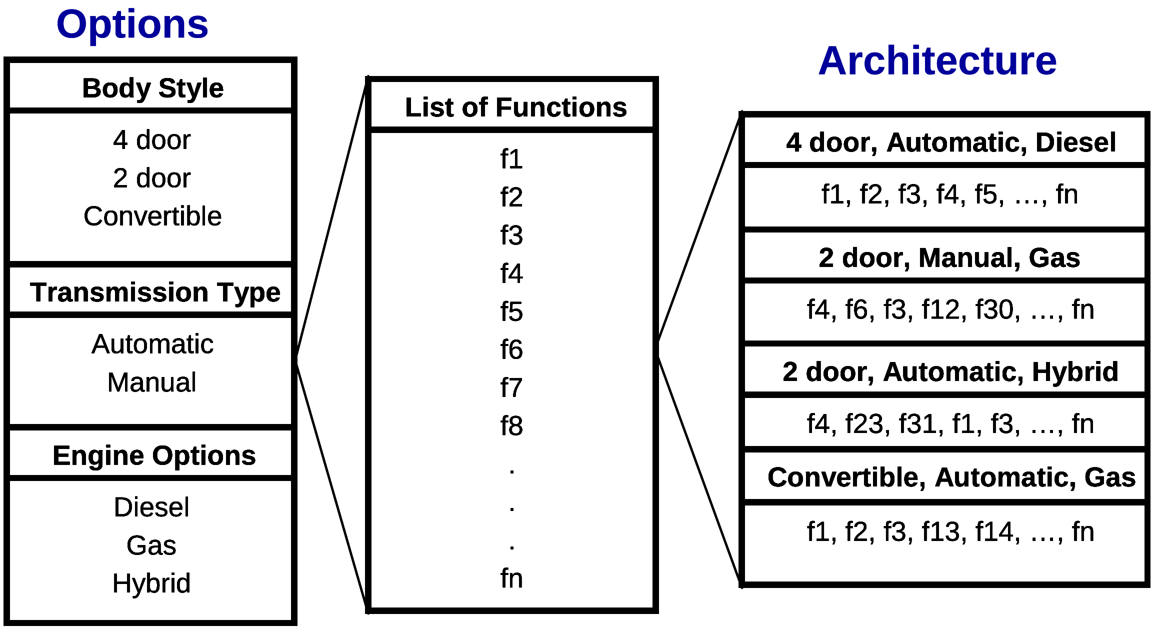
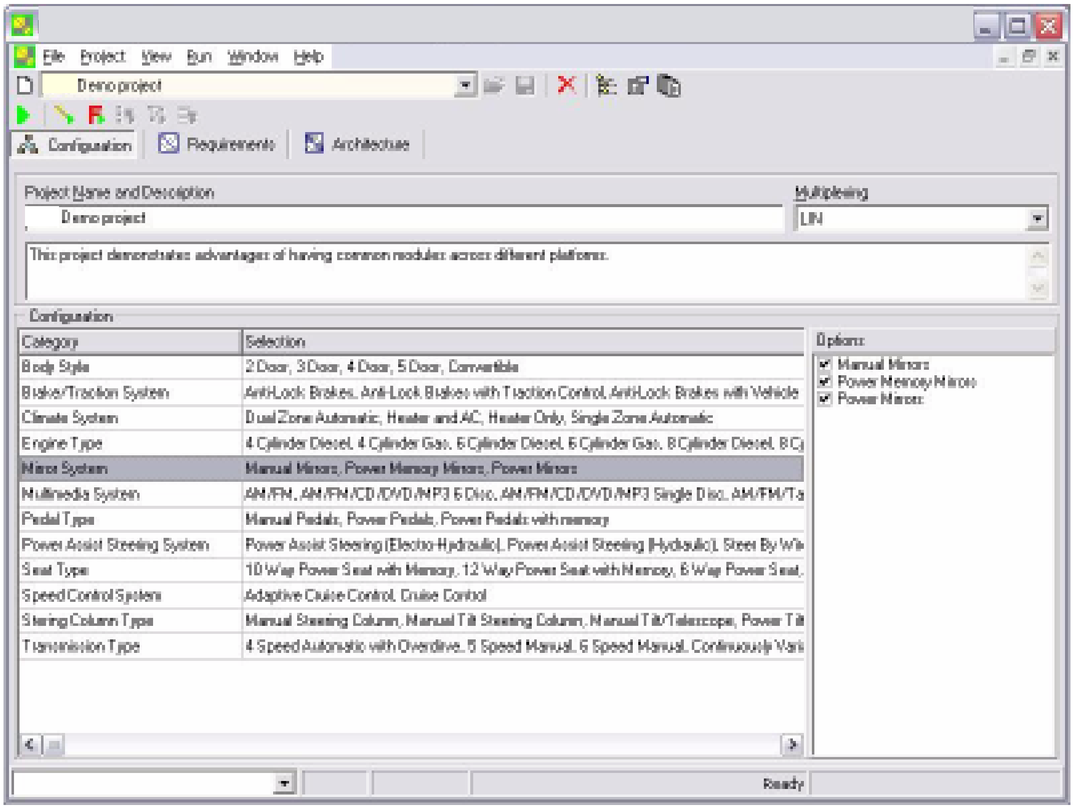

