INTERNATIONAL DESIGN CONFERENCE - DESIGN 2010
Dubrovnik - Croatia, May 17 - 20, 2010.

COMPATIBILITY MATRIX METHODOLOGY APPLIED TO THE IDENTIFICATION OF VEHICLE ARCHITECTURES AND DESIGN REQUIREMENTS

C. Gorbea, D. Hellenbrand, T. Srivastava, W. Biedermann and U. Lindemann

Keywords: compatibility matrix, vehicle architecture

1. Introduction

When considering vehicle architecture over the last century, several significant changes in the outer body design, engine placement and various drive configurations come to mind. However, in a broader view, the basics of the internal combustion engine car (ICE) architecture have remained relatively unchanged ever since late 1920 [Gorbea, et al., 2008]. The re-emergence of hybrid and electric cars now, represent the first car architectures that challenge the established ICE car architecture norm. As the automotive industry explores new hybrid electric vehicle (HEV) architectures, the need exists for a systematic approach to explore a wide range of architectural innovations. These innovations are formed by reconfiguring already known systems in new ways that deliver improved or varied functionality [Henderson, et al., 1990].

This paper presents a *compatibility matrix methodology* that is applied to the search for HEV architecture configurations and dimensioning requirements. The methodology builds on previous design structure matrix (DSM) research work for early concept selection presented by Deubzer [Deubzer, et al., 2008] and further refined by Hellenbrand [Hellenbrand, et al., 2008]. The latter author presents the original idea of the "compatibility DSM" used to identify partial design solutions that can be combined to create a set of "valid" overall concept combinations of partial solutions.

Here we choose to rename the *compatibility DSM* as simply *compatibility matrix* given the fact that although the matrix holds an nxn format, it is not used to cluster or analyze feedback loops as are DSMs in literature. The compatibility matrix is in fact the inverse of a consistency matrix as presented by Pahl and Beitz [Pahl, et al., 2006]. The consistency matrix shows which partial solutions of a morphological solution tree are not consistent, whereas the compatibility matrix presented here displays which partial solutions are compatible.

1.1 Motivation for Research and Contribution

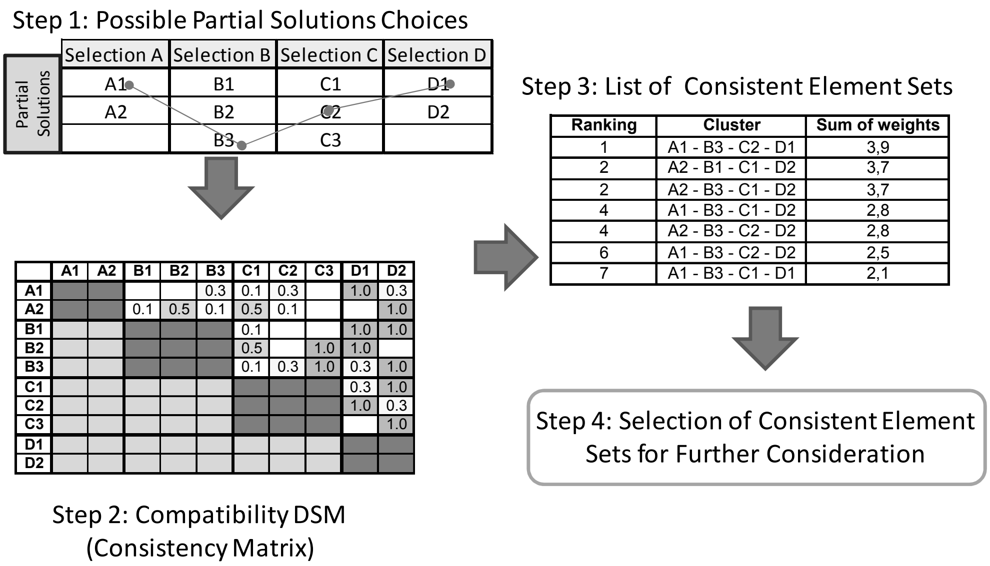
The work was generated in direct cooperation with industry experts in the area of HEV architecture concept work at a leading German premium automotive manufacturer. The challenge of building HEV concepts lie in the "n-dimensional" nature of establishing the corner points of what a car must accomplish "in functions" and how the major components can be configured "in form" within the powertrain to best accomplish these goals. During this pre-development phase the most difficult task for practitioners is to develop a link between the many structural aspects such as the configuration and placement of major sub-systems, weight, handling, etc.; and the requirements that constrain the size, cost, capacity, and safety of the vehicle. The methodology presented in this paper is tailored to the generate a structural solution space for HEV architects and link it with specific requirements that allow for the actual dimensioning of the major component systems for the electric system of HEVs.

