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ORIGINAL PAPER

An integrated approach to product family redesign using commonality and variety metrics

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Abstract Redesigning a product family entails carefully balancing the trade-offs between commonality and differentiation that are governed by the underlying platform architecture. Numerous metrics for commonality and variety exist to support product family and product platform design; however, rarely are they used in concert to help redesign platforms and families of products effectively. In this paper, we introduce an integrated approach that uses multiple product family metrics to establish an effective platform redesign strategy. Specifically, we present a detailed procedure to integrate the generational variety index, product line commonality index, and design structure matrix to prioritize components for redesign based on variety and commonality needs in a family of products. While all three of these tools exist in the literature and have been used extensively to support product family design, the novelty in our work lies in their integration to establish a redesign strategy for platform architectures that achieves a better balance between the commonality and variety within a product family. To demonstrate the proposed approach, case studies involving two generations of wireless computer mice and two families of dishwashers are presented. Ongoing and future work is also discussed.

Keywords Product family redesign · Commonality · Variety · Generational variety index · Design structure matrix

1 Introduction

In many industries, product family design is a competitive strategy not only to capture total cost savings and speed time to market but also to maintain differentiation and competitiveness. Across generations, the components in a family of products should be continuously evolved to maintain a balance between commonality and differentiation. This is particularly difficult in today's global marketplace where platforms are leveraged across multiple regions with diverse customer needs (Eppinger and Chitkara 2006; Nadadur et al. 2012). Add to this the numerous mergers and acquisitions that many companies are undertaking to increase their global presence, and the need for methods and tools to harmonize product lines and redesign platforms effectively becomes imperative.

A variety of methods and tools have been extensively developed to support product family redesign. Existing approaches have been primarily focused on each specific objective (e.g., analyzing customer requirements (Chan and Wu 2002; Hauser and Clausing 1988), identifying components that should be redesigned to meet future market needs (Martin and Ishii 2002), evaluating commonality (Collier 1981; Kota et al. 2000; Martin and Ishii 1997; Wacker and Trelevan 1986), and architecting product families (Alizon et al. 2007; Hsiao and Liu 2005; Luh et al. 2011). However, redesigning a product family based on a specific approach does not necessarily resolve the trade-offs between variety, commonality, and platform architecture during redesign. So while there are numerous metrics to help evaluate commonality and variety within a product family, using them in combination to develop an effective platform redesign strategy remains an open area of research that this paper addresses.

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Redesigning a product family entails carefully balancing the trade-offs between commonality and differentiation that are governed by the underlying platform architecture. In this paper, we suggest an integrated approach for product family redesign that takes into account variety needs, commonality, and the platform architecture simultaneously in a product family. Related work is discussed in the next section. Section 3 describes a detailed procedure to integrate platform metrics for product family redesign. Section 4 presents a case study to compare an established redesign strategy and an actual change in a family of dishwashers. Finally, Sect. 5 provides closing remarks and a discussion of ongoing work.

2 Literature review

Numerous metrics related to variety and commonality within a product family have been developed over the past two decades (Simpson et al. 2005, 2013). To satisfy the variety needs in the market, collecting and analyzing customer requirements are essential when establishing a redesign strategy for a product family. Kano et al. (1984) introduced a conceptual model to analyze customer preferences. In Kano's model, customer requirements are classified into three different types of needs: (1) basic, (2) performance, and (3) attractive needs. Conjoint analysis (Green and Srinivasan 1990; Michalek et al. 2006) was also developed to estimate customer preferences for the combination of requirements or product's features. Likewise, quality function deployment (QFD) (Chan and Wu 2002; Hauser and Clausing 1988) is a popular tool to gather customer requirements and translate them into specific engineering requirements. Martin and Ishii (2002) extended QFD to product family design and introduced the generational variety index (GVI) to identify components that should be redesigned to meet future market needs. In the GVI matrix, the engineering requirements from a QFD matrix are mapped to corresponding components in a family of products, and GVI ratings are determined according to the amount of redesign for each component. The GVI has been employed to redesign real-world product families such as water coolers (Martin and Ishii 2002) and unmanned ground vehicles (UGVs) (Simpson et al. 2012), and the evolution of iPhones across generations was analyzed using GVI (Nadadur et al. 2013).

The design structure matrix (DSM) (Browning 2001; Steward 1981a, b) has been also extensively utilized to help architect product families such as coffee makers (Hsiao and Liu 2005), herbicide spraying systems (Krause et al. 2014), water coolers (Martin and Ishii 2002), power line communications (Luh et al. 2011), and single-use cameras (Alizon et al. 2007). The DSM is a matrix-based technique to represent and analyze connections among elements within a system or process such as a complex engineered system or a product development process (Yassine and Braha 2003; Yassine et al. 2003). For example, Hsiao and Liu (2005) investigated the connections between components in the DSM to manage the variety within a product family. Alizon et al. (2007) introduced a three-dimensional DSM to identify common, variant, and unique modules and interfaces in a product family. Luh et al. (2011) suggested a design method for product variety using an extended direct graph and a DSM with different connection strengths between components. However, these existing approaches for identifying modules and architecting product families have not been integrated with metrics or methods to capture the degree of commonality and variety within a product family even though product families should be (re)designed by balancing the trade-offs between commonality and differentiation that are governed by the underlying platform architecture.

Redesigning components in a platform architecture is closely related to the redesign of interfaces between components. The approaches to define the strengths of interactions between components vary in the literature (Browning 2001; Dobberfuhl and Lange 2009; Hölttä and Otto 2005; Sosa et al. 2007; Yassine and Braha 2003), but the binary DSM using 0–1 representation (i.e., 1 indicates a connection and 0 indicates no connection) is still widely employed (Eppinger and Browning 2012) since the representation is objective and simple compared with other representation approaches. The characteristics of connectivity in the DSM such as modularity (Gershenson et al. 2003, 2004; Hölttä-Otto et al. 2012) are also important information to analyze and redesign a platform architecture. For example, the highly connected components and corresponding interfaces can be candidates for redesign to reduce their connectivity and increase modularity (Braha and Bar-Yam 2004a, b, 2007). To evaluate the degree of modularity and sparsity, respectively, Hölttä-Otto and de Weck (2007) suggest the singular value modularity index (SMI) and the nonzero fraction (NZF). Hölttä-Otto et al. (2012) conducted a detailed study to identify coupling modularity metrics to capture modularity consistently.

To determine components that should be redesigned in a product family, it is often helpful to measure commonality of components to provide a benchmark for measuring redesign impact (Thevenot and Simpson 2007a, b, c). Thevenot and Simpson (2006) performed a comparative analysis of six commonality indices for product family redesign. While many commonality indices are based on the number of common components to evaluate commonality (Collier 1981; Martin and Ishii 1997; Wacker and Trelevan 1986), the product line commonality index (PCI) suggested by Kota et al. (2000) can capture the degree of commonality for the size and shape of components, materials and manufacturing processes, and assembly and fastening schemes. When a family of products is dissected to calculate the PCI, variation in the collected information can occur because the product dissection is a human-based activity. Thevenot and Simpson (2007a, b, c) suggested a guideline to minimize variation when estimating the PCI through product family dissection. Commonality indices involving cost information for components in a product family have also been proposed (Jiao and Tseng 2000; Thevenot and Simpson 2007a, b, c).

