From User Requirements to Commonality Specifications: An Integrated Approach to Product Family Design

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Across many industries, the prevailing practice is to design families of products that exploit commonality to take advantage of economies of scale and scope while targeting a variety of market applications. A *product family* is a group of related products that are derived from a common set of components, modules, and/or subsystems to satisfy a variety of market applications where the common "elements" constitute the *product platform*. Successful development of a platform and deployment of the product family requires input from multiple disciplines (e.g., marketing, engineering, manufacturing), and a variety of methods and tools exist to support different aspects of product family design. Unfortunately, many of these methods and tools have been developed – and consequently exist – in isolation from one other. In this paper, we introduce a new approach for integrating several of these disparate tools to translate user needs and requirements into commonality specifications during product family design. In particular, we integrate the market segmentation grid, Generational Variety Index (GVI), Design Structure Matrix (DSM), commonality indices, mathematical modeling and optimization, and multi-dimensional data visualization tools to translate user requirements into commonality specifications for a product family: what to make common, what to make unique, and the best parameter settings for each component and/or subsystem. The design of a family of unmanned ground vehicles (UGVs) is included to demonstrate the proposed approach and highlight its benefits and limitations.

I. Introduction

ACROSS many industries, the prevailing practice is to design families of products that exploit commonality to take advantage of economies of scale and scope while targeting a variety of market applications. A *product family* is a group of related products that are derived from a common set of components, modules, and/or subsystems to satisfy a variety of market applications where the common "elements" constitute the *product platform.*[1] The platform is used to create individual products either through addition/subtraction/substitution of one or more modules to realize a module-based product family, or by scaling and/or "stretching" one or more design variables to realize a scale-based product family.[2] Successful examples can be found in a variety of companies, including Airbus,[3] Black & Decker,[1] Boeing,[4] and Rolls Royce.[5]

Product family design is a difficult task – it involves all of the complexities of product design compounded by the challenges of coordinating the design of multiple products. There are many advantages to product families, however, most of which stem from increased commonality among the set of products. As Robertson and Ulrich[6] point out, "By sharing components and production processes across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing processes, and take market share away from competitors that develop only one product at a time." Platforms promote better learning across products, and the use of common components and modules can decrease lead-time and risk in the development stage since the technology has already been proven in other products.[7,8] Inventory and handling costs are also reduced due to the presence of fewer components in inventory. The reduction of product line complexity,

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the reduction of set-up and retooling time, and the increase of standardization and repeatability improve processing time and productivity, and hence also reduce costs.[7,9] Fewer components also need to be tested and qualified, which reduces cost as well as time-to-market.[10,11]

Successful development of a platform and deployment of a product family requires input from multiple disciplines (e.g., marketing, engineering, manufacturing),[12] and a variety of tools and methods exist to support different aspects of product family design as discussed in the next section. Unfortunately, many of these tools and methods have been developed – and consequently exist – in isolation from one other. Consequently, in this paper we introduce a new approach for effectively integrating several of these disparate tools to translate user requirements into commonality specifications during product family design. Section III introduces our approach for integrating these tools and methods into a coherent framework to translate user requirements into commonality specifications for a product family. Section IV demonstrates the proposed approach using an example based on a family of unmanned ground vehicles. The benefits and limitations of the proposed approach along with future work are discussed in Section V.

II. Related Work: Methods and Tools to Support Product Family Design

Product family design involves all of the complexities of product design compounded by the difficulties of coordinating the simultaneous design of multiple products. A variety of tools and methods have been developed over the past two decades to support product family design and platform-based product development.[12,13] For instance, the market segmentation grid maps market segments and price/performance tiers to help marketing and engineering identify potential platform leveraging strategies for the product family as it is being developed.[1] As shown in Figure 1, market segments (e.g., user groups) are listed on the horizontal axis while the price/performance tiers (i.e., range of uses) are plotted on the vertical axis. Within this grid, four platform leveraging strategies can be identified: (1) no leveraging; (2) horizontal leveraging, which shares common technology across several market segments within a given price/performance tier; (3) vertical leveraging, which scales technology up/down within market segment to address different price/performance tiers; and (4) beachhead approach, which combines vertical and horizontal leveraging to attack all of the market segments within a single platform. Market segmentation grids are useful in a wide range of applications,[1,14] including platform-based development at start-up firms.[15,16] They have also been used to identify potential platform leveraging strategies during product family redesign.[17]

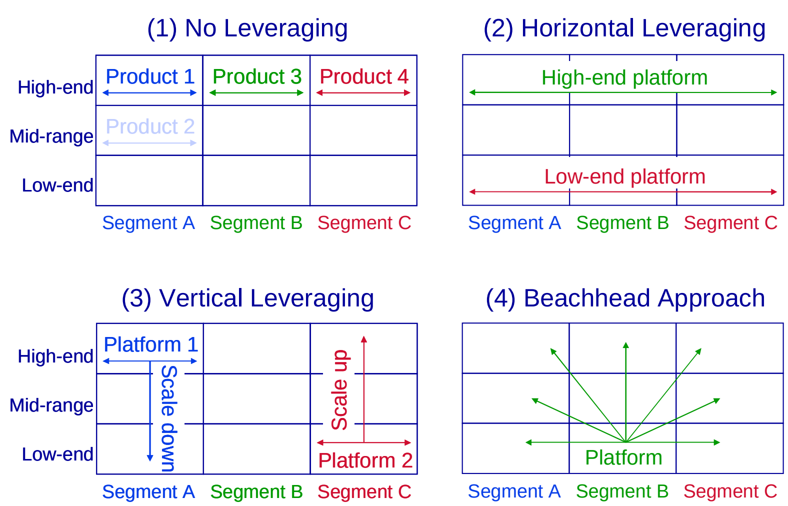


Figure 1. Market Segmentation Grid and Platform Leveraging Strategies

Identifying ways to leverage a platform and reuse common "elements" within a product family is not trivial. Martin and Ishii[18] modified Quality Function Deployment (QFD) and the House of Quality – a good tool for integrating marketing and engineering[19] – to compute a Generational Variety Index (GVI) that can be used to help identify subsystems/components that will need to be redesigned over the lifetime of the product line; those that are not subject to a lot of redesign are potential platformable "elements" within the family. Figure 2 illustrates part of the seven-step process that Martin and Ishii use to compute GVI. After determining the market and desired life for the platform (Step 1), a QFD matrix is used to map customer requirements to engineering requirements (Step 2); the example in Figure 2 is for a water cooler that has four planned variants over its lifetime – the requirements for each variant are not shown. The expected changes in customer requirements (Step 3) and engineering metric target values (Step 4) are identified, and a normalized target value matrix is calculated (Step 5) based on the mapping of engineering requirements to subsystems/components (see QFD Matrix II in Figure 2). Using the GVI rating scale shown in the lower right of the figure, the GVI matrix is created by replacing each x in the second QFD matrix with a 1, 3, 6, or 9 (Step 6). Finally, the ratings in each column are tallied (Step 7) to compute the GVI value for each subsystem/component. As noted in the figure, subsystems and components with low GVI values will not require a lot of redesign over the life of the product; therefore, they can be integrated into the platform. Meanwhile, the "elements" with high GVI values will require a lot of redesign to accommodate the anticipated variation in the customer requirements; therefore, these subsystems/components should not be part of the platform.