Options
Body Style
4 door
2 door
Convertible
Transmission Type
Automatic
Manual
Engine Options
Diesel
Gas
Hybrid
List of Functions
f1
f2
f3
f4
f5
f6
f7
f8
.
.
.
fn
Architecture
4 door, Automatic, Diesel
f1, f2, f3, f4, f5, …, fn
2 door, Manual, Gas
f4, f6, f3, f12, f30, …, fn
2 door, Automatic, Hybrid
f4, f23, f31, f1, f3, …, fn
Convertible, Automatic, Gas
f1, f2, f3, f13, f14, …, fn

Figure 2 - Developing Requirements Model for Various Vehicle Configurations



Demo project

Project Name and Description: Demo project

Multiplexing: LIN

This project demonstrates advantages of having common modules across different platforms.

Configuration

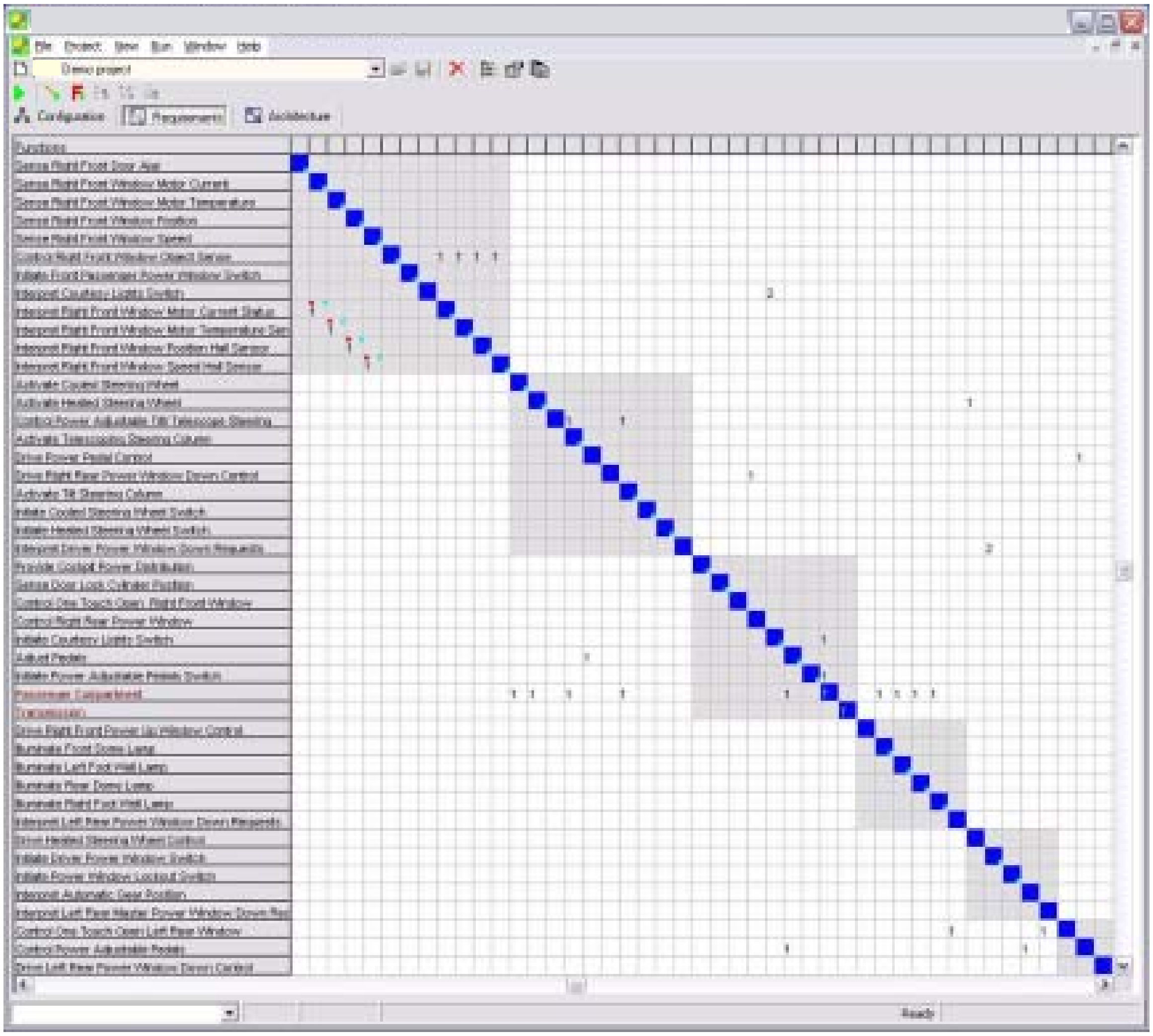
Category	Selection
Body Style	2 Door, 3 Door, 4 Door, 5 Door, Convertible
Brake/Traction System	Anti-Lock Brakes, Anti-Lock Brakes with Traction Control, Anti-Lock Brakes with Vehicle
Climate System	Dual Zone Automatic, Heater and AC, Heater Only, Single Zone Automatic
Engine Type	4 Cylinder Diesel, 4 Cylinder Gas, 6 Cylinder Diesel, 6 Cylinder Gas, 8 Cylinder Diesel, 8 C
Mirror System	Manual Mirrors, Power Memory Mirrors, Power Mirrors
Multimedia System	AM/FM, AM/FM/CD/DVD/MP3 6 Disc, AM/FM/CD/DVD/MP3 Single Disc, AM/FM/Ta
Pedal Type	Manual Pedals, Power Pedals, Power Pedals with memory
Power Assist Steering System	Power Assist Steering (Electro-Hydraulic), Power Assist Steering (Hydraulic), Steer By Wi
Seat Type	10 Way Power Seat with Memory, 12 Way Power Seat with Memory, 6 Way Power Seat,
Speed Control System	Adaptive Cruise Control, Cruise Control
Steering Column Type	Manual Steering Column, Manual Tilt Steering Column, Manual Tilt/Telescope, Power Tilt
Transmission Type	4 Speed Automatic with Overdrive, 5 Speed Manual, 6 Speed Manual, Continuously Vari

Options
- ☑ Manual Mirrors
- ☑ Power Memory Mirrors
- ☑ Power Mirrors

Figure 3 - SA builder Software Interface for Selecting Various Vehicle Configurations

SA builder software presented in this paper allows the system design experts to import the requirements model into a database; and select constraints for the various vehicle configurations (see Figure 3). Once the requirements for each vehicle configuration are identified the **SA** builder software tool automatically builds a function – function interaction matrix (see Figure 4). A function - function interaction matrix [a_{ij}] is shown in Figure 4 and includes integer, as well as "blank" entries, where an integer entry indicates the information, material or energy link (data flow) between functions i and j, and the direction of the link (flow) is from j to i. The integer also indicates the number of signals or flows sent from function j to function i. One may see that the matrix in Figure 4 is not binary but weighted.