There have been recent efforts to integrate commonality and variety metrics to support product family redesign (Alizon et al. 2009). Thevenot and Simpson (2006) suggested a framework for redesigning a product family using multiple commonality indices according to company's perspective, but the metrics related to commonality indices are only employed in the framework. Simpson et al. (2012) proposed an integrated approach to product family design using the GVI, DSM, and multi-objective optimization to translate user requirements to commonality specifications. The approach is more focused on the study of trade-offs between differentiation and commonality plans for design parameters in a product family.

As discussed in this section, numerous metrics for commonality and variety exist to support product family design; however, rarely are they used in concert to help redesign platforms—and the ensuing product family—effectively. In the next section, we introduce an integrated approach to product family redesign that combines three existing tools, namely GVI, PCI, and DSM, to improve the balance between the commonality and variety within a product family. Based on the integrated approach, designers can identify and prioritize components for redesign based on variety and commonality needs and establish a redesign strategy for interfaces in a platform architecture. In the next section, we describe a detailed approach to integrate the platform metrics and methods to support product family redesign.

3 Integrated approach for product family redesign

To address the needs discussed in the previous section, we propose the integrated approach in Fig. 1 for product family redesign. To obtain a balanced redesign strategy considering variety needs, commonality, and the platform architecture, GVI (Martin and Ishii 2002), PCI (Kota et al. 2000), and DSM (Eppinger and Browning 2012; Steward 1981a, b) are integrated and linked to each other. GVI helps identify which components should be common (or unique) based on an assessment of customer needs (through QFD) while PCI identifies which components are already common (and unique) based on the current platform architecture. By aligning GVI and PCI, the platform components/subsystems for redesign are identified, and the DSM provides insight into the extent of the redesign, which will propagate through the interfaces based on the current platform architecture (Clarkson et al. 2004; Eckert et al. 2004).

The proposed approach entails four steps as follows:

Step 1: Create QFD and GVI matrices for the desired product family and calculate GVI values for each component.
Step 2: Compute the PCI values for each component in the current product family.
Step 3: Plot the GVI and PCI values against each other and prioritize components/subsystems for redesign.
Step 4: Analyze the DSM for the current platform architecture and establish a redesign strategy for interfaces.

An example involving wireless computer mice from Microsoft is used to demonstrate the proposed approach. We selected and dissected three products among the Microsoft wireless computer mice released from 2009 to 2010: Wireless Mobile Mouse 1000, Wireless Mobile Mouse 3500, and Wireless Mobile Mouse 4000.[1] As seen in Table 1, one low-end mouse and two different kinds of mid-range mice are selected. The Arc Touch Mouse[1] for high-end users was not included in the set of products because the mouse has a totally different structure and unique functions such as flexible housing and touch-scrolling compared with the other products.

The first step in the proposed approach begins by creating a QFD matrix to translate customer needs into engineering requirements. As seen in Fig. 2, the engineering requirements are mapped to corresponding components/subsystems in the GVI matrix, and the GVI rating for each component is determined based on the expected change to the components. The GVI rating scale shown in Fig. 2 is then applied to each "X" in the GVI matrix, following the approach developed by Martin and Ishii (2002). The GVI value for each component is finally computed in the GVI matrix. The GVI value indicates the amount of redesign required for each component/subsystem to accommodate the variety necessary to achieve the customer needs. If a component has a high GVI value, then it means that a lot of redesign is required for the component, and it should not be part of the platform. A low GVI value indicates that little redesign is needed and thus a good candidate component/subsystem for the platform. To

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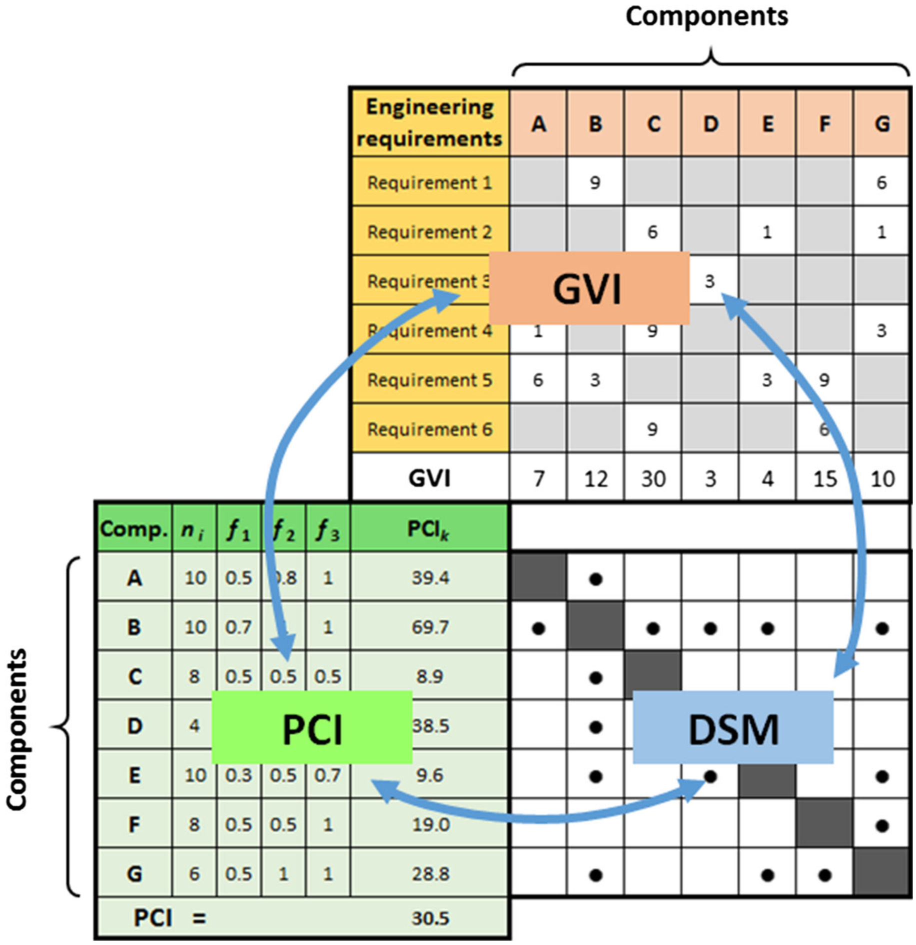
[1] For more information, visit: http://www.microsoft.com/hardware/en-us/mice.