QFD Matrix I

Engineering Requirements

Customer Requirements	Cool down time (min)	Water Temperature (C)	Cold water volume (gal)	Power consumption (W)	Width (in)	Height (in)	Depth (in)	Volume flow rate (gal/min)	MTBF (hrs)	Cost ($)
Fast cool down	x									
Cold water		x								
High capacity			x							
Low energy usage				x						
Compact					x	x	x			
Fill cup quickly								x		
Reliable									x	
Low cost										x

QFD Matrix II

Components

Engineering Requirements	Fan	Heat Sink	Thermo-Elec Cooler	Power Supply	Chassis	Plumbing	Reservoir	Insulation	Fascia
Cool down time (min)	x	x	x	x			x	x	x
Water Temperature (C)									
Cold water volume (gal)							x		
Power consumption (W)	x		x	x					
Width (in)					x				x
Height (in)									
Depth (in)					x				x
Volume flow rate (gal/min)						x	x		
MTBF (hrs)									
Cost ($)		x		x	x		x		x

GVI Ratings

Rating	Description
9	Requires major redesign of the component (>50% of initial redesign costs)
6	Requires partial redesign of component (<50%)
3	Requires numerous simple changes (<30%)
1	Requires few minor changes (<15%)
0	No changes required

GVI Matrix

	Fan	Heat Sink	Thermo-Elec Cooler	Power Supply	Chassis	Plumbing	Reservoir	Insulation	Fascia
Cool down time (min)	3	6	3	1			6	1	6
Water Temperature (C)									
Cold water volume (gal)							9		
Power consumption (W)	1		3	3					
Width (in)					6				6
Height (in)									
Depth (in)					6				6
Volume flow rate (gal/min)						9	1		
MTBF (hrs)									
Cost ($)		1		1	3		3		6
GVI:	4	7	6	5	15	9	19	1	24

Elements with higher GVI values will require most redesign for future markets; platform low GVI elements and embed flexibility into/for high GVI elements

Figure 2. Example of Computing the Generational Variety Index (GVI) for a Water Cooler

To complement the GVI analysis, Martin and Ishii[18] introduce a Coupling Index derived from the product's Design Structure Matrix (DSM)[20] to identify ways to modularize the product and standardize interfaces between high GVI "elements", thereby minimizing the impact of their redesign on the system. DSMs have actually been used extensively for identifying modules within a product architecture,[21,22] which influences not only how the product family will be designed[23,24] but also how teams should be staffed, structured, and organized for effective product development.[25] DSM-based methods are also being developed to identify platforms within a family[26,27] as well as strategies for embedding flexibility into subsystems/components that may vary over the product lifecycle.[28] These methods draw heavily on the findings from recent research into change propagation in complex systems.[29,30]

Concurrently, metrics for product family design have focused primarily on assessing (1) modularity and (2) commonality.[31] Metrics for modularity abound in the literature and are reviewed elsewhere;[32,33] instead, we focus on commonality indices for product family design and their use as surrogates for estimating the manufacturing and production cost savings of platform-based product development.[2] Numerous commonality indices have been developed to assess the "goodness" of a product family,[34] and multiple perspectives (e.g., design, fabrication, assembly) can be used when performing this assessment on a product family.[35] While most of these indices rely on discrete component and part counts (e.g., count the number of component instances that have the same size/shape, material/manufacturing, and assembly/fastening scheme within a family[36]), a few indices have been developed to assess parametric variety, i.e., variations in the settings of design parameters across products in a family.[37,38] One such index is the Product Family Penalty Function (PFPF) introduced by Messac, et al.,[39] which can be used during product family optimization. As defined in Eq. (1), PFPF is used to measure the dissimilarity among the different parameter settings for each design variable used to define the product family.

$$\text{PFPF} = \sum_{j=1}^{n} \frac{deviation_j}{\bar{x}_j} \qquad \text{where: } \bar{x}_j = \sum_{i=1}^{p} \frac{x_{ij}}{p} \qquad deviation_j = \sqrt{\sum_{i=1}^{p} \frac{(x_{ij} - \bar{x}_j)^2}{(p-1)}} \tag{1}$$

In Eq. (1), x_{ij} is the individual value of the i^{th} design variable for the j^{th} product, n is the number of design variables being considered, and p is the number of products in the family. The deviation is expressed as a percentage of the mean for each design variable so that while the parameter values change during optimization, the percent deviation is normalized against mean value of each variable. Minimizing PFPF during product family optimization reduces the parametric variation in the family, which is equivalent to maximizing commonality in the family. PFPF has been applied to electric motor family design[39,40] as well as the design of a family of General Aviation Aicraft.[41]

Finally, to support product family optimization, more than 40 different optimization-based methods have been developed,[42] ranging from those that are engineering-centric[43] to those that include manufacturing considerations[44] and market analysis.[45] A wide range of algorithms have been used to support product family optimization, including linear and non-linear programming (e.g., sequential linear/quadratic programming, generalized reduced gradient) as well as derivative-free methods such as pattern search, simulated annealing, and genetic algorithms.[42] Newer optimization algorithms such as ant colony optimization are also finding use in product family design;[46] however, genetic algorithms (GAs) are becoming the predominant approach for product family optimization given the flexibility in their problem formulation, capability to handle multiple objectives, and ability to be run in parallel computing environments.[47,48] Multi-objective optimization approaches for product family design are also being used to combine other methods and tools, such as the market segmentation grid to identify effective platform leveraging strategies,[49] and integrate engineering design, customer value, and production cost models to identify profitable portfolios of products and platforms.[50] Given the potential synergies among these methods and tools, an integrated approach to product family design would provide an effective means to translate user requirements into commonality specifications. Our proposed approach is introduced next.

III. Proposed Approach: An Integrated Framework for Product Family Design

The starting point for our integrated approach is the product platform planning framework introduced by Robertson and Ulrich.[6] Their framework consists of three steps as shown in Figure 3: (1) product plan, (2) differentiation plan, and (3) commonality plan. In the product plan, the goal is to identify which products to offer when. Identifying how products will be positioned within the each market segment is part of the differentiation plan. Finally, the commonality plan outlines which "chunks" (i.e., subsystems/components) will be shared between each of these products. Taken together, the three steps define the product platform plan for a product family.

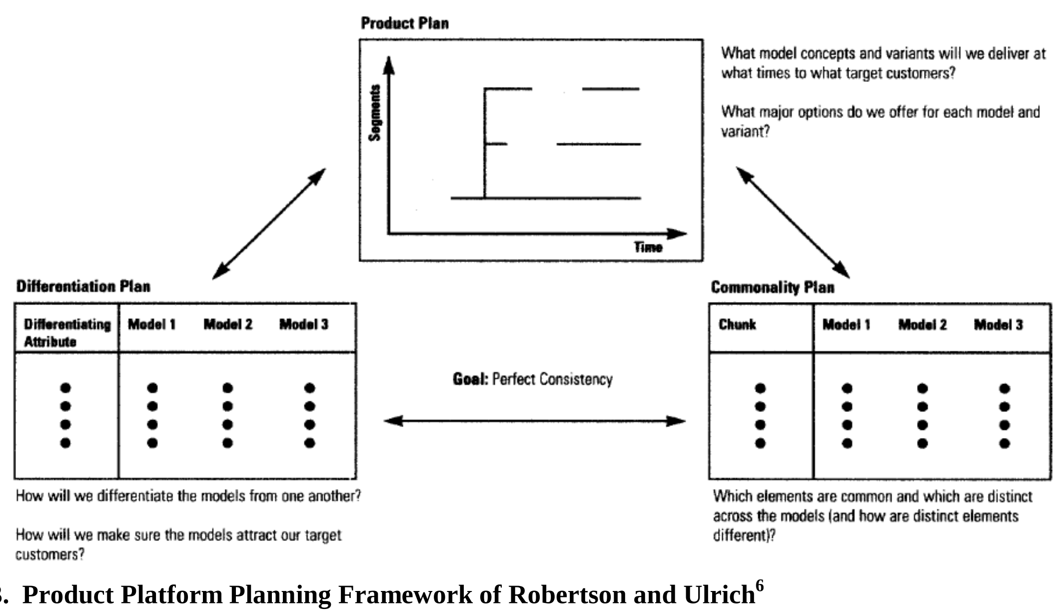


Figure 3. Product Platform Planning Framework of Robertson and Ulrich[6]