The generated solution space must then be further refined and detailed during the development process – these steps are outside the scope of this paper. The research that follows allowed the early design phase systems architects to consider many architectural innovations and their impact to the requirements in discussion with engineers from functional areas.
The compatibility matrix methodology applies to any choice selection set to include multiple design domains – specifically the product architecture *structure* domain with its multiple sub-domains and the system *requirements* domain with its own multiple sub domains. The theory is tested in the practical setting of HEV concept work.
The motivation of this study is to create a solution space of HEV and battery electric vehicle (BEV) architecture structures that can achieve a given set of functional requirements. We use the methodology to explore only *consistent* or *valid* architecture concepts built from the configuration of key HEV sub-system components and dimensioning requirements. Developers can use this information to appropriately choose and size HEV architectures that achieve specific design goals. The methodology is not meant to consider all detailed aspects of automotive design outside of early concept selection, but the authors believe that it can be applied at more detailed design phases as well.

2. Morphological concept selection of consistent structures

Zwicky demonstrated that a morphological matrix [Zwicky 1966] can be used to identify solution concepts available for partial functions in a design. The compatibility of the many partial solutions identified in a morphological matrix can be further analyzed using tree structures or a consistency matrix [Lindemann, 2007]. In considering consistent configurations of HEV component subsystems, the latter has proven to be a more useful tool as the number of partial solutions is large and handled easier in a matrix.
A generic four step process for the selection of consistent architectures is presented below.

- Step 1: Determine selection choices and possible partial solutions choices
- Step 2: Determine which partial solutions are compatible using a compatibility matrix
- Step 3: Identify consistent partial solutions sets
- Step 4: Select consistent partial solutions sets for further analysis



Selection A	Selection B	Selection C	Selection D
A1	B1	C1	D1
A2	B2	C2	D2
	B3	C3	

	A1	A2	B1	B2	B3	C1	C2	C3	D1	D2
A1					0.3	0.1	0.3		1.0	0.3
A2			0.1	0.5	0.1	0.5	0.1			1.0
B1						0.1			1.0	1.0
B2						0.5		1.0	1.0	
B3						0.1	0.3	1.0	0.3	1.0
C1									0.3	1.0
C2									1.0	0.3
C3										1.0
D1										
D2										

Ranking	Cluster	Sum of weights
1	A1 - B3 - C2 - D1	3,9
2	A2 - B1 - C1 - D2	3,7
2	A2 - B3 - C1 - D2	3,7
4	A1 - B3 - C1 - D2	2,8
4	A2 - B3 - C2 - D2	2,8
6	A1 - B3 - C2 - D2	2,5
7	A1 - B3 - C1 - D1	2,1

Figure 1. The procedure presented above can help map a consistent design space by revealing which choices within the possible selection elements can be combined. The procedure can be used in linking physical components as well a choice set of design requirement parameters

Figure 1 shows the generic four step model. In step one, four design selection choices are presented (A thru D) as column headers with the possible partial solution choices listed for each selection, similar to a morphological matrix. Because not all combinations of partial solutions are consistent, a compatibility matrix (or consistency matrix) shows which combinations of solutions are compatible by filling in the matrix elements with numbers from 0-1, as shown in step 2.

A value of “1” is awarded to partial solutions that are completely compatible whereas a “0” or blank entry shows that the two partial solutions are incompatible. Values that are closer to “1” denote higher compatibility based on the judgement of the design team. In filling out the compatibility matrix, developers only fill the upper triangular half, as it is sufficient to examine all combination pairs of partial solutions.

In step 3, Algorithms used in finding DSM completely interlinked clusters are used to list all consistent selections [Lindemann, et al., 2008], given that at least one partial solution item must be selected from each selection field. The resulting list includes only valid element clusters that can be successfully combined. Hellenbrand [Hellenbrand, et al., 2008] shows that the selection process in step 4 can be aided by summing the compatibility values assigned for consistent partial solution sets (or completely interlinked clusters). Those sets with a higher sum are presumably more compatible and can be ranked at the top of the list for consideration. However, when many compatible sets are available with similar compatibility scores, other decision criteria and decision methodologies must be considered.

2.1 Methodology applied to HEV architecture structures

Cars are examples of complex systems that comprise many component subsystems. Architectural innovations that result from the reconfiguration of component or sub-systems can be identified by identifying possible structural variations in a methodical manner.