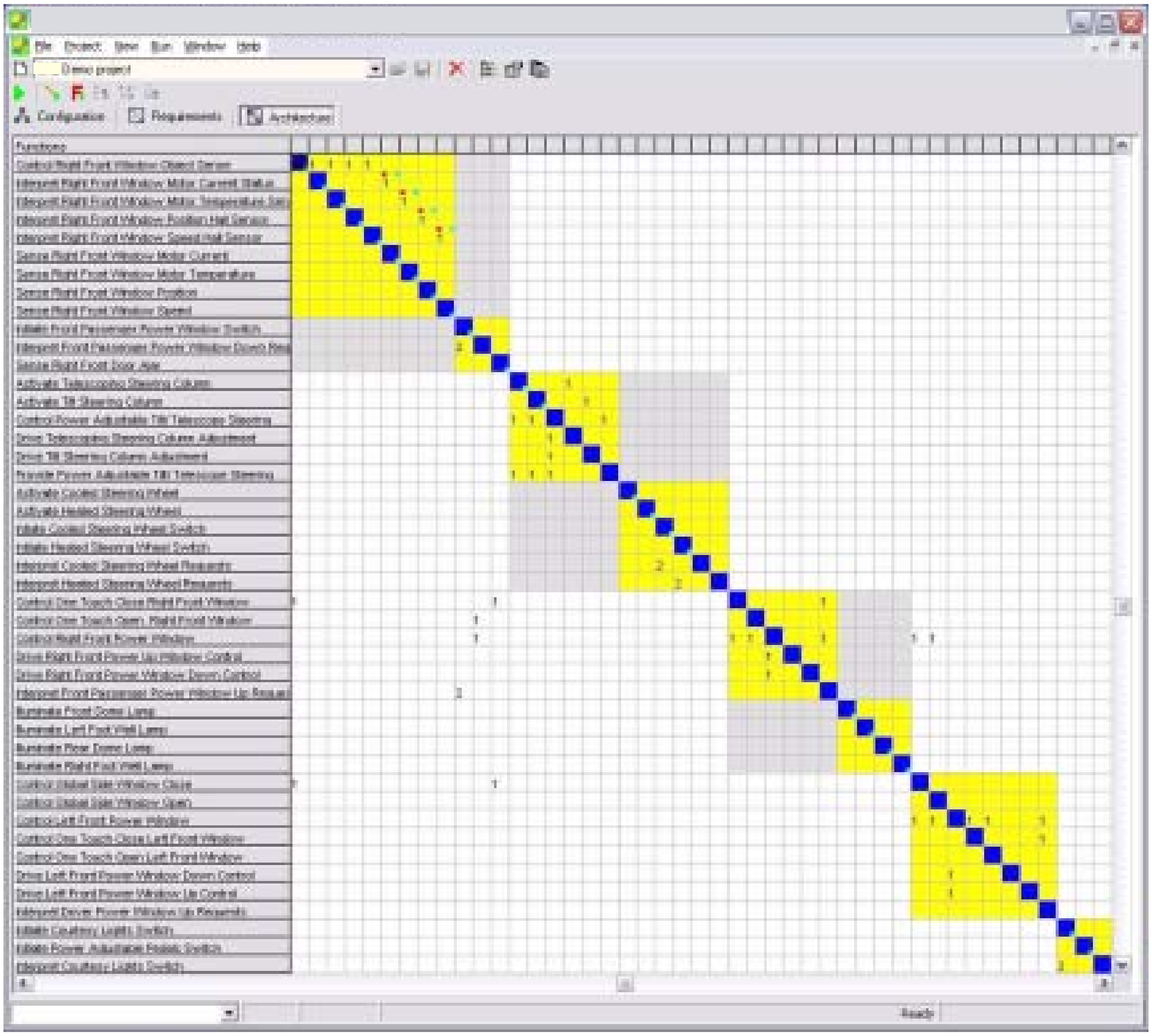
Before the optimization algorithms are applied to the function – function interaction matrix, the software tool allows the user to build predefined, or carryover, modules. The software tool allows the user to select functions from the incidence matrix and group them into a single predefined module. The functions grouped into a predefined module will not be moved into separate modules or grouped with other modules, but the interactions will be maintained. In other words, this step makes sure that in the final vehicle architecture the functions of carryover or predefined modules will appear in a single cluster/ module. Once the carryover modules are identified, the user can cluster the matrix to identify optimal functional grouping in the vehicle architecture (see Figure 5).