While these three steps are a useful guide to structure product platform planning, the framework itself can be difficult to implement as it has not been linked to specific methods and tools to support each step. Therefore, we propose the integrated approach in Figure 4 to link the methods and tools discussed in the previous section into the product family planning framework advocated by Robertson and Ulrich. In particular, we integrate the market segmentation grid, DSMs, GVI, commonality indices, and optimization to translate user requirements (i.e., customer needs) into commonality specifications for a product family (i.e., what to make common, what to make unique, and the best parameter settings for each component and/or subsystem[41]). As shown in Figure 4, the market segmentation grid (along with reverse engineering and benchmarking of existing systems) is used to identify a promising product plan, and GVI and DSMs are used to initiate the differentiation plan. GVI is also used to define a potential commonality plan, which is verified using commonality indices and multi-objective optimization for detailed trade studies. Multi-dimensional data visualization tools[51] are used to display results, allowing designers to change and modify their preferences, targets, etc. "on the fly" to bring the commonality and differentiation plans into alignment. In essence, our integrated approach enables a "Design by Shopping" paradigm[52] for product family design.

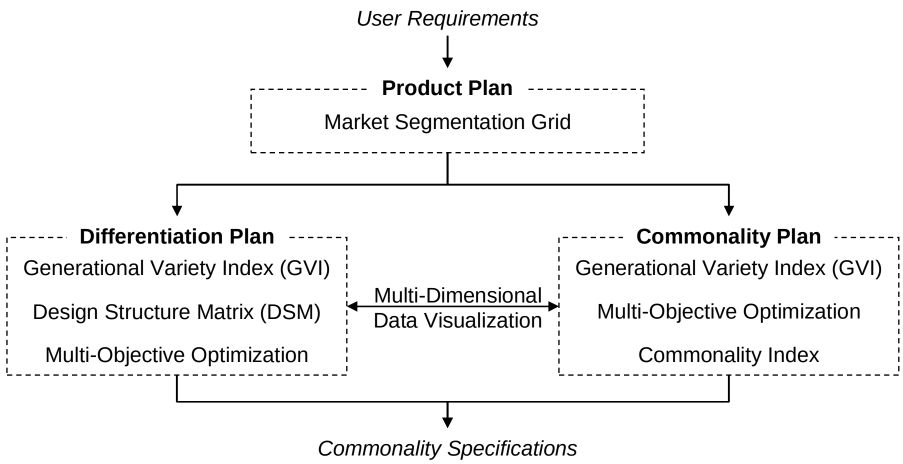


Figure 4. Integrated Approach to Product Family Design

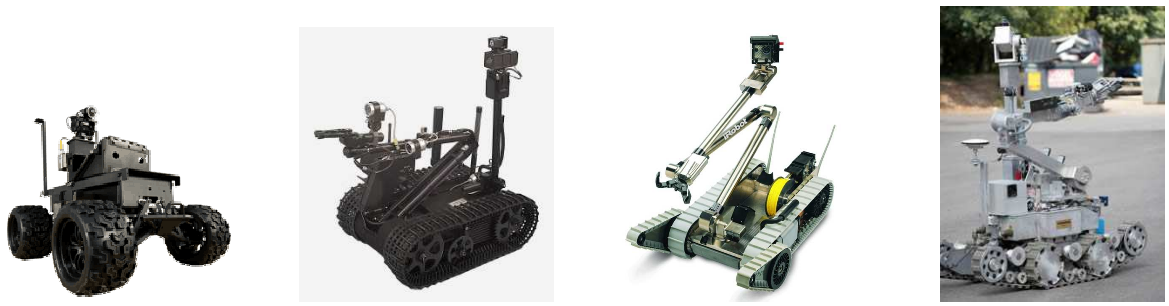
IV. Example: Design of a Family of Unmanned Ground Vehicles

To demonstrate the proposed approach, consider the design of a family of unmanned ground vehicles (UGVs). While the existing systems offered by companies like Foster-Miller (e.g., the Talon) and iRobot (e.g., the Packbot) are effective, there is no sharing or part commonality across existing systems as there is little to no incentive for manufacturers to collaborate with one another. As a result, users must maintain multiple sets of spare parts, manuals, and tools; keep multiple specialized technicians on staff for logistical support and maintenance; and conduct different sets of training and certification procedures for each robot since the operating systems and user controls are different for each robot. Furthermore, there is no plug-and-play capability across systems from different manufacturers, e.g., a manipulator arm from one manufacturer will not work on the other manufacturer's UGV and vice versa. By applying our approach to this problem, we hope to identify promising opportunities for commonality within future UGV systems.

A. Market Segmentation and Product Plan for UGV Family

To develop the product plan for the UGV family, we gathered a set of requirements for the UGV capabilities (e.g., weight, speed, range, lift capacity) for different missions, and threshold and objective values were identified for each capability for each mission. Threshold values represent the minimum values that must be met in order to complete a mission while the objective values provide targets that users would like to achieve. Over 50 different missions were identified based on type of ordnance, UGV functionality (e.g., dig, detonate, diffuse), location of operation, etc. Initially, formal clustering techniques (e.g., fuzzy clustering[53,54]) were used to group similar missions into representative "market segments", but it made better sense to group the UGVs into three classes consistent with current systems. In the end, three "performance tiers" were identified corresponding to small, medium, and large UGVs based on weight, and threshold and objective values are then defined for each of these three weight classes.

In parallel to this effort, we also dissected and analyzed several existing systems, including the Talon, Packbot, Bombot, and RONS (see Figure 5). The capabilities of each UGV were measured (e.g., weight, speed, battery life, lift capacity) to establish a baseline for comparison as well as provide data for validating the mathematical models developed for optimization and product family trade studies. These systems were also used to construct a "generic" UGV architecture, which is shown in the DSM in Figure 6. This DSM shows not only the connections between subsystems and components but also the extent to which a change in one component is will likely impact another component (L = low, M = medium, H = high) by taking into consideration the potential for change propagation within the system.[29] This information is particularly useful when conducting GVI analysis to identify how the commonality and differentiation plans.