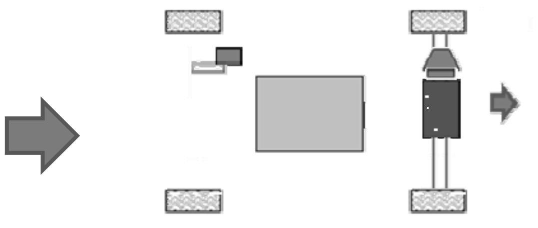
The compatibility matrix methodology is applied to HEV architectures with the goal of exploring possible HEV configurations. The configuration tool allows HEV developers to explore many possible combinations of cars with electric powertrains[2]. We present the methodology in the steps outlined in the previous section.

Step 1: Determine concept selection choices and possible partial solutions – Following several team workshops with experts from industry, nine concept selection choices were created to generate a generic HEV architecture concept depiction. These selection choices follow a strict order starting at an abstract choice level, working down to specific architecture selections on key component configurations for the engine, electric motors and the high voltage battery.

Table 1. ‘Abstract to concrete” architecture selection criteria for electric powertrain vehicles

1. Concept	2. Architecture	3. Engine Placement	4. Engine Orientation	5. Engine Transmission	6. Engine E-Motor	7. Engine Axle
Micro Hybrid	Through-the-Road	Front, 4WD	Parallel to axle	Manual	Pre-Transmission	Axle E-Motor
Mild Hybrid	Parallel	Front, RWD	Perpendicular to axle	Automatic	Starter-Generator	2 Wheel E-Motors
Full Hybrid	P-Split	Front, FWD	No Engine	CVT/ECVT	No Engine	No E-Motors
PHEV	Combined	Rear, 4WD		No Transmission		
BEV	Series	Rear, RWD				
	BEV	No Engine				

8. Other Axle	9. HV Battery Placement
Axle E-Motor	Sandwich
2 Wheel E-Motors	Drive Axle
No E-Motors	Other Axle
	Tunnel
	No HV Battery



Selected Architecture Schematic

Table 1 shows the HEV architecture selection choices in the selection order. Developers are to select one partial solution in each column category to lock-in an HEV/BEV architecture structure in drop

2 In this study we include all electric powertrain architectures spanning from micro hybrids on through battery electric vehicles.

down menu manner. Based on the selection choices a schematic depiction of the architecture structure is generated automatically with assistance of a computer program.

It was particularly important to have the team define how detailed the necessary concepts needed to be. In this case, developers were in the early design stages and wanted to open an architecture solution space that did not specify more than the placement of the key component subsystems. This facilitated the reduction of the number of selections to a manageable set of 9 selections and a total of 38 possible choice elements. The names of the selection choices were assigned particular meaning after productive debate sessions by the team of developers. For example, clear definitions were assigned to what makes a "micro hybrid" different from a "mild" or "full" hybrid. These definitions were tied to system functional requirements as we will see in section 4.

	Concept					Architecture						Engine Placement						Engine Orientatio			Engine Transmission				Engine E-Motor			Engine Axle			Other Axle			HV Battery Placement				
	Micro Hybrid	Mild Hybrid	Full Hybrid	PHEV	BEV	Through-the-Road	Parallel	P-Split	Combined	Series	BEV	Front, 4WD	Front, RWD	Front, FWD	Rear, 4WD	Rear, RWD	No Engine	Parallel to axle	Perpendicular to axle	No Engine	Manual	Automatic	CVT/ECVT	No Transmission	Pre-Transmission	Starter-Generator	No Engine	Axle E-Motor	2 Wheel E-Motors	No E-Motors	Axle E-Motor	2 Wheel E-Motors	No E-Motors	Sandwich	Drive Axle	Other Axle	Tunnel	No HV Battery
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
1	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	1	0	1	0	0	0	1	0	0	1	0	0	0	0	1
2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	0
3	0	0	1	0	0	1	1	1	0.5	0.5	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
4	0	0	0	1	0	0.1	0.1	0.1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	0	1	1	1	1	1	1	1	0
6	0	0	1	0.1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	1	0	1	1	1	0	0	1	0	0	0	1	1	1	0	1	1	1	1	1
7	1	1	1	0.1	0	0	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
8	0	0	1	0.1	0	0	0	1	0	0	0	1	1	1	1	1	0	1	1	0	0	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1
9	0	0	0.5	1	0	0	0	0	1	0	0	0.1	0.1	1	0.1	1	0	1	1	0	0	0.1	0.1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
10	0	0	0.5	1	0	0	0	0	0	1	0	1	1	1	1	1	0	1	1	0	0	0.1	0.1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
11	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0.1	0.1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	0	0	1	1	0.1	1	0	1	0	0	0	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	0	1
13	1	1	1	1	0	0	1	1	0.1	1	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	0	1
14	1	1	1	1	0	1	1	1	1	1	0	0	0	1	0	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	1
15	1	1	1	1	0	0	1	1	0.1	1	0	0	0	0	1	0	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	0.5	0	1	1	1
16	1	1	1	1	0	1	1	1	1	1	0	0	0	0	0	1	0	1	1	0	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	0	1
17	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
18	1	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	0	1	1	1	1	1	0	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0.5	1
20	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
21	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	1	0	1	1	0	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	0	1	1	0	0.1	0.1	0.1	1	1	1	1	1	0	1	1	0	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	0	1	1	1	0.1	0.1	0.1	1	1	1	1	1	0	1	1	0	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	0	0	0	1	1	1	0	0	0	0	0	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
25	0	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	0	1	1	0	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	0	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
27	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0
28	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
29	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1
30	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1
31	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1
32	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1
33	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
34	0	1	1	1	1	1	1	1	1	1	1	0.5	0.5	1	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
35	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0
36	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0
37	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
38	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	1