Functions
Sense Right Front Door Ajar
Sense Right Front Window Motor Current
Sense Right Front Window Motor Temperature
Sense Right Front Window Position
Sense Right Front Window Speed
Control Right Front Window Object Sense
Initiate Front Passenger Power Window Switch
Interpret Courtesy Lights Switch
Interpret Right Front Window Motor Current Status
Interpret Right Front Window Motor Temperature Sen
Interpret Right Front Window Position Hall Sensor
Interpret Right Front Window Speed Hall Sensor
Activate Cooled Steering Wheel
Activate Heated Steering Wheel
Control Power Adjustable Tilt Telescope Steering
Activate Telescoping Steering Column
Drive Power Pedal Control
Drive Right Rear Power Window Down Control
Activate Tilt Steering Column
Initiate Cooled Steering Wheel Switch
Initiate Heated Steering Wheel Switch
Interpret Driver Power Window Down Requests
Provide Cockpit Power Distribution
Sense Door Lock Cylinder Position
Control One Touch Open Right Front Window
Control Right Rear Power Window
Initiate Courtesy Lights Switch
Adjust Pedals
Initiate Power Adjustable Pedals Switch
Passenger Compartment
Transmission
Drive Right Front Power Up Window Control
Illuminate Front Dome Lamp
Illuminate Left Foot Well Lamp
Illuminate Rear Dome Lamp
Illuminate Right Foot Well Lamp
Interpret Left Rear Power Window Down Requests
Drive Heated Steering Wheel Control
Initiate Driver Power Window Switch
Initiate Power Window Lockout Switch
Interpret Automatic Gear Position
Interpret Left Rear Master Power Window Down Req
Control One Touch Open Left Rear Window
Control Power Adjustable Pedals
Drive Left Rear Power Window Down Control

Figure 4 - Function – Function Interaction Matrix

The EES architecture matrix shown in Figure 5 is only a small portion of a complete EES architecture matrix that could include up to 20000 functions. From Figure 5, one may see that the total cost of the common EES architecture is calculated and the EES architecture is partitioned into different zones with modules contained in those zones. One may also see the cost break down between the architecture overhead, giveaway, and wiring/multiplexing costs. It was explained earlier that various vehicle configurations could have mutually exclusive functions. Functions that support a two door body style configuration may not, or should not, appear in the four door body style configuration. Note: The EES architecture shown in Figure 5 supports all body style configurations identified using the menus shown in Figure 3. Therefore, when the EES architecture in Figure 5 is implemented for the two door body style configuration, functions that are mutually exclusive in the four door and convertible body style configurations will not be included, but will contribute to the giveaway costs.



Functions
Control Right Front Window Object Sensor
Interpret Right Front Window Motor Current Status
Interpret Right Front Window Motor Temperature Sen
Interpret Right Front Window Position Hall Sensor
Interpret Right Front Window Speed Hall Sensor
Sense Right Front Window Motor Current
Sense Right Front Window Motor Temperature
Sense Right Front Window Position
Sense Right Front Window Speed
Initiate Front Passenger Power Window Switch
Interpret Front Passenger Power Window Down Req
Sense Right Front Door Ajar
Activate Telescoping Steering Column
Activate Tilt Steering Column
Control Power Adjustable Tilt Telescope Steering
Drive Telescoping Steering Column Adjustment
Drive Tilt Steering Column Adjustment
Provide Power Adjustable Tilt Telescope Steering
Activate Cooled Steering Wheel
Activate Heated Steering Wheel
Initiate Cooled Steering Wheel Switch
Initiate Heated Steering Wheel Switch
Interpret Cooled Steering Wheel Requests
Interpret Heated Steering Wheel Requests
Control One Touch Close Right Front Window
Control One Touch Open Right Front Window
Control Right Front Power Window
Drive Right Front Power Up Window Control
Drive Right Front Power Window Down Control
Interpret Front Passenger Power Window Up Reques
Illuminate Front Dome Lamp
Illuminate Left Foot Well Lamp
Illuminate Rear Dome Lamp
Illuminate Right Foot Well Lamp
Control Global Side Window Close
Control Global Side Window Open
Control Left Front Power Window
Control One Touch Close Left Front Window
Control One Touch Open Left Front Window
Drive Left Front Power Window Down Control
Drive Left Front Power Window Up Control
Interpret Driver Power Window Up Requests
Initiate Courtesy Lights Switch
Initiate Power Adjustable Pedals Switch
Interpret Courtesy Lights Switch

Figure 5 - Common EES Architecture Matrix

Next, we present a review on different clustering techniques and briefly explain the approach of the optimization algorithms used in the **SA** Builder software tool.