(a) Bombot http://www.defensetech.org | (b) Talon http://www.foster-miller.com | (c) Packbot http://www.irobot.com | (d) RONS http://www.globalsecurity.org

Figure 5. Existing UGVs Dissected and Analyzed

	Chassis	Battery	Battery Bays	Flipper	Main Track	Com Box	Elect Box	Arm	Mast	Head	Gripper/ Wrist	3 Cameras	Payload Bay	Aiming laser	Antenna	OCU
Chassis		M	M	M	M			M	L			L	H		L	
Battery	M						M									
Battery Bays	M															
Flipper	M				M											
Main Track	M			M												
Com Box							M					L			M	
Elect Box		M				M		L			L			L		
Arm	M						L		L	M	H	L				
Mast	L							L				L				
Head								M				L		L		
Gripper/Wrist							L	H								
3 Cameras	L					L		L	L	L				L		
Payload Bay	H															
Aiming Laser							L			L		L				
Antenna	L					M										M
OCU															M	

Figure 6. DSM of "Generic" UGV Architecture[55]

B. Commonality and Differentiation Plan

With this as our "generic" reference architecture for the UGV family, we proceeded to compute GVI for each subsystem based on the requirements for the different "performance tiers", i.e., small, medium, and large UGVs. The GVI results are summarized in Figure 7. Subsystems with low GVI values will not vary much across the family, while subsystems with high GVI values will vary considerably in order to achieve the performance requirements for the different sized UGVs. For instance, the arm and gripper had high GVI values based on the different capabilities and desired functionality; therefore, the recommendation is to modularize these subsystems and standardize their interfaces in order to allow different manipulators and grippers to be easily swapped out (and upgraded) for different missions. Batteries, on the other hand, have a low GVI value, and it appears that common batteries may be used across different UGVs; however, the number of batteries needs to be scalable given the power requirements for larger UGVs. Meanwhile, the chassis falls in the middle – many requirements drive chassis sizing (e.g., long vs. short and wide vs. narrow for maneuverability as well as reach capability). Note that while GVI helps identify which subsystems/components can be common between products in the family, it does not indicate what the best parameters settings are for those shared "elements" – that is the role that optimization plays in our approach.

	Range (feet)	Slope Climb (deg)	Maneuver width (in)	On board vol (in^3)	On board wt (lb)	Drag/Roll/ Push (lb)	Horiz reach (in)	Vert high reach (in)	Sensing type	Video vert high reach (in)	Large Obj Pickup (length)	Large Obj Pickup (width)	Large Obj Pickup (height)	Lift capac (lb)	Tool precision	Tool size (in^3)	Tool wt (lb)	Comm range (ft)	GVI
chassis		3	3	6	6	6	6	1		1				6					38
battery					3	3													6
tracks		3	3			6													12
communication box	6														1			6	13
electronics box																			0
arm		1				6	9	9		9	3	3	3	9	3	3	3		61
gripper						6	1	1		1	6	6	6	3	6	6	6		48
cameras															1				1
payload bay				6	6				3										15
antennae	6																	6	12
OCU															1			3	4

Figure 7. GVI Analysis for "Generic" UGV Architecture[55]

A subsequent analysis of each pair of UGVs (e.g., small and medium, medium and large, small and large) was used to translate these GVI recommendations to the parameter level.[55] For instance, even though the chassis will vary across each weight class, we sought to identify potential opportunities for scaling the chassis in one or more dimensions based on the threshold and objective values for each UGV pair. Alternatively, one could use Martin and Ishii's Coupling Index to facilitate this analysis;[18] however, it was in our best interest to understand each subsystem at the parameter level before creating mathematical models to estimate the performance of new UGV designs. The final GVI recommendations are listed in **Error! Not a valid bookmark self-reference.** where an "x" indicates common settings across two or more UGVs, e.g., chassis height can be common to all three UGVS, but only the small and medium have common chassis length and width based on the threshold and objective requirements. Based on these GVI recommendations, we develop a mathematical model and use multi-optimization, commonality indices, and multi-dimensional data visualization to perform trade studies and determine the best parameter settings for the subsystems/components in the UGV family.

Table 1. GVI Recommendations for Commonality in Key Subsystems of UGV Family

Subsystem	Design Parameters	Small	Medium	Large
Chassis	Length	x	x	
	Width	x	x	
	Height	x	x	x
Mobility	Wheels/Tracks	x	x	x
	Wheel Diameter			
	Track Width			
	Wheelbase			
Batteries	Length	x	x	x
	Width	x	x	x
	Mass	x	x	x
Manipulators	Outer Arm Radius	x	x	
	Arm Segment Length	x	x	
	Number of Links	x	x	

C. Mathematical Modeling and Multi-Objective Optimization

In order to finalize our commonality specifications for the UGV family, we developed a mathematical model to simulate system performance. The model was developed to estimate UGV capabilities for the specific threshold and objective requirements that defined each "market segment", e.g., the analysis for the chassis needed to compute its weight as well as estimate its stair climbing capability and ground clearance for obstacle avoidance. The DSM was also used to help identify subsystem interactions of interest to include the model, e.g., the interactions between the chassis and manipulator that dictate lift capacity and center of gravity, which impacts tipping, self-righting, etc.

The model was developed in Simulink® and employed a combination of physics-based models, allometric design principles, curve fits, and look up tables to estimate the capabilities of the different subsystems in a new UGV design alternative. The overall structure of the model is shown in Figure 8, which is divided into 14 analysis blocks. The first 11 blocks size the specified subsystem while the last 3 blocks compare the predicted performance against the capabilities defined for each weight class to compute an effectiveness measure for each UGV based on how well the threshold and objective values are met. The blocks are sequenced to minimize feedback loops in the model as each block relies on a combination of user-specified inputs (e.g., battery type) and inputs from other subsystems (e.g., chassis mass) in order to perform its analysis. Key parameters that serve as both inputs and outputs for analysis (e.g., chassis mass, vehicle mass, vehicle velocity) require iteration in the model as indicated by the feedback loops in Figure 8. Even with these iterations, the model executes a complete analysis in 4 seconds on a moderately equipped desktop PC.

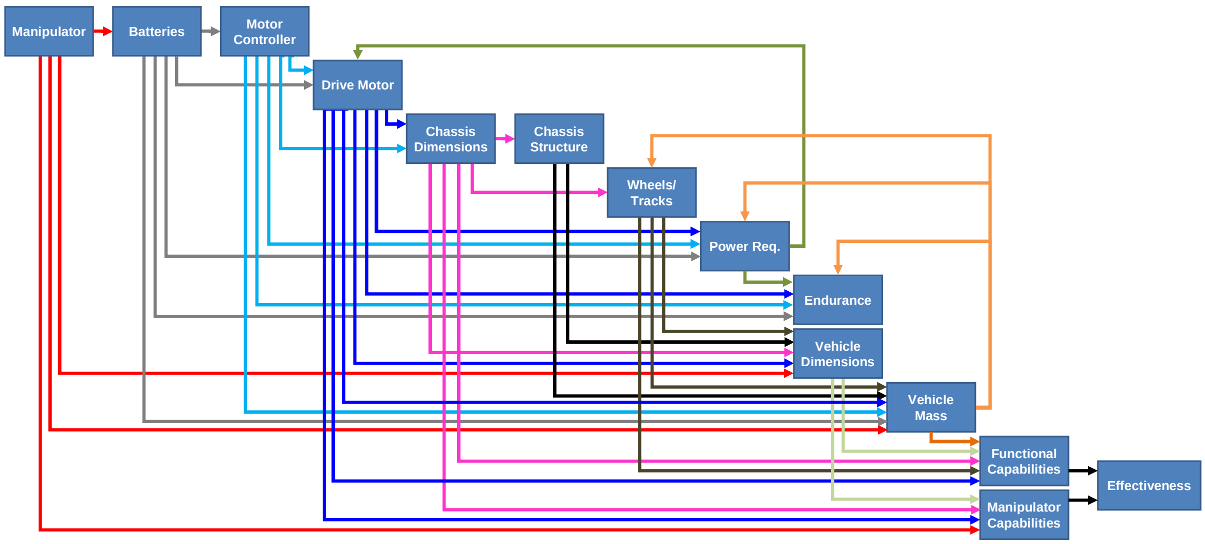


Figure 8. System Decomposition for UGV Mathematical Model

After model convergence was verified, we confirmed trends in the model, e.g., as battery size increased, vehicle range increased for a given vehicle mass and velocity. We validated the individual subsystems and overall model using data from the four existing UGVs that we dissected and analyzed (see Figure 5). The model is linked directly to our trade space visualization software (ATSV),[51,56] which is used to generate new design alternatives to study the tradeoff between commonality and effectiveness in the UGV family. Details on model convergence, validation, and linking to ATSV can be found elsewhere.[57,58]

Once the model is linked to ATSV, random sampling and visual steering are used to generate about 15,000 design alternatives that span the small, medium, and large weight classes. Figure 9 plots the predicted effectiveness of each UGV versus its size; the best 90 UGV designs in each weight class are color-coded while the remaining designs are shown in gray. While the majority of the designs fall into the medium weight class, there are many small and large alternatives; unfortunately, while the small and medium designs appear to be relatively effective, many of the large designs in this study are not. Regardless, these alternatives provide a basis for a product family trade study, which considers families composed of different combinations of these small, medium, and large UGVs.