Figure 2. Compatibility matrix for HEV/BEV architecture structures

Step 2: Determine which partial solutions are compatible using a compatibility matrix – Figure 2 shows the results of the compatibility matrix for the architecture selection criteria. The figure shows a symmetric matrix that was generated through team workshops with HEV architecture experts from the industry. A weighting scheme was utilized to determine the degree of compatibility between choice pairs (1 = compatible, 0.5 = compatible but less practical, 0.1 = compatible but impractical, 0 = incompatible). The compatibility of selection pairs was done merely considering structural aspects of the design with no regards to dimensioning of components

The compatibility matrix above works similar to a decision tree. Once an item is picked in the first selection category “concept”, it has a direct influence on which picks are available for the second selection category “Architecture” and so on until the last selection category. Consistent solutions are those that allow for one selection for each category allowing for a total of 9 selections as depicted in Figure 2 based on the selection example from table 1. The order of selection must not necessarily be sequential. A valid architecture is generated so long each element selected develops a valid link.
In order to check for consistency, the compatibility matrix was utilized to power dynamic drop down menus as a tool for checking sets of choices. The dynamic drop down menus clearly shows what tree branches are available based on the previous branch’s selection. The meanings of the structural selection fields are briefly discussed below.

- **Concept** – This selection refers to classification for HEVs that are assigned based on functionality of the electric powertrains as defined by our team.
- **Architecture** – This selection categorizes a basic fundamental powertrain structure according to specific definitions relevant to the field of HEV/BEV architecting.
- **Engine Placement** – This selection specifies the general engine placement in the front or rear in the vehicle (only 2 axles and four wheels are assumed) and the drive type (Rear Wheel Drive, Front Wheel Drive or Four Wheel Drive)
- **Engine Orientation** – This selection specifies whether the engine is placed parallel or perpendicular to the axle it rests on.
- **Engine Transmission –** Basic selection of transmission type: manual, automatic, or current variable transmission/electric current variable transmission (CVT/ECVT)
- **Engine E-Motor –** This selection field specifies whether there is an e-motor integrated with the engine module between the engine and transmission or as a starter generator.
- **Engine Axle –** This selection field specifies the placement of an electric motor within the axle where the engine is located.
- **Other Axle –** This field specifies the placement of an electric motor within the axle opposite from where the internal combustion engine is placed.
- **High Voltage (HV) Battery Placement –** This field specifies the placement location of a high voltage battery (only one HV battery system is assumed).

Step 3: Analyze consistent partial solutions – Computer program tools such as Loomeo® and Microsoft Excel® were used to analyze and list the set of consistent partial solutions.
Out of 291,600 (5x6x6x3x4x3x3x3x5) possible solution choice sets only 5,451 solutions exhibit compatible architecture concepts. This finding shows that less than 2% of all possible combinations generate a valid HEV architecture structural concept. There are literally still thousands of ways to build a hybrid/electric car!
Step 4: Select consistent partial solutions for further analysis – With such a large number of possible hybrid architectures it is clear that the HEV market today still has a number of architectural innovations waiting to come to market. The best architectures are the ones that meet the design requirements brought by the customer, legal requirements, safety, costs and many other considerations. Linking the right product architecture to the requirement set becomes a that requires decision making methodologies such as trade space analysis or decision matrices that are beyond the scope of this paper.