Cluster Analysis Techniques

Clustering techniques are used to group objects into homogenous clusters based on object features. Clustering is also a generic name for a variety of mathematical methods that are used to find natural groupings in a given object/data set. Cluster analysis techniques have been widely used for solving various engineering problems, e.g., design of modular systems (see Zakarian and Rushton 2001, Pimmler and Eppinger 1994, Kusiak and Huang 1996, 1994), group technology (see Kusiak and Chow 1998, King 1980, Ng 1991, pattern recognition (Ni and Jain 1998, Tambouratzis 2002), and so on. The technique has been also widely used in the natural sciences (see Sneath and Sokal 1973) and increasingly in social and management sciences (see Birnbaum 1977, Mahajan and Jain 1978).

Traditional clustering algorithms can be classified into two main categories: hierarchical and partitional methods. Partitional methods create a unique partition of objects or data sets while hierarchical methods produce several nested partitions of objects.

Hierarchical clustering techniques construct tree structures reflecting the underlying patterns in a given data set. The trees obtained by this clustering method are called dendograms and are typically binary. A dendogram consists of several layers of nodes representing different clusters and are typically used to highlight the similarity between clusters. From the dendogram data analysis, different partitions can be built by cutting the tree horizontally using similarity values. The two most commonly used hierarchical clustering approaches are single link and complete link methods (Jain and Dubes 1988, Sneath and Sokal 1973).

Partitional methods create a single partition of points. Approaches in partitional clustering include error square clustering (Cheng and Tong 1991), clustering based graph theory (Tarjan 1972), and density estimation clustering. Error square clustering methods minimize the square error for a fixed number of clusters. Graph based clustering methods examine graph structure, for example using spanning tree method, to identify and remove inconsistent edges of the graph and determine strongly connected components.

Several algorithms and mathematical models have been developed for clustering binary matrices. Most of the mathematical models, i.e., *p*–median, generalized *p*–median (Kusiak 2000), require calculations of similarity distances between columns (rows) of the interaction matrix. Other algorithms, i.e., similarity coefficient method (McAuley 1972), rank order clustering algorithms (King 1980), and cluster identification algorithms (Kusiak and Chow 1987) use matrix row and column swapping techniques to obtain clusters in the binary matrix.

Incidence matrices of vehicle system models are large in size (greater than 1,000 rows/columns) and may have binary and non-binary structures. Most of the clustering techniques developed in the literature are primarily designed for clustering binary matrices. Furthermore, algorithms presented in the literature are designed for decomposing binary matrices into mutually separable clusters. System level interaction matrices are large and practically impossible to decompose into mutually separable clusters. In other words, for large matrices, like the ones developed in this research, bottleneck elements (functions) will always exist. An element (entry x_{ij} = integer number) is considered a bottleneck, when it does not allow the decomposition of the function – function interaction matrix into mutually separable clusters.

The **SA** Builder software presented in this paper uses a new clustering algorithm and cost optimization techniques for development of low cost, modular architectures that can be shared across various product platforms. The algorithms can be used for clustering both binary and non-binary (weighted) matrices. The clustering algorithm identifies clusters in the $n \times n$ incidence matrix. For the function - function incidence matrix, the algorithm first creates n clusters. Once initial clusters are obtained, the algorithm continuously improves the initial solution by moving the bottleneck elements to a cluster, if such an assignment improves the quality of the solution, i.e., minimizes the average total cost of the EES architecture that supports multiple vehicle platforms (configurations).

EES Architecture Development Around Common Modules

In this section we present an approach that allows system design engineers to identify common modules between EES architectures that support various vehicle platforms (configurations). These common modules are then used in developing optimal low cost EES architectures for each product platform (configuration). Using a system design process similar to that shown in Figure 1, one may develop a requirements model for various vehicle configurations and construct a function – function interaction matrix for each configuration (refer to Figure 4). Once the interaction matrices for the various vehicle configurations are constructed, clustering and graph based techniques may be used to identify common modules (chunks) in the incidence matrices. For example, Figure 6 represents the Interaction matrices of two different requirements models with 14 and 18 functions, respectively. Using clustering and graph based optimization techniques, one may find two clusters that are identical (common) in both incidence matrices (i.e., EES architectures). As shown in Figure 7 clusters (modules) 2 and 3 are in both matrices and have the same structure. Once common modules are identified, one can further cluster matrices in Figure 7 to obtain a final EES architecture (see Figure 8). One may see that in both clustered matrices in Figure 8, the structure of modules 2 and 3 are identical.