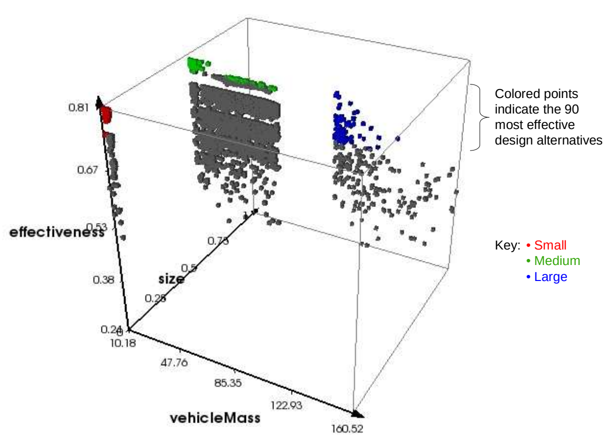


Figure 9. Effectiveness vs. Vehicle Size (0/red = Small, 0.5/green = Medium, 1/blue = Large) and Mass

D. Product Family Trade Study and Commonality Specifications

For this product family trade study, we consider the best 90 designs from each weight class (see colored designs in Figure 9) to create families based on the GVI recommendations, e.g., select a set of small, medium, and large UGVs that have common batteries, scaled chassis, and different manipulators as recommended by GVI. For each family, we compute the effectiveness of the family by averaging the individual effectiveness of each UGV as well as the dissimilarity in the family using PFPF from Eq. 1. Figure 10 shows the results of this analysis with red points being an exact match with the GVI recommendations; green points match the GVI recommendations within one parameter, i.e., all but one subsystem parameter are shared as recommended by GVI. Based on this analysis, we identify five families that are an exact match and about 250 families that are within a few parameters of the GVI recommendations. Table 2 lists some of the key subsystem parameters for the five families that match the GVI recommendations. Additional parameters that are common within these families are also highlighted, indicating that we may have been too conservative and missed opportunities for commonality given the level of analysis we used.

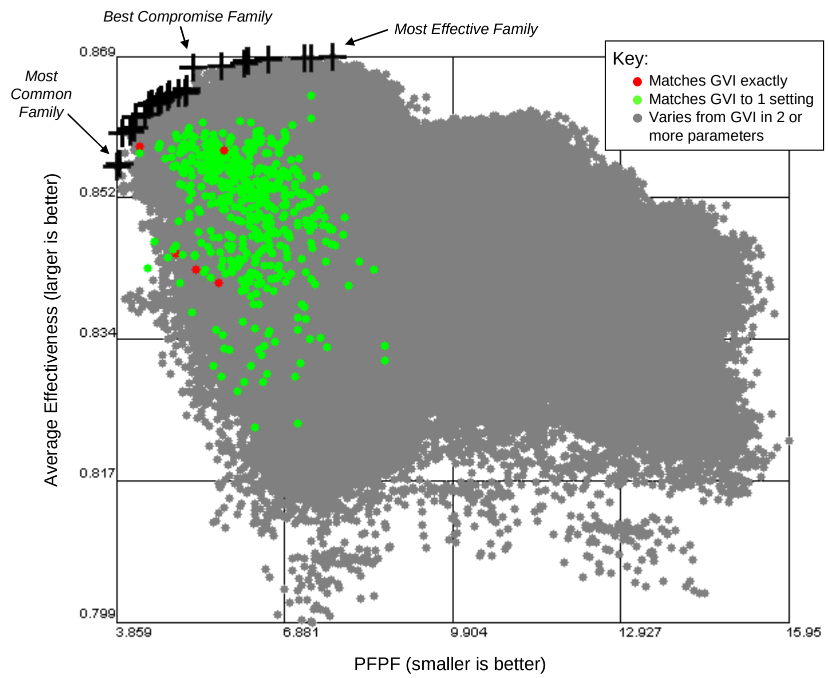


Figure 10. UGV Families based on GVI Recommendations (red/green) and Enumerated Options (gray)

In parallel to identifying the GVI-based families, we enumerate all 729,000 possible UGV families (= 90 small designs x 90 medium designs x 90 large designs) and computed the average effectiveness and PFPF for each family. These UGV families are shown in gray in Figure 10. Unfortunately, when compared to all of these possible options, none of the GVI-based families fall on the Pareto frontier – the families indicated by +'s in the figure that offer the best combination of commonality (i.e., minimum PFPF) and effectiveness. Of these families, three are of particular interest as highlighted in the figure: (1) the Most Effective Family, (2) the Most Common Family, and (3) the Best Compromise Family. The Most Effective Family does the best job in satisfying the effectiveness requirements for the small, medium and large UGVs (Average Effectiveness = 86.8%), but it has less commonality than the other designs, although by no means the worst. The Most Common Family provides the opposite – it offers the most commonality among the three UGVs in the family, but this comes at a small sacrifice in performance (Average Effectiveness = 86.0%). Finally, the Best Compromise Family falls between the two – it has more commonality than the Most Effective Family but with less sacrifice in performance compared to the Most Common Family. In fact, the Average Effectiveness is 86.7%, indicating a remarkably good compromise in this family.

The corresponding parameter settings for these three UGV families are listed in Table 3. Here, color is used to highlight parameter values that are common (in orange) and similar (in yellow), i.e., within 5% across two or more UGVs within a given family. Note that even though some of the parameter values are the same across families (i.e., they all use tracks, and nearly all of them have the same battery specifications), the color coding for common and similar parameter values are within a single family, not across the three families.