Engineering requirements	A	B	C	D	E	F	G
Requirement 1		9					6
Requirement 2			6		1		1
Requirement 3				3			
Requirement 4	1		9				3
Requirement 5	6	3			3	9	
Requirement 6			9			6	
GVI	7	12	30	3	4	15	10

Comp.	n_i	f_1	f_2	f_3	PCI_k	A	B	C	D	E	F	G
A	10	0.5	.8	1	39.4	■	●					
B	10	0.7		1	69.7	●	■	●	●	●		●
C	8	0.5	0.5	0.5	8.9		●	■				
D	4				38.5		●					
E	10	0.3	0.5	0.7	9.6		●		●	■		●
F	8	0.5	0.5	1	19.0						■	●
G	6	0.5	1	1	28.8		●			●	●	■
PCI =					30.5							

Fig. 1 Integrated approach to product family redesign

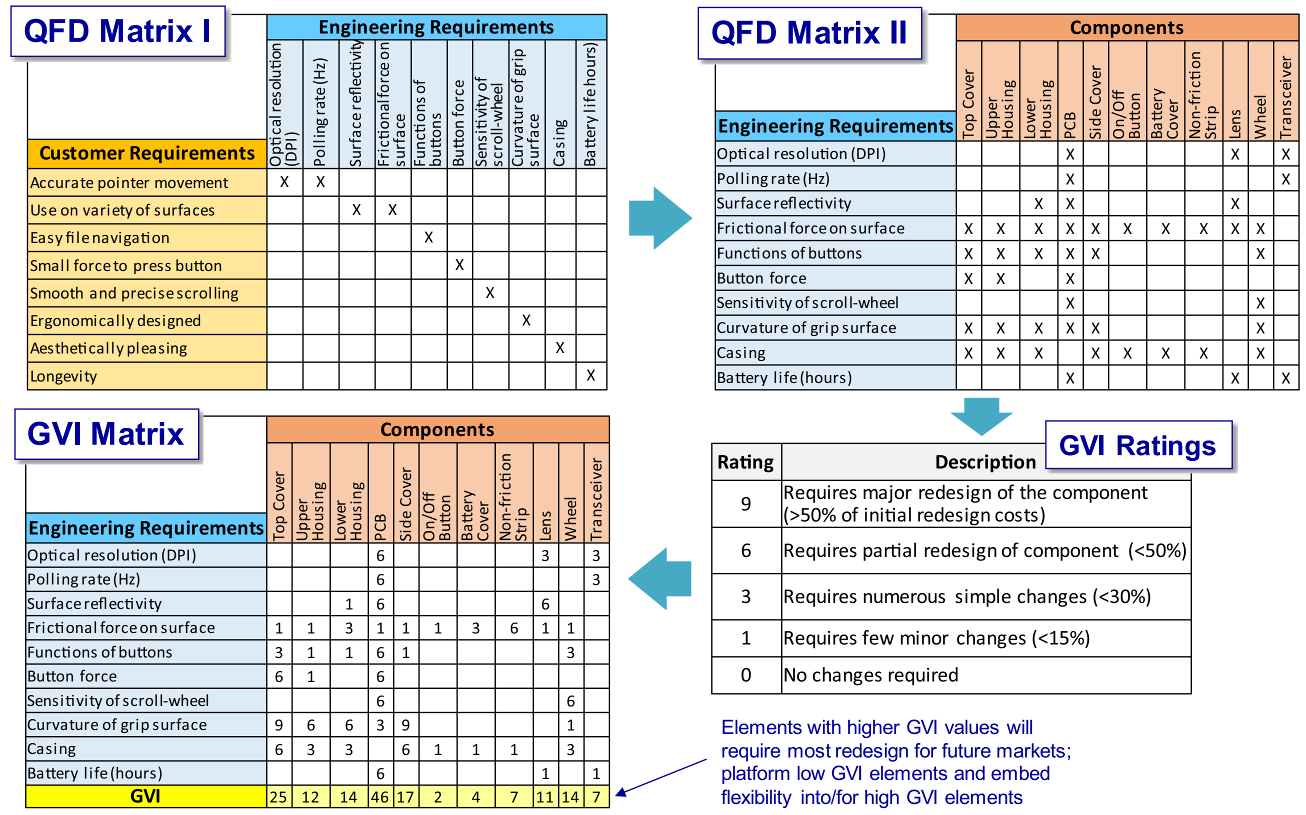
Table 1 Family of wireless mice released in 2009–2010

Product	 Wireless mobile mouse 1000	 Wireless mobile mouse 3500	 Wireless mobile mouse 4000
MSRP	$14.95	$29.95	$34.95
Release date	Oct. 2010	Jun. 2010	Nov. 2009

create the QFD and GVI matrices, it is necessary to use engineering expertise and design judgment to estimate the redesign effort, cost, and variety needs for each component. The criteria for assigning GVI ratings are shown in Fig. 2. Further details for computing GVI can be found in (Martin and Ishii 2002), and example applications can be found in (Nadadur et al. 2013; Simpson et al. 2012).

Figure 2 shows the QFD and GVI matrices for the wireless computer mice example. To generate the QFD matrix, the customer requirements for the wireless mice were determined to be (Kumar and Allada 2007; Zhou et al. 2010): (1) accurate translation of mouse movement to pointer movement, (2) use on variety of surfaces, (3) easy file navigation, (4) small force needed to press button, (5) smooth and precise scrolling, (6) ergonomically designed, (7) aesthetically pleasing, and (8) longevity. After creating the QFD matrix, the GVI rating for each component in the GVI matrix is determined according to the component's change required by the engineering requirements. As seen in Fig. 2, the PCB has a high GVI value (i.e., 46), while the battery cover, on/off button, non-friction strip, and transceiver have lower GVI values comparatively.

In Step 2, PCI is utilized to compute the commonality in a product family following the procedure introduced by Kota et al. (2000). While many commonality indices in the literature are defined based on the number of common components, the PCI can take into account size and shape, materials and manufacturing processes, and assembly and fastening schemes. The PCI is computed as follows:



QFD Matrix I

Customer Requirements	Optical resolution (DPI)	Polling rate (Hz)	Surface reflectivity	Frictional force on surface	Functions of buttons	Button force	Sensitivity of scroll-wheel	Curvature of grip surface	Casing	Battery life hours)
Accurate pointer movement	X	X								
Use on variety of surfaces			X	X						
Easy file navigation					X					
Small force to press button						X				
Smooth and precise scrolling							X			
Ergonomically designed								X		
Aesthetically pleasing									X	
Longevity										X

QFD Matrix II

Engineering Requirements	Top Cover	Upper Housing	Lower Housing	PCB	Side Cover	On/Off Button	Battery Cover	Non-friction Strip	Lens	Wheel	Transceiver
Optical resolution (DPI)				X					X		X
Polling rate (Hz)				X							X
Surface reflectivity			X	X					X		
Frictional force on surface	X	X	X	X	X	X	X	X	X	X	
Functions of buttons	X	X	X	X	X					X	
Button force	X	X		X							
Sensitivity of scroll-wheel				X						X	
Curvature of grip surface	X	X	X	X	X					X	
Casing	X	X	X		X	X	X	X		X	
Battery life (hours)				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