2.2 Methodology applied to HEV dimensioning requirements

The methodology presented in section 3 applies to any design choice element selection. Applying the same methodology to design dimensioning requirements allowed us to explore which requirement sets are compatible.
Figure 3 shows the resulting compatibility matrix for requirements generated in step 2 of the methodology. The presence of many zero cells, show that these requirement dimensioning choices are more restrictive than the previous structural considerations.
In the example, requirements were selected that could help designers size the electric powertrain system components. These dimensioning requirement parameters include:

- **Electrification index** – A measure of the size of the electric propulsion system. The index is defined as the ratio of peak electric power available to the total power available (P_{el}/P_{total}). A low electrification index number represents car architectures with small electric motors that are used in conjunction to large internal combustion engine systems, whereas an electrification index value of “1” represents a pure battery electric vehicle with no internal combustion engine.
- **All Electric Range** – This is a dimensioning requirement that defines the all electric range of the car in miles without use of an ICE.
- **Power to Energy ratio (kW/kWh)** – The power to energy ratio helps determine the battery chemistry and structure required for the design of the HEV or BEV. Low P/E ratios of 1-5 are characteristic of plug-in HEVs and BEVs whereas high P/E ratios of 20+ are common in hybrids with small electric systems.
- **% Battery Depth of Discharge (% DOD)** – This parameter is important for HEV architecture concept work with battery control strategies. Batteries with small %DOD are found in smaller electric systems and result in longer battery life. Large %DOD is characteristic of electric powertrains designed for large all electric range such as plug in HEVs and BEVs.

			Electrification Index Range (P el / P tot)					All Electric Range (AER) in miles								Power/Energy Ratio (kW/kWh)					% DOD				
			0 - 0.05	0.05 - 0.15	0.2 - 0.3	0.3 - 0.8	0.8-1	0 - 0.5	0.5 - 2	2 - 10	10 - 20	20 - 30	30 - 40	40 - 50	> 50	1 - 5	5 - 10	10 - 20	20 - 30	> 30	10 - 15%	15 - 30%	30 - 50%	50 - 70%	> 70%
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Electrification Index Range (P el / P tot)	0 - 0.05	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.05 - 0.15	2	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	0.2 - 0.3	3	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0
	0.3 - 0.8	4	0	0	0	1	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1
	0.8-1	5	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
All Electric Range (AER) in miles	0 - 0.5	6	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.5 - 2	7	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	2 - 10	8	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1
	10 - 20	9	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	1	1
	20 - 30	10	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1
	30 - 40	11	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1
	40 - 50	12	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1
	> 50	13	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
Power/Energy Ratio (kW/kWh)	1 - 5	14	0	0	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1
	5 - 10	15	0	0	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1
	10 - 20	16	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1
	20 - 30	17	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1
	> 30	18	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
% DOD	10 - 15%	19	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
	15 - 30%	20	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0
	30 - 50%	21	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	1	0	0
	50 - 70%	22	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
	> 70%	23	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1

Figure 3. Compatibility matrix of electrification system requirement parameters

A compatibility matrix analysis (step 3) of the dimensioning requirements yields 41 compatible combinations out of a possible 1000 (5x8x5x5) selection choice sets. This represents only 4.1% consistency. Having examined structural solutions in section 3.2 and now dimensioning requirements in section 3.3, it is of little value to maintain the information analyzed in separate domains. The question arises, how can various choice element selection sets be combined or linked to complement each other?

3. Linking HEV Architecture Structures with Requirements

In order to link two or more choice sets, a combination matrix with both selection elements can be created by incorporating sub selection elements in the consistency matrix as shown in figure 4. A so called "branch and cut" algorithm [Biedermann, et al., 2008] could then be used to determine consistency amongst both elements and sub elements of the matrix. However, the increased number of fields and computations make this approach impractical.

		A1					A2				B1			
			A11	A12	A13	A14		A21	A22	A23		B11	B12	...
A1														
	A11													
	A12													
	A13													
	A14													
A2														
	A21													
	A22													
	A23													
B1														
	B11													
	B12													
	...													

Figure 4. An impractical alternative to linking two sets of selection criteria In a consistency DSM by creating sub-selection elements fields

A more practical solution is to create a shared selection field amongst both choice sets as depicted in figure 5. Building on the previous HEV/BEV architecture example, the structural selection choices and the system requirements selection fields can be worked concurrently. The first three steps of the compatibility matrix methodology is applied to both selection set domains, however each set containing at least one linking selection. The common linking field facilitates a detailed search of selection choices that are valid in both the structure and requirement domain fulfilment.