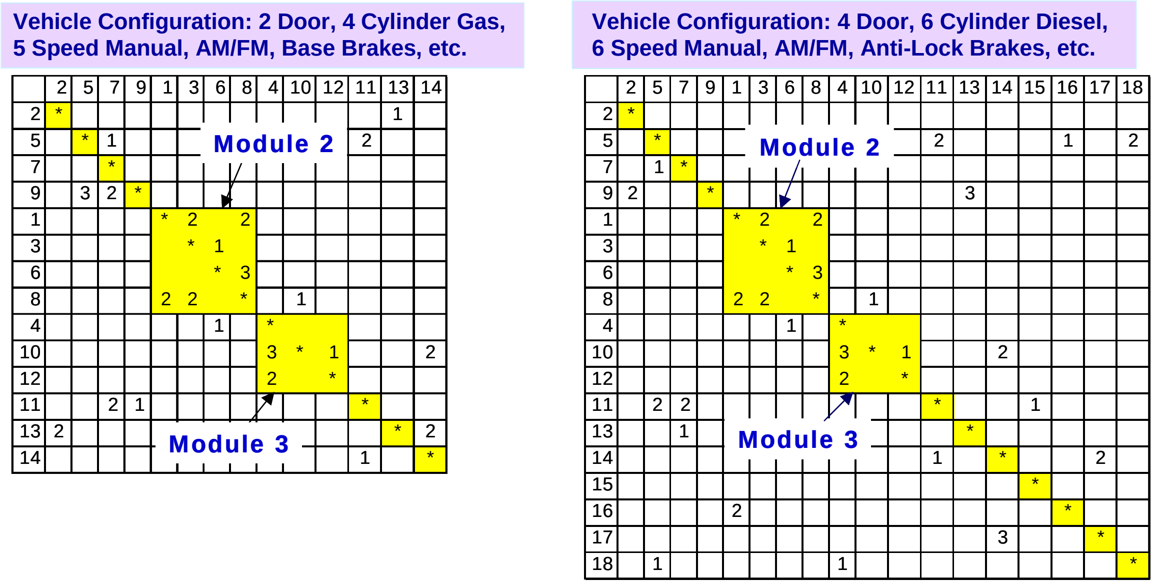
**Vehicle Configuration: 2 Door, 4 Cylinder Gas,
5 Speed Manual, AM/FM, Base Brakes, etc.**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	*		2					2						
2		*												
3			*			1								
4				*		1								
5					*		1				2			
6						*		3						
7							*							
8	2		2					*		1				
9							2		*					
10				3						*		1		2
11							2		1		*			
12				2								*		
13		2											*	2
14											1			*

**Vehicle Configuration: 4 Door, 6 Cylinder Diesel,
6 Speed Manual, AM/FM, Anti-Lock Brakes, etc.**

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	*		2					2										
2		*																
3			*			1												
4				*		1												
5					*						2					1		2
6						*		3										
7					1		*											
8	2		2					*		1								
9		2							*				3					
10				3						*		1		2				
11					2		2				*				1			
12				2								*						
13							1						*					
14											1			*			2	
15															*			
16	2															*		
17														3			*	
18				1	1													*

Figure 6 - Function-Function Interaction Matrices of Two Different Systems



Vehicle Configuration: 2 Door, 4 Cylinder Gas, 5 Speed Manual, AM/FM, Base Brakes, etc.