Engineering Requirements	Top Cover	Upper Housing	Lower Housing	PCB	Side Cover	On/Off Button	Battery Cover	Non-friction Strip	Lens	Wheel	Transceiver
Optical resolution (DPI)				6					3		3
Polling rate (Hz)				6							3
Surface reflectivity			1	6					6		
Frictional force on surface	1	1	3	1	1	1	3	6	1	1	
Functions of buttons	3	1	1	6	1					3	
Button force	6	1		6							
Sensitivity of scroll-wheel				6						6	
Curvature of grip surface	9	6	6	3	9					1	
Casing	6	3	3		6	1	1	1		3	
Battery life (hours)				6					1		1
GVI	25	12	14	46	17	2	4	7	11	14	7

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

Fig. 2 QFD and GVI matrices for the family of wireless computer mice

$$\mathrm{PCI} = \frac{\sum_{i=1}^{P} n_i \times f_{1i} \times f_{2i} \times f_{3i} - \sum_{i=1}^{P} \frac{1}{n_i^2}}{P \times N - \sum_{i=1}^{P} \frac{1}{n_i^2}} \times 100 \qquad (1)$$

where P is the total number of non-unique components; N is the number of products in the product family; n_i is the number of products that have component i; f_{1i} is the size and shape factor for component i; f_{2i} is the materials and manufacturing processes factor for component i; and f_{3i} is the assembly and fastening schemes factor for component i. For example, if the component i in all products is identical in size and shape, then f_{1i} is equal to 1. On the other hand, if each component i has a different size and shape, then f_{1i} has a minimum value as $1/n_i$. An example of a PCI calculation is given in Table 2, and the PCI is computed as 22.082 as listed at the bottom of the table. As seen in Table 2, we employed PCI_k to calculate the commonality for the kth component/subsystem as follows:

$$\mathrm{PCI}_k = \frac{\sum_{i=1}^{P_k} n_i \times f_{1i} \times f_{2i} \times f_{3i} - \sum_{i=1}^{P_k} \frac{1}{n_i^2}}{P_k \times N - \sum_{i=1}^{P_k} \frac{1}{n_i^2}} \times 100 \qquad (2)$$

where P_k is the number of components within the kth subsystem.

The basic concept of PCI is to maximize commonality for non-differentiating components. In many product families, however, many components do not differentiate the product and therefore need not be unique. For example, in a family of dishwashers discussed in Sect. 4, the number of components that have differentiating (i.e., unique) functions is <10 % of the total number of components. Thus, balancing the trade-offs between commonality and differentiation of non-differentiating components should be carefully considered.

In Step 3 of the proposed approach, we plot and analyze the GVI and PCI values for subsystems/components and then prioritize subsystems/components for redesign based on variety and commonality needs. Figure 3 shows PCI values plotted against GVI values for the computer mice example. The values of the GVI and PCI in the plot are normalized to range from 0 and 1. As seen in Fig. 3, the battery cover, side cover, upper housing, lower housing, lens, and wheel all have low commonality values compared to the other components; their GVI values are relatively low as well.

By plotting GVI versus PCI, we can identify four regions of platforming as shown in Fig. 4: (1) valued variety, (2) properly platformed, (3) unvalued uniqueness, and (4) confusing commonality. If a component has low PCI and high GVI values, then the variety in the component (high GVI) is valued, and the component is

Table 2 PCI value for wireless mice released in 2009–2010

No.	Component	n_i	f_{1i}	f_{2i}	f_{3i}	$n_i{*}f_{1i}{*}f_{2i}{*}f_{3i}$	PCI_k
1	Top cover	3	0.333	0.333	1.000	0.333	7.692
2	Upper housing	3	0.333	0.333	0.333	0.111	0.000
3	Lower housing	3	0.333	0.333	0.333	0.111	0.000
4	PCB	3	0.333	0.333	0.333	0.111	0.000
5	Left side cover	2	0.500	0.500	0.500	0.250	0.000
6	Right side cover	2	0.500	0.500	0.500	0.250	0.000
7	Battery cover	3	0.333	0.333	1.000	0.333	7.692
8	Non-friction strip 1	3	0.667	1.000	1.000	2.000	65.385
9	Non-friction strip 2	3	0.333	1.000	1.000	1.000	30.769
10	On/off button	3	0.667	1.000	1.000	2.000	65.385
11	Lens	3	0.333	0.667	0.667	0.444	11.538
12	Wheel	3	0.667	0.333	0.667	0.444	11.538
13	Transceiver	3	1.000	1.000	1.000	3.000	100.00
14	Product label	3	0.333	1.000	1.000	1.000	30.769
15	Battery label	3	0.333	1.000	1.000	1.000	30.769
16	LED cover	2	0.500	0.500	0.500	0.250	0.000
Sum of $n_i{*}f_{1i}{*}f_{2i}{*}f_{3i}$							12.639
Sum of $1/n_i^2$							2.194
Number of parts, P							16
Number of products, N							3
PCI							22.082

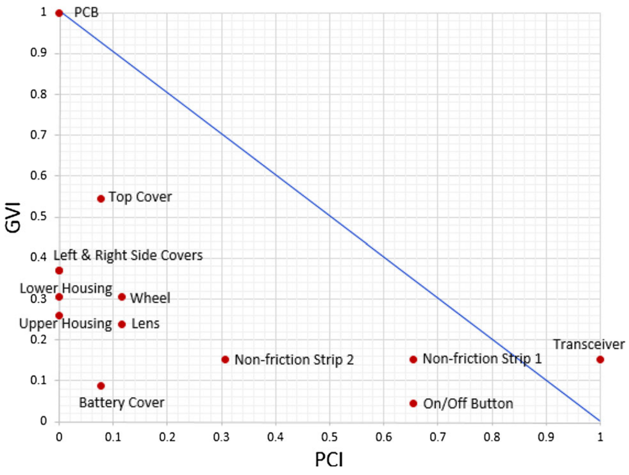


Fig. 3 PCI versus GVI (2009–2010)