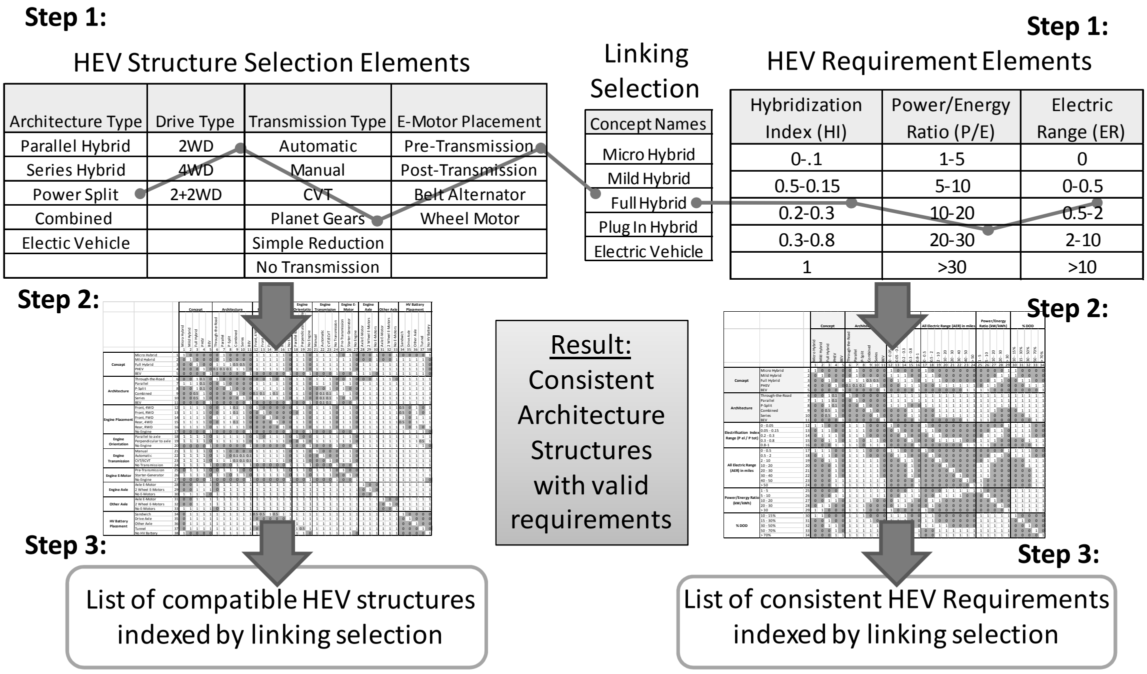


Figure 5. By creating one or more linking selections used in both the "HEV requirements" and "structure" selection elements, the system architect can generate a solution space of valid architectures compatible in both domains

The exemplary depiction provided in Figure 5 designates the selection field "concept names" as the selection element that can be found in both the "requirements" and "structural" selection fields. By selecting one field in each category of the “HEV structure selection elements” (see Figure 5, top left), there is enough information to generate a detailed architecture component structure[Gorbea, et al. 2008]. Similarly, a simplified set of “HEV requirement elements” that affect HEV designs are analyzed for consistency (see Figure 5, top right).

3.1 Results with the introduction of a linking selection

The first three steps of the compatibility matrix methodology where applied to both the “structural” and “requirements” data sets again using two “linking selections”, namely the selection fields “concept” and “architecture” were added to the “requirements” data. Figure 6 shows the new compatibility matrix used for the requirements data set incorporating the new linking selection fields. The incorporation of the linking fields allowed the developers to consider what functional requirement meanings should be linked to the various concept and architecture categories.

			Concept					Architecture						Electrification Index Range (P el / P tot)					All Electric Range (AER) in miles								Power/Energy Ratio (kW/kWh)					% DOD				
			Micro Hybrid	Mild Hybrid	Full Hybrid	PHEV	BEV	Through-the-Road	Parallel	P-Split	Combined	Series	BEV	0 - 0.05	0.05 - 0.15	0.2 - 0.3	0.3 - 0.8	0.8-1	0 - 0.5	0.5 - 2	2 - 10	10 - 20	20 - 30	30 - 40	40 - 50	> 50	1 - 5	5 - 10	10 - 20	20 - 30	> 30	10 - 15%	15 - 30%	30 - 50%	50 - 70%	> 70%
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Concept	Micro Hybrid	1	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	Mild Hybrid	2	0	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
	Full Hybrid	3	0	0	1	0	0	1	1	1	0.5	0.5	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0
	PHEV	4	0	0	0	1	0	0.1	0.1	0.1	1	1	0	0	0	1	1	1	0	0	1	1	1	1	1	1	0	1	1	0	0	0	0	1	1	1
	BEV	5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1
Architecture	Through-the-Road	6	0	0	1	0.1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Parallel	7	1	1	1	0.1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	P-Split	8	0	0	1	0.1	0	0	0	1	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Combined	9	0	0	0.5	1	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1
	Series	10	0	0	0.5	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	BEV	11	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
Electrification Index Range (P el / P tot)	0 - 0.05	12	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.05 - 0.15	13	0	1	1	0	0	1	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	0.2 - 0.3	14	0	1	1	1	0	1	1	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	1	0	1	1	1	0	0
	0.3 - 0.8	15	0	0	1	1	0	1	1	0	1	1	0	0	0	0	1	0	0	0	1	1	1	1	0	0	1	1	1	0	0	0	0	1	1	1
	0.8-1	16	0	0	0	1	1	1	1	0	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	1	1
All Electric Range (AER) in miles	0 - 0.5	17	1	1	1	0	0	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
	0.5 - 2	18	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	1	1	1	0	0
	2 - 10	19	0	0	1	1	0	1	1	1	1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1
	10 - 20	20	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	1	1
	20 - 30	21	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1
	30 - 40	22	0	0	0	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1
	40 - 50	23	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1
	> 50	24	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
Power/Energy Ratio (kW/kWh)	1 - 5	25	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1
	5 - 10	26	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1
	10 - 20	27	0	0	1	1	0	1	1	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1
	20 - 30	28	0	1	1	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1
	> 30	29	1	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
% DOD	10 - 15%	30	1	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
	15 - 30%	31	0	0	1	0	0	1	1	1	1	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0
	30 - 50%	32	0	0	1	1	0	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	0	1	0	0
	50 - 70%	33	0	0	0	1	0	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0
	> 70%	34	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1