Table 2. UGV Families that Most Closely Resemble GVI Recommendations

		Chassis			Mobility			Batteries			Manipulator		
	Robot	Vehicle Length [m]	Chassis Width [m]	Chassis Height [m]	Wheels(=1)/ Tracks(=2)	Wheel Diameter [m]	Wheel or Track Width [m]	Battery Length [m]	Battery Width [m]	Battery Mass [kg]	Outer Arm Radius [m]	Arm Segment Length [m]	Number of Arm Links
Family 1	Small	0.557	0.227	0.318	2	0.261	0.028	0.112	0.062	1.4	0.021	0.565	3
	Medium	0.592	0.221	0.334	2	0.291	0.032	0.112	0.062	1.4	0.021	0.524	3
	Large	0.665	0.301	0.344	2	0.181	0.13	0.112	0.062	1.4	0.021	0.306	3
Family 2	Small	0.544	0.203	0.079	2	0.269	0.034	0.112	0.062	1.4	0.021	0.134	3
	Medium	0.575	0.191	0.086	2	0.279	0.043	0.112	0.062	1.4	0.021	0.133	3
	Large	0.911	0.5	0.079	2	0.121	0.061	0.112	0.062	1.4	0.021	0.112	3
Family 3	Small	0.578	0.208	0.08	2	0.277	0.03	0.112	0.062	1.4	0.021	0.569	3
	Medium	0.603	0.205	0.08	2	0.297	0.035	0.112	0.062	1.4	0.021	0.568	3
	Large	0.911	0.5	0.079	2	0.121	0.061	0.112	0.062	1.4	0.021	0.112	3
Family 4	Small	0.646	0.223	0.35	2	0.307	0.025	0.112	0.062	1.4	0.021	0.104	3
	Medium	0.608	0.224	0.32	2	0.301	0.035	0.112	0.062	1.4	0.021	0.11	3
	Large	0.665	0.301	0.344	2	0.181	0.13	0.112	0.062	1.4	0.021	0.306	3
Family 5	Small	0.643	0.234	0.349	2	0.307	0.021	0.112	0.062	1.4	0.021	0.104	3
	Medium	0.608	0.224	0.32	2	0.301	0.035	0.112	0.062	1.4	0.021	0.11	3
	Large	0.665	0.301	0.344	2	0.181	0.13	0.112	0.062	1.4	0.021	0.306	3

\# = GVI & PFPF Suggest Commonality

\# = PFPF Suggests Additional Commonality

\# = Neither GVI or PFPF Suggest Commonality

Table 3. Common, Similar, and Unique Parameter Settings in the UGV Families on the Pareto Frontier

		Chassis			Mobility			Batteries			Manipulator		
	Robot	Vehicle Length [m]	Chassis Width [m]	Chassis Height [m]	Wheels(=1)/ Tracks(=2)	Wheel Diameter [m]	Wheel or Track Width [m]	Battery Length [m]	Battery Width [m]	Battery Mass [kg]	Outer Arm Radius [m]	Arm Segment Length [m]	Number of Arm Links
Best Compromise Family	Small	0.542	0.206	0.198	2	0.264	0.033	0.112	0.062	1.4	0.021	0.418	3
	Medium	0.788	0.416	0.249	2	0.078	0.039	0.112	0.062	2.8	0.021	0.243	3
	Large	1.007	0.498	0.257	2	0.175	0.058	0.112	0.062	2.8	0.021	0.229	3
Most Common Family	Small	0.543	0.224	0.135	2	0.251	0.025	0.112	0.062	1.4	0.021	0.105	3
	Medium	0.732	0.409	0.163	2	0.051	0.047	0.112	0.062	1.4	0.021	0.283	3
	Large	1.007	0.475	0.170	2	0.178	0.049	0.112	0.062	1.4	0.021	0.218	3
Most Effective Family	Small	0.543	0.224	0.135	2	0.251	0.025	0.112	0.062	1.4	0.021	0.105	3
	Medium	0.792	0.418	0.236	2	0.057	0.033	0.112	0.062	1.4	0.021	0.292	3
	Large	0.763	0.371	0.117	2	0.115	0.108	0.112	0.062	2.8	0.022	0.408	3

\#   \# = Similar (< 5%) Values

Comparing Table 2 and Table 3, we see that UGV families that lie on the Pareto frontier have less commonality than the GVI-based families as one might expect. While key battery and manipulator parameters are made common across both sets of families along with the use of tracked designs, the families on the Pareto frontier have very few chassis parameters in common. At best, the chassis height or length is shared between the medium and large UGVs, and the small UGV has a completely different chassis in all cases. It is interesting that the results differ so much and yet the average effectiveness of the family is within 1-2% of each other.

Finally, to gain more insight into the differences between the UGV families based on the GVI recommendations and the enumerated families, we color code all of the families in Figure 10 based on how closely they "match" the GVI recommendations and plot the results in Figure 11. The scale in Figure 11 shows that the families range from a complete or very close match (red) to little to no match (blue). As expected, the closer the match to GVI, the lower the PFPF values (i.e., the more commonality), and the tradeoff is remarkably favorable in the family in that families with high PFPF values (i.e., less commonality) actually do not perform well either. Based on the results in Figure 9, we conclude that this drop-off in effectiveness is driven largely by the poorly performing large UGVs in this study. Apparently, these poorly performing designs are also very dissimilar to the small and medium designs while the most effective large designs also have a lot in common with the small and medium designs. In many situations, this may not be the case; however, this is a promising and useful finding from this product family trade study.

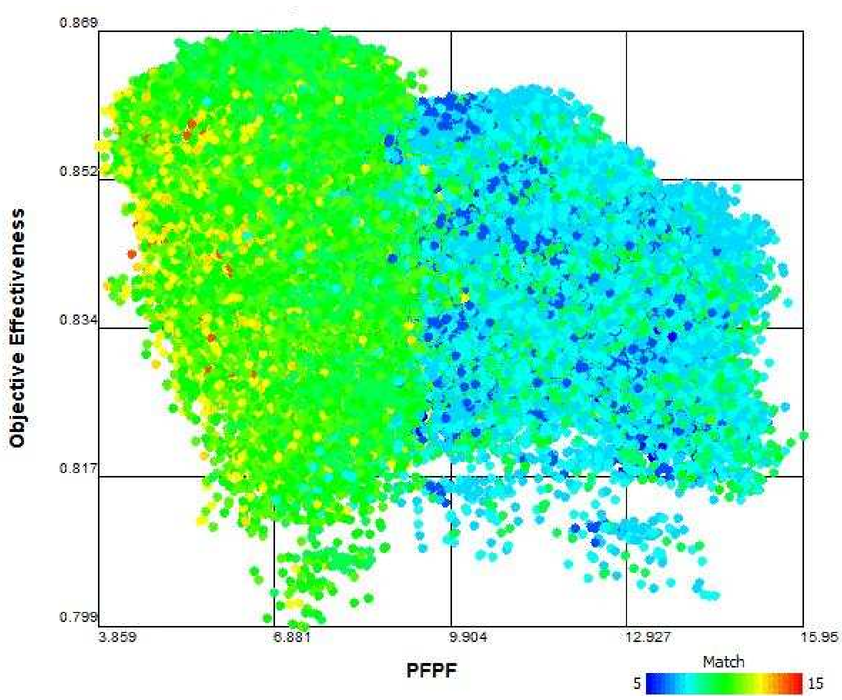


Figure 11. Comparison of GVI-based Families with Enumerated Families

An important take-away from this analysis is that GVI may suggest too much commonality because its analysis is done at the subsystem/component level (e.g., make the chassis common) and not at the parametric level (e.g., the chassis should have common height and width but the length should be scaled). Furthermore, GVI analysis is done for the entire family and may miss opportunities for commonality between subsets of products within the family (e.g., the small and medium chassis can be common but the large chassis should be unique). In both cases, using GVI in concert with quantitative analysis – a mathematical model of the system and optimization – will provide additional insight into the commonality-performance tradeoffs within the family. In this UGV product family trade study, we are fortunate that the effective small, medium, and large designs tended to have a lot of commonality; however, that may not happen in practice. This is why multi-dimensional data visualization is important to product family trade studies: the ability to "see" trends in the data is critical to making effective design decisions particularly when identifying the platform elements within a family.