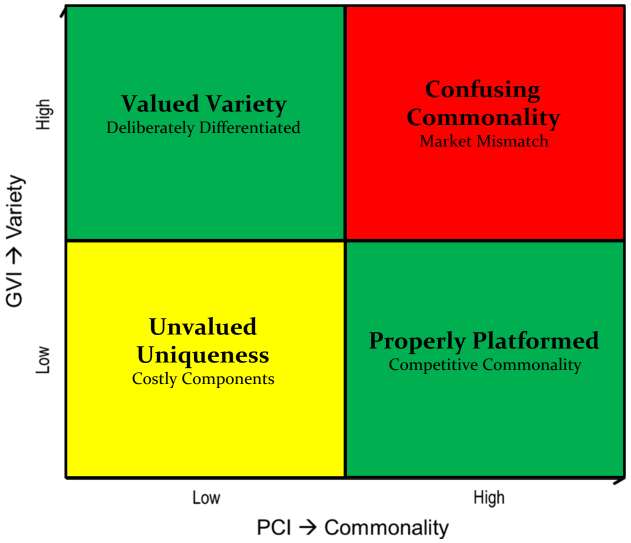


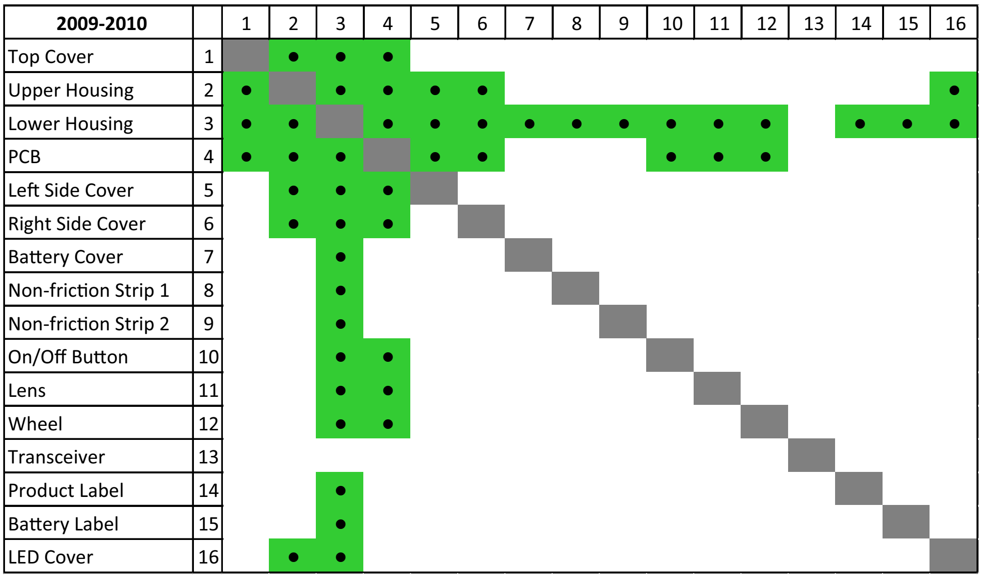
Fig. 4 Four different types of variety and commonality characteristics of components

deliberately differentiated (low PCI). Likewise, components with high PCI and low GVI values have achieved a good balance between commonality and variety because they are properly platformed and are using commonality competitively. In both of these cases, the commonality and variety needs have been achieved well within the platform architecture, and no redesign is needed. Conversely, if a component has a low PCI value as well as a low GVI value, then its uniqueness is unvalued—customers do not want variety (low GVI) yet the components are different (low PCI). Components falling in this region of the plot are good candidates for redesign to improve standardization, increase commonality, and reduce costs. Components on the other side of the diagonal—high GVI and high PCI values—should also be considered for redesign as the lack of differentiation may be creating a market mismatch that is adversely affecting sales. This creates confusing commonality because the components within the family are the same (high PCI) yet customers want variety within the family (high GVI).

Based on this logic, data points that lie along the diagonal in Fig. 3 have achieved a good balance between commonality and variety at both the low end and the high end. Components with high GVI scores should have low PCI scores and vice versa. Components far away from the diagonal may be opportunities for redesign. Specifically, *components falling below the diagonal indicate that the manufacturer may be leaving money on the table by not having as much commonality as possible*. Components above the diagonal may have too much commonality and lack distinctiveness, which will likely lower sales. For the example shown in Fig. 3, the transceiver, on/off button, non-friction strip 1, and PCB are relatively close to the diagonal, while the battery cover, side cover, upper housing, lower housing, lens, and wheel are far away from the diagonal. Components far away from the diagonal are good candidates for redesign.

In Step 4, the integrated approach extends to the platform architecture and establishes a redesign strategy for interfaces between components in the platform architecture. First, the DSM for the platform architecture is created as seen in Fig. 5 for the computer mice example. In the DSM, an off-diagonal element represents a connection between components. In this paper, the binary DSM using 0–1 representation for interfaces is utilized since many representation methods rely on subjective information such as "engineering intuition" (Asikoglu and Simpson, 2012). Using the DSM, we focus on improving the connectivity between components based on the GVI and PCI values. For example, if a component that has high GVI and low PCI values is connected with many other components in the DSM, then it needs to be modularized in the family to enable variation and reduce interfaces for the component. This is because it is highly likely that the component will be differentiated due to the market needs. To create a better platform architecture, components with high GVI values should be modularized, and the corresponding interfaces should be standardized.

As seen in Fig. 5, the platform architecture for the family of mice is *integral* (Hölttä-Otto and de Weck 2007) because the lower housing is a bus-type (Yu et al. 2007) component that is connected to nearly all of the components. The GVI value of the lower housing is in the middle range in Fig. 3, and the PCI value is zero. In many cases, the bus-type modules/components are usually designed focusing on the standardization of the corresponding interfaces to be changed without affecting other components instead of reducing the number of interfaces. Engel and Reich (2015) showed that the highest degree of modularity does not always guarantee the best architecture in terms of costs; however, in order to establish a redesign strategy for components, each component's GVI value and variety needs should also be carefully considered. Although the lower housing is a bus-type component, it has the variety necessary to achieve the range of customer needs since the corresponding GVI value is in the middle range. Thus, the change and variety of the lower housing have the potential for propagating changes to many of the other components, and we refer the reader to the work of Clarkson, et al. (2004) for more details on assessing this change propagation. Unlike other bus-type components with low variety needs and standardized interfaces, therefore, the lower housing should be redesigned to reduce the



2009-2010		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Top Cover	1	■	●	●	●												
Upper Housing	2	●	■	●	●	●	●										●
Lower Housing	3	●	●	■	●	●	●	●	●	●	●	●	●		●	●	●
PCB	4	●	●	●	■	●	●				●	●	●				
Left Side Cover	5		●	●	●	■											
Right Side Cover	6		●	●	●		■										
Battery Cover	7			●				■									
Non-friction Strip 1	8			●					■								
Non-friction Strip 2	9			●						■							
On/Off Button	10			●	●						■						
Lens	11			●	●							■					
Wheel	12			●	●								■				
Transceiver	13													■			
Product Label	14			●											■		
Battery Label	15			●												■	
LED Cover	16		●	●													■

Fig. 5 DSM of the platform architecture (2009–2010)

Table 3 Family of wireless mice released in 2013–2014

Product	 Wireless mobile mouse 1850	 Sculpt mobile mouse	 Sculpt comfort mouse
MSRP	\$14.95	\$29.95	\$39.95
Release date	Jun. 2014	Aug. 2013	Sep. 2013

number of interfaces and standardize the interfaces and potentially increase the value of PCI. In addition, the PCB has many connections with other components even though the variety needs for the PCB are greater than the other components. Thus, the connectivity between the PCB and the other components should also be decreased to improve the platform architecture.

To test the redesign strategy for the family, we compare our analysis results with a more recent set of Microsoft wireless computer mice released from 2013 to 2014. As seen in Table 3, we selected three kinds of computer mice within the three tiers, respectively, similar to the three tiers in Table 1. The two comparison sets of the mice are described as the *Group 1* and *Group 2* as follows:

> *Group 1:* Wireless Mobile Mouse 1000, Wireless Mobile Mouse 3500, and Wireless Mobile Mouse 4000 (released from 2009 to 2010).
> *Group 2:* Wireless Mobile Mouse 1850, Sculpt Mobile Mouse, and Sculpt Comfort Mouse (released from 2013 to 2014).