Figure 6. Linking selections are added to the dimensioning requirements data to allow indexing with the structural architecture database

For example a “micro hybrid” concept can only occur in a ‘parallel’ HEV configuration with a hybridization index (P_{el}/P_{total}) of 0-.05, a minimal electric range of 0-.5 miles, a power to energy ratio above 30 and a %DOD of 10-15%. Given this information valid architecture dimensioning requirements can now be linked to the valid structural configurations for a micro hybrid.

With computational help, step 3 of the methodology provides a listing of compatible structures as well as a listing of compatible requirements. The data generated is presented in a manner that can be further sorted in a database as presented in Figure 7. The figure only shows an excerpt of all completely interlinked clusters that are valid in both data sets listing the choice selection sets in order.

The combination of the two data sets is useful for developers to find new architectural innovations and be able to apply a valid set of requirements. The valid requirement set aids in the dimensioning of key components of the electric powertrain.

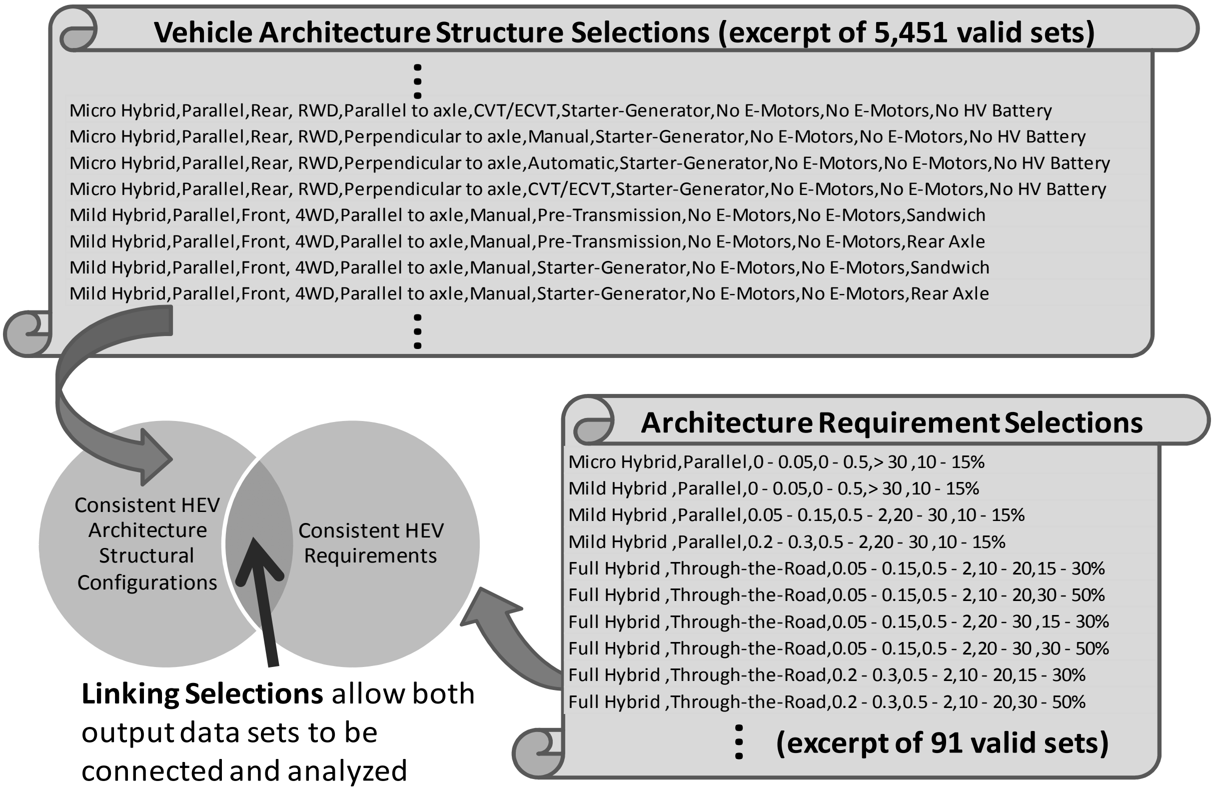


Figure 7. Excerpt of results for both valid architecture structure and dimensioning requirement selection choices