V. Closing Remarks and Future Work

This paper introduces an integrated approach to product family design that links several existing methods and tools within a three-step framework to help translate user requirements into commonality specifications for the family, i.e., what to make common, what to make unique, and the best parameter settings for each component and/or subsystem. The integrated approach includes both qualitative (e.g., market segmentation grid, GVI) and quantitative (e.g., multi-objective optimization, commonality indices) with multi-dimensional data visualization to realize an effective approach for product family design. The proposed approach is applied to the design of a family of unmanned ground vehicles (UGVs) to demonstrate its effectiveness and shed light on its shortcomings. Families of UGVs are successfully created based on the recommendations from GVI as well through enumeration of all possible combinations of small, medium, and large designs. While the GVI-based families do not fall directly on the Pareto frontier, they provide reasonably good solutions that are very close to the best families that can be obtained. As such, using GVI to guide product family formation from sets of existing designs provides a basis for future work in product family commonality selection.[59]

The impetus for this work was integrating several methods and tools that existed in the literature into a coherent framework that can help translate user requirements into commonality specifications. In many cases, designers may not have the mathematical models that are necessary for multi-objective optimization and product family trade studies; in which case, using the market segmentation grid, GVI, and DSM can still assist designers in determining preliminary commonality specifications for the family. The next step is to integrate the tools into a single software package – the process would be expedited, and errors would be minimized, if the output from one tool fed directly into the input of another, which was not the case in this example. Finally, depending on the computational expense of the models involved, some multi-objective optimization approaches may become intractable and limit the ability to "steer and interact" with the data while it is being generated.

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[1]Meyer, M. H. and Lehnerd, A. P., *The Power of Product Platforms: Building Value and Cost Leadership*, New York, NY, Free Press, 1997.

[2]Simpson, T. W., "Product Platform Design and Customization: Status and Promise," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 18, No. 1, 2004, pp. 3-20.

[3]Aboulafia, R., "Airbus Pulls Closer to Boeing," *Aerospace America*, Vol. 38, No. 4, 2000, pp. 16-18.

[4]Sabbagh, K., *Twenty-First Century Jet: The Making and Marketing of the Boeing 777*, New York, NY, Scribner, 1996.

[5]Rothwell, R. and Gardiner, P., "Robustness and Product Design Families", *Design Management: A Handbook of Issues and Methods*, Oakley, M., Cambridge, MA, Basil Blackwell Inc., 1990, pp. 279-292.

[6]Robertson, D. and Ulrich, K., "Planning Product Platforms," *Sloan Management Review*, Vol. 39, No. 4, 1998, pp. 19-31.

[7]Collier, D. A., "The Measurement and Operating Benefits of Component Part Commonality," *Decision Sciences*, Vol. 12, No. 1, 1981, pp. 85-96.

[8]Collier, D. A., "Aggregate Safety Stock Levels and Component Part Commonality," *Management Science*, Vol. 28, No. 22, 1982, pp. 1296-1303.

[9]Kim, K. and Chhajed, D., "Commonality in Product Design: Cost Saving, Valuation Change and Cannibalization," *European Journal of Operational Research*, Vol. 125, No. 3, 2000, pp. 602-621.

[10]Fisher, M. L., Ramdas, K. and Ulrich, K. T., "Component Sharing in the Management of Product Variety: A Study of Automotive Braking Systems," *Management Science*, Vol. 45, No. 3, 1999, pp. 297-315.

[11]Caffrey, R. T., Simpson, T. W., Henderson, R. and Crawley, E., "The Technical Issues with Implementing Open Avionics Platforms for Spacecraft", *40th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, AIAA, 2002, AIAA-2002-0319.

[12]Jiao, J., Simpson, T. W. and Siddique, Z., "Product Family Design and Platform-Based Product Development: A State-of-the-Art Review," *Journal of Intelligent Manufacturing*, Vol. 18, No. 1, 2007, pp. 5-29.

[13]Simpson, T. W., Siddique, Z. and Jiao, J., Eds., *Product Platform and Product Family Design: Methods and Applications*, New York, Springer, 2005.

[14]Marion, T. J. and Simpson, T. W., "Platform Leveraging Strategies and Market Segmentation", *Product Platform and Product Family Design: Methods and Applications*, Simpson, T. W., Siddique, Z. and Jiao, J., New York, Springer, 2005, pp. 73-90.

[15]Shooter, S. B., Evans, C. M. and Simpson, T. W., "Building a Better Ice Scraper – A Case in Product Platforms for the Entrepreneur," *Journal of Intelligent Manufacturing*, Vol. 18, No. 1, 2007, pp. 159-170.

[16]Marion, T. J. and Simpson, T. W., "New Product Development Practice Application to an Early-Stage Firm: The Case of the PaperPro® Stackmaster™," *Design Studies*, Vol. 30, No. 5, 2009, pp. 561-587.

[17]Farrell, R. S. and Simpson, T. W., "A Method to Improve Platform Leveraging in a Market Segmentation Grid for an Existing Product Line," *ASME Journal of Mechanical Design*, Vol. 130, No. 3, 2008, pp. 031403 (11 pages).

[18]Martin, M. V. and Ishii, K., "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," *Research in Engineering Design*, Vol. 13, No. 4, 2002, pp. 213-235.

[19]Hauser, J. R. and Clausing, D., "The House of Quality," *Harvard Business Review*, Vol. 66, No. 3, 1988, pp. 63-73.

[20]Steward, A. D., "The Design Structure System: A Method for Managing the Design of Complex Systems," *IEEE Transaction on Software Engineering*, Vol. 28, No. 3, 1981, pp. 71-74.

[21]Browning, T. R., "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions," *IEEE Transactions on Engineering Management*, Vol. 48, No. 3, 2001, pp. 292-306.

[22]Kusiak, A. and Larson, N., "Decomposition and Representation Methods in Mechanical Design," *Journal of Mechanical Design (Special 50th Anniversary Design Issue)*, Vol. 117, No. 2, 1995, pp. 17-24.

[23]Sudjianto, A. and Otto, K. N., "Modularization to Support Multiple Brand Platforms", *ASME Design Engineering Technical Conferences - Design Theory and Methodology Conference*, Pittsburgh, PA, ASME, 2001, Paper No. DETC2001/DTM-21695.

[24]Dahmus, J. B., Gonzalez-Zugasti, J. P. and Otto, K. N., "Modular Product Architecture," *Design Studies*, Vol. 22, No. 5, 2001, pp. 409-424.

[25]Sosa, M. E., Eppinger, S. D. and Rowles, C. M., "Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions," *ASME Journal of Mechanical Design*, Vol. 125, No. 2, 2003, pp. 240-252.

[26]Kalligeros, K. C., de Weck, O., de Neufville, R. and Luckins, A., "Platform Identification using Design Structure Matrices", *Sixteenth Annual International Symposium of the International Council On Systems Engineering (INCOSE)*, Orlando, FL, 2006.

[27]Alizon, F., Moon, S. K., Shooter, S. B. and Simpson, T. W., "Three Dimensional Design Structure Matrix with Cross-Module and Cross-Interface Analysis", *ASME Design Engineering Technical Conferences - Design Automation Conference*, Las Vegas, NV, ASME, 2007, Paper No. DETC2007/DAC-34510.

[28]Suh, E. S., de Weck, O. L., Kim, I. Y. and Chang, D., "Flexible Platform Component Design under Uncertainty," *Journal of Intelligent Manufacturing*, Vol. 18, No. 1, 2007, pp. 115-126.

[29]Clarkson, P. J., Simons, C. and Eckert, C., "Predicting Change Propagation in Complex Design," *ASME Journal of Mechanical Design*, Vol. 126, No. 5, 2004, pp. 788-797.