Figure 6 shows the PCI plotted against the GVI for *Group 2*. Compared to Fig. 3, the data points for the wheel, lens, right side cover, and top cover were closer to the diagonal because the PCI_k values for the components have increased in the new family. As seen at the bottom of Table 4, the value of the PCI was also increased from 22.082 to 27.460.

We also compared the DSMs for *Group 1* and *Group 2*. As shown in Fig. 7, the total number of components and interfaces within the DSM has increased because the new components related to the wheel (i.e., wheel rubber, pin, ball, connector, and wheel frame) were added to the new platform architecture. Nevertheless, the number of interfaces for the PCB was reduced from 16 to 14. Also, the number of interfaces for the lower housing decreased from 28 to 24. Thus, the result shows that the PCB and lower housing were modularized more in the new family compared with *Group 1*.

When components are redesigned to reduce interfaces between components yet still enable variety, the total connectivity in the system should be improved or maintained. To assess the degree of connectivity in the platform architecture, SMI and NZF as suggested by Hölttä-Otto and de Weck (2007) are applied to measure modularity (or integrality) and sparsity (or density). SMI and NZF are computed as:

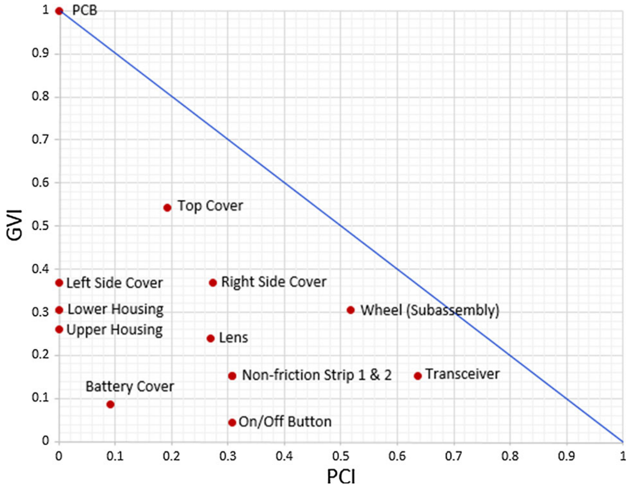


Fig. 6 PCI versus GVI (2013–2014)

$$\mathrm{SMI} = \frac{1}{N} \arg\min_{\alpha} \sum_{i=1}^{N} \left| \frac{\sigma_i}{\sigma_1} - e^{-[i-1]/\alpha} \right| \tag{3}$$

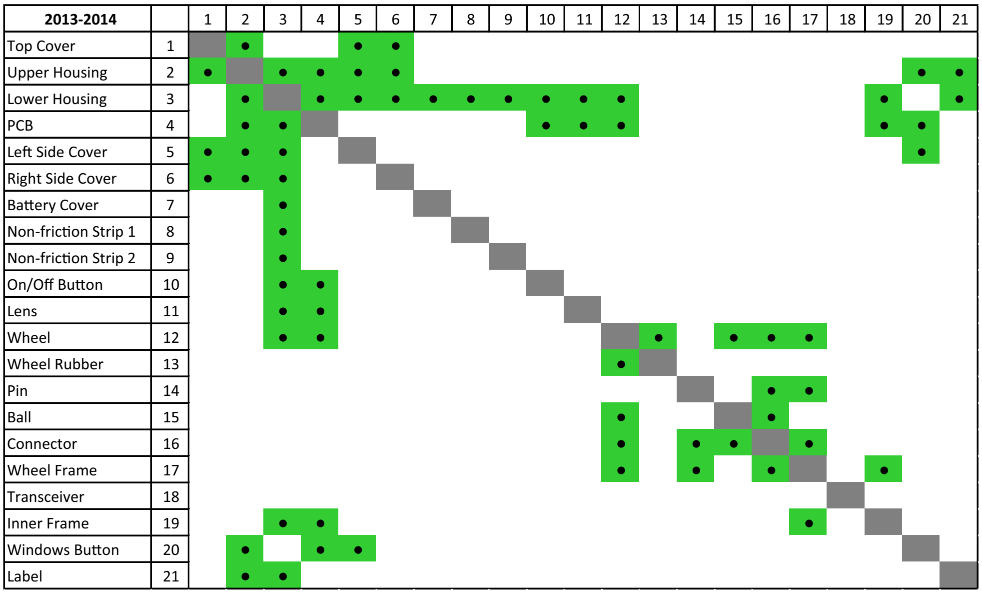
$$\mathrm{NZF} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} \mathrm{DSM}_{ij}}{N(N-1)} \tag{4}$$

where N is the number of components; σ_i is the ith singular value obtained by performing a singular value decomposition (SVD) on the binary DSM; and DSM_{ij} is the value of the ith row and jth column element within the binary DSM. The SMI and NZF can consistently measure the modularity and sparsity regardless of module boundaries and the order of rows and columns in the DSM. The values of the SMI and NZF for *Group 1* and *2* can thus be compared. SMI increased from 0.158 to 0.242 while NZF decreased from 0.208 to 0.167 for *Group 1* and *Group 2*, respectively. These results indicate that the platform architecture for *Group 2* is more modular and sparser than that of *Group 1* even though the total numbers of interfaces and components have increased due to adding new components and functions.

This section introduced a step-by-step procedure for the integrated approach to support product family redesign using the GVI, PCI, and DSM. We observed that the change in the computer mice family released in 2013–2014

Table 4 PCI value for wireless mice released in 2013–2014

No.	Component	n_i	f_{1i}	f_{2i}	f_{3i}	$n_i{*}f_{1i}{*}f_{2i}{*}f_{3i}$	PCI_k
1	Top cover	3	0.333	0.667	1.000	0.667	19.231
2	Upper housing	3	0.333	0.333	0.333	0.111	0.000
3	Lower housing	3	0.333	0.333	0.333	0.111	0.000
4	PCB	3	0.333	0.333	0.333	0.111	0.000
5	Left side cover	2	0.500	0.500	0.500	0.250	0.000
6	Right side cover	2	0.500	1.000	1.000	1.000	27.273
7	Battery cover	2	0.500	0.500	1.000	0.500	9.091
8	Non-friction strip 1	3	0.333	1.000	1.000	1.000	30.769
9	Non-friction strip 2	3	0.333	1.000	1.000	1.000	30.769
10	On/off button	3	0.333	1.000	1.000	1.000	30.769
11	Lens	3	0.667	0.667	0.667	0.889	26.923
12	Wheel	3	0.667	0.667	0.667	0.889	26.923
13	Wheel rubber	3	1.000	0.667	1.000	2.000	65.385
14	Pin	2	1.000	1.000	1.000	2.000	63.636
15	Ball	2	1.000	1.000	1.000	2.000	63.636
16	Connector	2	1.000	1.000	1.000	2.000	63.636
17	Wheel frame	2	0.500	1.000	1.000	1.000	27.273
18	Transceiver	2	1.000	1.000	1.000	2.000	63.636
19	Inner frame	2	0.500	1.000	1.000	1.000	27.273
20	Windows button	2	0.500	0.500	0.500	0.250	0.000
21	Label	3	0.333	0.333	0.667	0.222	3.846
Sum of $n_i{*}f_{1i}{*}f_{2i}{*}f_{3i}$							20.000
Sum of $1/n_i^2$							3.722
Number of parts, P							21
Number of products, N							3
PCI							27.460