4. Conclusions and Future Work

The compatibility matrix enables a systematic approach that can be applied in the search for consistent design choices throughout the development of a system or product. The four step methodology presented in this paper builds on the authors' previous work on concept selection in the early product development stages. Use of the compatibility matrix is further developed in this work to include a "linking selection" that bridges two choice meta-domains with multiple sub-domains. In the example presented, the linking selections allow developers of HEV architectures to explore both new structural configurations of HEVs alongside important system requirement parameters.

In this applied example, we learn that there are many ways to build a hybrid by car simply looking at structural configurations of the three key system design elements: the internal combustion engine, the electric motors and the high voltage battery. The study led to the finding of over 5,400 distinct architectural arrangements for HEV/BEVs at this high level of abstraction. The structural configurations explored were further enhanced by specifying system requirements that can help size the three key components in an HEV structure. Combining architectural structure and system dimensioning requirements provides the ability to specify architecture concept parameters important in determining design feasibility.

The limitations of this methodology lie in the linear linking of choice sets. Consistency depends on the linking of each element with its immediate left and right selections - similar to a decision tree. The "linking selections" for new domains must occur at a high level of abstraction to allow for more flexibility – for example the "concept" and "architecture" fields are abstract enough to allow themselves to be linking fields for both the structures and requirements. Linking in other more detailed choices specific fields to the engine for example can be linked to the "engine placement" and "engine orientation" fields. The methodology aids in documentation of linking constraints, however it can become tedious in filling out the matrices despite the information value they provide.

Further work utilizes the structural configurator and dimensioning tool developed in this paper to analyze life cycle costs of HEVs. Once an architecture is configured and sized, a cost estimate of manufacturing costs and operation costs are calculated. Combining, product architecture and life cycle costs allows developers to make more informed decisions up front in the early development stages to significantly reduce design costs.

References

Biedermann, W., and Lindemann, U., "Cycles in the Multiple-Domain Matrix – Interpretation and Applications", Proceedings of the 10th International DSM Conference, M. Kreimeyer, et al. (Ed.), Stockholm, 2008, pp.25-34.

Deubzer, F., Braun, T., Maurer, M., and Lindemann, U., "Applying the Multiple Domain Mapping Approach to New Variant Management", Proceedings of the 10th International Design Conference - Design 2008, Dubrovnik, 2008, pp.335-342.

Gorbea, C., Fricke, E., and Lindemann, U., "The Design of Future Cars in a New Age of Architectural Competition", ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE, Brooklyn, New York, 2008 of Conference.

Gorbea, C., Spielmannleitner, T., Lindemann, U., and Fricke, E., "Analysis of Hybrid Vehicle Architectures Using Multiple Domain Matrices", Proceedings of the 10th International DSM Conference, M. Kreimeyer, et al. (Ed.), Stockholm, 2008, pp.375-387.

Hellenbrand, D., and Lindemann, U., "Using the Dsm to Support the Selection of Product Concepts", Proceedings of the 10th International DSM Conference, M. Kreimeyer, et al. (Ed.), Stockholm, 2008, pp.363-374.

Henderson, R. M., and Clark, K. B., "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms", Administrative Science Quarterly, 35, No.1, year, pp. 9-30.

Lindemann, U., "Methodische Entwicklung Technischer Produkte", Springer Berlin, 2007.

Lindemann, U., Maurer, M., and Braun, T., "Structural Complexity Management: An Approach for the Field of Product Design", Springer Verlag 2008.

Pahl, G., Beitz, W., and Grote, K.-H., "Konstruktionslehre", Springer Berlin, 2006.

Zwicky, F., "Entdecken, Erfinden, Forschen Im Morphologischen Weltbild", Droemer Knaur Munich, 1966.

Carlos Gorbea
Technische Universität München
Institute for Product Development
Boltzmannstraße 15
85748 Garching, Germany
Telephone:+49.163.450.9409
Telefax:+49.89.289.15137
Email: carlos.gorbea@pe.mw.tum.de