[30]Eckert, C., Clarkson, P. J. and Zanker, W., "Change and Customisation in Complex Engineering Domains," *Research in Engineering Design*, Vol. 15, No. 1, 2004, pp. 1-21.

[31]Fixson, S. K., "Modularity and Commonality Research: Past Developments and Future Opportunities," *Concurrent Engineering: Research and Applications*, Vol. 15, No. 2, 2007, pp. 85-111.

[32]Gershenson, J. K., Prasad, G. J. and Zhang, Y., "Product Modularity: Measures and Design Methods," *Journal of Engineering Design*, Vol. 15, No. 1, 2003, pp. 33-51.

[33]Hölttä-Otto, K. and de Weck, O., "Metrics for Assessing Coupling Density and Modularity in Complex Products and Systems", *ASME Design Engineering Technical Conferences - Design Theory & Methodology Conference*, Las Vegas, NV, ASME, 2007, Paper No. DETC2007/DTM-34871.

[34]Thevenot, H. J. and Simpson, T. W., "Commonality Indices for Product Family Design: A Detailed Comparison," *Journal of Engineering Design*, Vol. 17, No. 2, 2006, pp. 99-119.

[35]Thevenot, H. J. and Simpson, T. W., "Commonality Indices for Assessing Product Families", *Product Platform and Product Family Design: Methods and Applications*, Simpson, T. W., Siddique, Z. and Jiao, J., New York, Springer, 2005, pp. 107-130.

[36]Kota, S., Sethuraman, K. and Miller, R., "A Metric for Evaluating Design Commonality in Product Families," *ASME Journal of Mechanical Design*, Vol. 122, No. 4, 2000, pp. 403-410.

[37]Nayak, R. U., Chen, W. and Simpson, T. W., "A Variation-Based Method for Product Family Design," *Engineering Optimization*, Vol. 34, No. 1, 2002, pp. 65-81.

[38]Khajavirad, A. and Michalek, J., "An Extension of the Commonality Index for Product Family Optimization", *ASME Design Engineering Technical Conferences - Design Automation Conference*, Las Vegas, NV, ASME, 2007, DETC2007/DAC-35605.

[39]Messac, A., Martinez, M. P. and Simpson, T. W., "A Penalty Function for Product Family Design Using Physical Programming," *ASME Journal of Mechanical Design*, Vol. 124, No. 2, 2002, pp. 164-172.

[40]Akundi, S., Simpson, T. W. and Reed, P. M., "Multi-objective Design Optimization for Product Platform and Product Family Design Using Genetic Algorithms", *ASME Design Engineering Technical Conferences - Design Automation Conference*, Long Beach, CA, ASME, 2005, Paper No. DETC2005/DAC-84905.

[41]Simpson, T. W. and D'Souza, B., "Assessing Variable Levels of Platform Commonality within a Product Family Using a Multiobjective Genetic Algorithm," *Concurrent Engineering: Research and Applications*, Vol. 12, No. 2, 2004, pp. 119-130.

[42]Simpson, T. W., "Methods for Optimizing Product Platforms and Product Families: Overview and Classification", *Product Platform and Product Family Design: Methods and Applications*, Simpson, T. W., Siddique, Z. and Jiao, J., New York, Springer, 2005, pp. 133-156.

[43]Dai, Z. and Scott, M. J., "Product Platform Design through Sensitivity Analysis and Cluster Analysis," *Journal of Intelligent Manufacturing*, Vol. 18, No. 1, 2007, pp. 97-113.

[44]Hernandez, G., Simpson, T. W., Allen, J. K., Bascaran, E., Avila, L. F. and Salinas, F., "Robust Design of Families of Products with Production Modeling and Evaluation," *ASME Journal of Mechanical Design*, Vol. 123, No. 2, 2001, pp. 183-190.

[45]Michalek, J. J., Ceryan, O., Papalambros, P. Y. and Koren, Y., "Balancing Marketing and Manufacturing Objectives in Product Line Design," *ASME Journal of Mechanical Design*, Vol. 128, No. 6, 2006, pp. 1196-1204.

[46]Kumar, R. and Allada, V., "Ant Colongy Optimization Methods for Product Platform Formation," *Journal of Intelligent Manufacturing*, Vol. 18, No. 1, 2007, pp. 127-142.

[47]Jiao, J., Zhang, Y. and Wang, Y., "A Generic Genetic Algorithm for Product Family Design," *Journal of Intelligent Manufacturing*, Vol. 18, No. 2, 2007, pp. 233-247.

[48]Khajavirad, A., Michalak, J. J. and Simpson, T. W., "An Efficient Decomposed Multiobjective Genetic Algorithm for Solving the Joint Product Platform Selection and Product Family Design Problem with Generalized Commonality," *Structural and Multidiscipilnary Optimization*, Vol. 39, No. 2, 2009, pp. 187-201.

[49]Kumar, D., Chen, W. and Simpson, T. W., "A Market-Driven Approach to Product Family Design," *International Journal of Production Research*, Vol. 47, No. 1, 2009, pp. 71-104.

[50]de Weck, O., "Determining Product Platform Extent", *Product Platform and Product Family Design: Methods and Applications*, Simpson, T. W., Siddique, Z. and Jiao, J., New York, Springer, 2005, pp. 241-301.

[51]Stump, G., Lego, S., Yukish, M., Simpson, T. W. and Donndelinger, J. A., "Visual Steering Commands for Trade Space Exploration: User-Guided Sampling with Example," *ASME Journal of Computing and Information Science in Engineering*, Vol. 9, No. 4, 2009, pp. 044501 (10 pgs).

[52]Balling, R., "Design by Shopping: A New Paradigm?" *Proceedings of the Third World Congress of Structural and Multidisciplinary Optimization (WCSMO-3)*, Buffalo, NY, University at Buffalo, 1999, pp. 295-297.

[53]Moon, S. K., Kumara, S. R. T. and Simpson, T. W., "Data Mining and Fuzzy Clustering to Support Product Family Design", *ASME Design Engineering Technical Conferences - Design Automation Conference*, Philadelphia, PA, ASME, 2006, Paper No. DETC2006/DAC-99287.

[54]Zhang, Y., Jiao, J. and Ma, Y., "Market Segmentation for Product Family Positioning based on Fuzzy Clustering," *Journal of Engineering Design*, Vol. 18, No. 3, 2007, pp. 227-241.

[55]Donaldson, B., 2010, "Application of Product Family Design Tools to Unmanned Ground Vehicles", *M.S. Thesis*, Mechanical & Nuclear Engineering, Penn State University, University Park, PA.

[56]Simpson, T. W., Spencer, D. B. and Yukish, M. A., "Visual Steering Commands and Test Problems to Support Research in Trade Space Exploration", *12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Victoria, British Columbia, Canada, AIAA, 2008, AIAA-2008-6085.

[57]Logan, D., Brennan, S. and Reichard, K., "Allometric Design Principles and Capabilities Modeling for Mobile Robotics", *IEEE Conference on Decision and Control*, IEEE, 2010, under review.

[58]Bobuk, A., 2010, "A Design Method for Product Family Trade Studies Utilizing GVI and PFPF Metrics with Application to Robot Ground Vehicles", *M.S. Thesis*, Mechanical & Nuclear Engineering, Penn State University, University Park, PA.

[59]Khire, R., Wang, J., Bailey, T., Lin, Y. and Simpson, T. W., "Product Family Commonality Selection through Interactive Visualization", *ASME Design Engineering Technical Conferences - Design Automation Conference*, New York, NY, ASME, 2008, DETC2008/DAC-49335.