2013-2014		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Top Cover	1	■	●			●	●															
Upper Housing	2	●	■	●	●	●	●														●	●
Lower Housing	3		●	■	●	●	●	●	●	●	●	●	●							●		●
PCB	4		●	●	■						●	●	●							●	●	
Left Side Cover	5	●	●	●		■															●	
Right Side Cover	6	●	●	●			■															
Battery Cover	7			●				■														
Non-friction Strip 1	8			●					■													
Non-friction Strip 2	9			●						■												
On/Off Button	10			●	●						■											
Lens	11			●	●							■										
Wheel	12			●	●								■	●		●	●	●				
Wheel Rubber	13												●	■								
Pin	14														■		●	●				
Ball	15												●			■	●					
Connector	16												●		●	●	■	●				
Wheel Frame	17												●		●		●	■		●		
Transceiver	18																		■			
Inner Frame	19			●	●													●		■		
Windows Button	20		●		●	●															■	
Label	21		●	●																		■

Fig. 7 DSM of the platform architecture (2013–2014)

was similar to the proposed redesign strategy. A family of dishwashers is considered in the next section to demonstrate the approach on a more complex product family.

4 Case study: a family of dishwashers

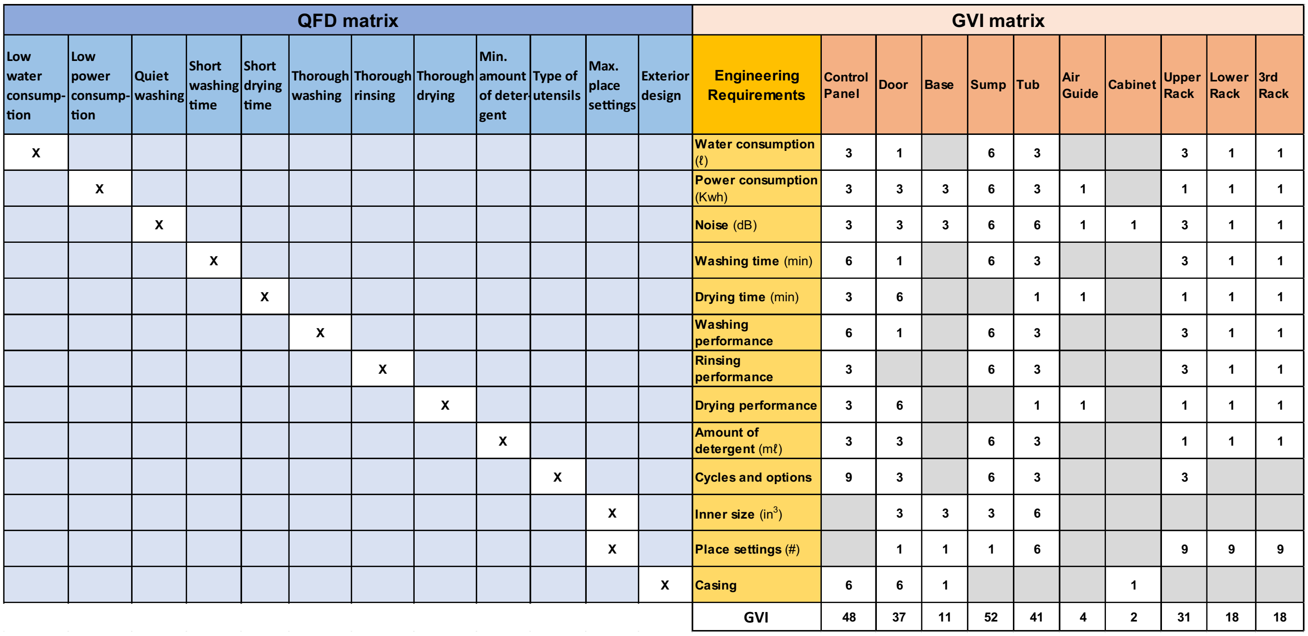
As a second example, a case study involving dishwashers is presented in this section. We selected four products among the LG dishwashers released from 2006 to 2007: LD-1204W, LD-1403W1, LD-1415M, and LD-1416T (LG 2006, 2007). As seen in Table 5, four different kinds of dishwashers ranging from low end to high end were selected to apply the proposed approach.

As the first step, the customer requirements for the dishwashers were identified based on the available literature (Li et al. 2009), and QFD and GVI matrices were created as seen in Fig. 8. In the GVI matrix, the engineering requirements and the ten kinds of subassemblies are listed in the first column and row, respectively. Using the GVI rating scale in Fig. 2, the GVI rating for each component is determined according to the expected changes across the range of customer needs. As seen in Fig. 8, the control panel and sump have relatively high GVI values while the GVI values for the air guide and cabinet are lower than those of the other subassemblies.

In Step 2, the values of the PCI are calculated are included in Appendix 1. Table 7 shows the computed PCI and PCI_k for each subassembly. The PCI of the family is computed as 70.912, and the values of PCI_k for the air guide, tub, and sump are nearly 100. This means that most of the components for each subassembly are already shared in the family.

Table 5 Family of dishwashers released in 2006–2007

Specifications	LD-1204W	LD-1403W1	LD-1415M	LD-1416T
MSRP	\$999	\$1124	\$1249	\$1624
Color	White	White	Titanium	Stainless steel
Place settings	12	14	14	14
Width (mm)	600	600	600	600
Height (mm)	850	850	850	850
Depth (mm)	600	600	600	600
Max noise level (dB)	49	47	49	47
Normal wash water use (*l*)	20	14.8	20.3	14.8
Energy consumption (KWh/year)	251	281	259	259
Release date	Mar. 2006	Dec. 2007	Mar. 2006	Mar. 2006



QFD matrix												GVI matrix										
Low water consumption	Low power consumption	Quiet washing	Short washing time	Short drying time	Thorough washing	Thorough rinsing	Thorough drying	Min. amount of detergent	Type of utensils	Max. place settings	Exterior design	Engineering Requirements	Control Panel	Door	Base	Sump	Tub	Air Guide	Cabinet	Upper Rack	Lower Rack	3rd Rack
X												Water consumption (ℓ)	3	1		6	3			3	1	1
	X											Power consumption (Kwh)	3	3	3	6	3	1		1	1	1
		X										Noise (dB)	3	3	3	6	6	1	1	3	1	1
			X									Washing time (min)	6	1		6	3			3	1	1
				X								Drying time (min)	3	6			1	1		1	1	1
					X							Washing performance	6	1		6	3			3	1	1
						X						Rinsing performance	3			6	3			3	1	1
							X					Drying performance	3	6			1	1		1	1	1
								X				Amount of detergent (mℓ)	3	3		6	3			1	1	1
									X			Cycles and options	9	3		6	3			3		
										X		Inner size (in^3)		3	3	3	6					
										X		Place settings (#)		1	1	1	6			9	9	9
											X	Casing	6	6	1				1			
												GVI	48	37	11	52	41	4	2	31	18	18