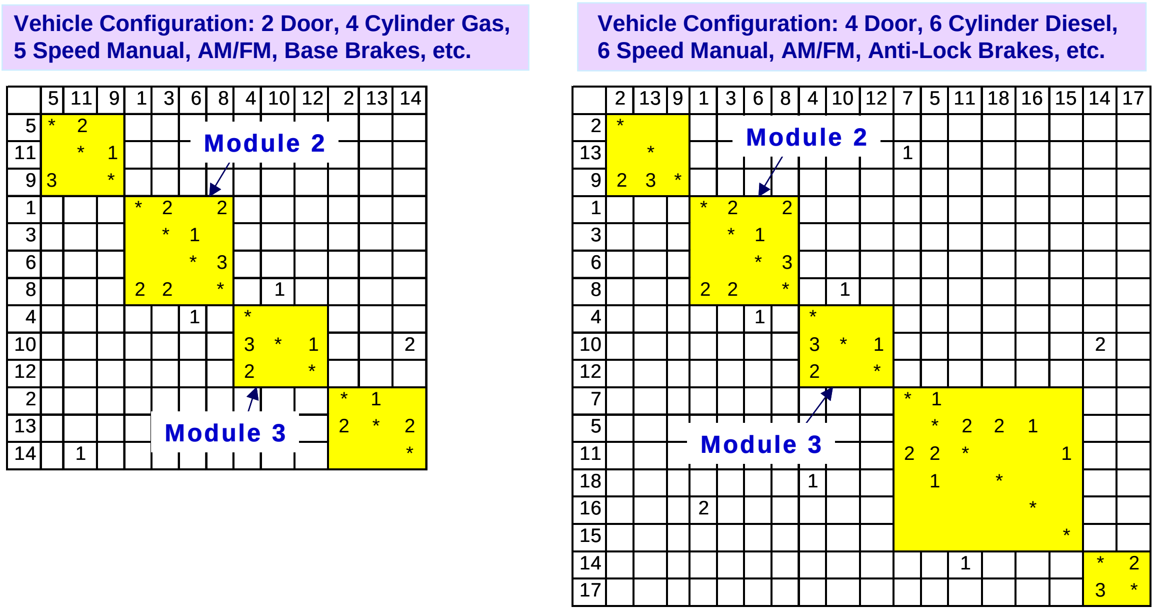
	2	5	7	9	1	3	6	8	4	10	12	11	13	14
2	*												1	
5		*	1									2		
7			*											
9		3	2	*										
1					*	2		2						
3						*	1							
6							*	3						
8					2	2		*		1				
4							1		*					
10									3	*	1			2
12									2		*			
11			2	1								*		
13	2												*	2
14												1		*

Vehicle Configuration: 4 Door, 6 Cylinder Diesel, 6 Speed Manual, AM/FM, Anti-Lock Brakes, etc.

	2	5	7	9	1	3	6	8	4	10	12	11	13	14	15	16	17	18
2	*																	
5		*										2				1		2
7		1	*															
9	2			*									3					
1					*	2		2										
3						*	1											
6							*	3										
8					2	2		*		1								
4							1		*									
10									3	*	1			2				
12									2		*							
11		2	2									*			1			
13			1										*					
14												1		*			2	
15															*			
16					2											*		
17														3			*	
18		1							1									*

Module 2
Module 3
Module 2
Module 3

Figure 7 - EES Architecture Matrices with Two Common Modules



Vehicle Configuration: 2 Door, 4 Cylinder Gas, 5 Speed Manual, AM/FM, Base Brakes, etc.

	5	11	9	1	3	6	8	4	10	12	2	13	14
5	*	2											
11		*	1										
9	3		*										
1				*	2		2						
3					*	1							
6						*	3						
8				2	2		*		1				
4						1		*					
10								3	*	1			2
12								2		*			
2											*	1	
13											2	*	2
14		1											*

Vehicle Configuration: 4 Door, 6 Cylinder Diesel, 6 Speed Manual, AM/FM, Anti-Lock Brakes, etc.

	2	13	9	1	3	6	8	4	10	12	7	5	11	18	16	15	14	17
2	*																	
13		*									1							
9	2	3	*															
1				*	2		2											
3					*	1												
6						*	3											
8				2	2		*		1									
4						1		*										
10								3	*	1							2	
12								2		*								
7											*	1						
5												*	2	2	1			
11											2	2	*			1		
18								1				1		*				
16				2											*			
15																*		
14													1				*	2
17																	3	*

Module 2
Module 3
Module 2
Module 3

Figure 8 - Clustered EES Architecture Matrices with Two Common Modules

CONCLUSION

Modular design approaches used in the development of vehicle electrical, electronic, and software (EES) systems allow sharing of architectures/modules between different product lines (vehicles). This modular design approach may provide economies of scale, reduced development time, reduced order lead-time, easier product diagnostics, maintenance and repair. Other benefits of this design approach include development of a variety of EES systems through component swapping and component sharing. In this paper, new approaches and software tools were presented that allow EES system design engineers to develop modular architectures/modules that can be shared across vehicle platforms (for OEMs) and across OEMs (for suppliers). Approaches presented in this paper used matrix clustering and graph based techniques. The application of the approach was illustrated with an example from the automotive industry

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