Fig. 8 QFD and GVI matrices for the family of dishwashers

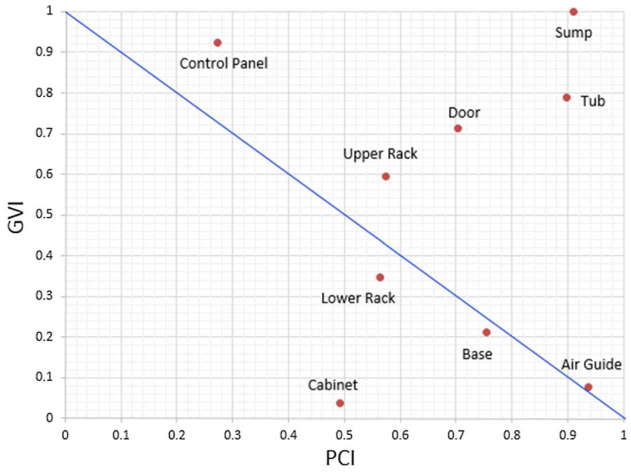


Fig. 9 PCI versus GVI (2006–2007)

In Step 3, the GVI and PCI values for each subassembly are plotted and analyzed. As seen in Fig. 9, while the air guide, base, lower rack, upper rack, and control panel are close to the diagonal, the cabinet, tub, and sump are far away from the diagonal. Interestingly, although the tub and sump have very high PCI values, they are not close to the diagonal. In Sect. 3, the computer mice example, it was necessary to increase the commonality for several components that had low GVI values. Here, the tub and sump within the family of the dishwashers should be redesigned to increase differentiation to satisfy the variety needs in the market.

In Step 4, the platform architecture for the family was created and analyzed. The DSM of the platform architecture is presented in Appendix 2 (see Fig. 11). As seen in Fig. 9, the control panel and sump have higher GVI values compared with the other components; so, it is highly likely that the control panel and sump are differentiated to meet variety needs. When we analyzed the interfaces between the control panel and the other components in the DSM, the control panel is connected with only the components related to the door and sump, and the number of the connections is 12. On the other hand, the sump is connected with the tub, air guide, door, control panel, and base, and the number of the connections is 42. Consequently, the control panel was considered to be more modularized than the sump, but the sump should reduce its interfaces with other components.

Our result is compared with a more recent family of dishwashers (released from 2009 to 2010). As seen in Table 6, the four kinds of dishwashers were selected within the same four tiers as given in Table 5 (LG 2009a, b, 2010). The two sets of the dishwasher are described as *Group 1* and *Group 2*:

Group 1: LD-1204W, LD-1403W1, LD-1415M, and LD-1416T (released from 2006 to 2007).

Group 2: LD-1415W1, LD-1419M2, LD-1420T2, and LD-1421T2 (released from 2009 to 2010).

The PCI calculation for the subsystems in the four dishwashers in *Group 2* is included in Appendix 1 (see Table 8), and the DSM for these subsystems can be found in Appendix 2 (see Fig. 12). This information is used to analyze *Group 2*.

Figure 10 shows PCI against GVI for *Group 2*. Compared to Fig. 9, the data points for the sump, tub, and door have shifted to closer to the diagonal because the PCI_k values for the subassemblies have decreased. On the other hand, the PCI_k for the cabinet was increased because of low variety needs for the cabinet, and the cabinet in the plot was also moved closer to the diagonal. In addition, the third rack is close to the diagonal even though the third rack is a new feature in the platform architecture of the *Group 2*.

To compare the redesign strategy established for interfaces and the actual change to the dishwashers, the platform architectures for *Group 1* and *Group 2* were analyzed. As shown in Fig. 12, the total numbers of components and interfaces within the DSM were increased because the third rack was new to this family. Nevertheless, the number of interfaces between the sump and other components has decreased from 42 to 36. Thus, the sump was modularized compared with *Group 1*. The number of interfaces between the control panel and the other components has not

Table 6 Family of dishwashers released in 2009–2010

Specifications	LD-1415W1	LD-1419M2	LD-1420T2	LD-1421T2
MSRP	$849	$1049	$1299	$1349
Color	White	Titanium	Stainless steel	Stainless steel
Place settings	14	14	14	14
Width (mm)	600	600	600	600
Height (mm)	850	850	850	850
Depth (mm)	600	600	600	600
Max noise level (dB)	49	46	43	43
Normal wash water use (*l*)	14.8	13.7	13.9	13.5
Energy consumption (KWh/year)	281	305	326	324
Release year	Aug. 2009	May 2010	Dec. 2009	Dec. 2010

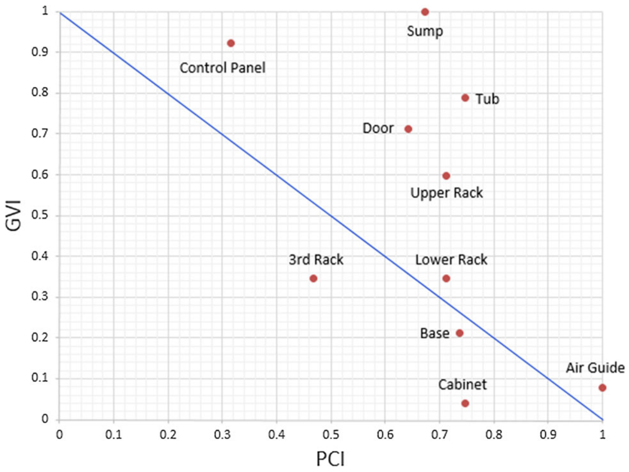


Fig. 10 PCI versus GVI (2009–2010)

changed, but the number of components and interfaces within the control panel has decreased.

In order to compare the connectivity between the control panel and other components in more detail, we created DSMs including both direct and *indirect* connections as seen in Figs. 13 and 14 (i.e., Figs. 11 and 12 show the DSMs with only direct connections between components). It is well known that indirect connections can propagate changes to many other components (Clarkson et al. 2004). To create the DSMs including indirect connections, the maximum path length to identify indirect connections (Clarkson et al. 2004) was set to 2 (i.e., indirect connections passing one other component between two components). Consequently, we observe that the number of direct and indirect connections between the control panel and other components has decreased from 164 to 144. This means that the control panel was redesigned to have a more compact and flexible platform architecture by reducing not only the number of components but also the number of indirect connections between the control panel and the other components.

Similar to the comparison in Sect. 3, the values for SMI and NZF for *Groups 1* and *2* are also compared. The SMI values for *Groups 1* and *2* are almost identical (0.203 and 0.200, respectively) while NZF has decreased from 0.031 to 0.027, respectively. As a result, the platform architecture of *Group 2* is sparser than that of *Group 1*, and the modularity of the architecture was maintained, even though the total numbers of interfaces and components were increased due to adding new subassembly and functions.

5 Closing remarks and ongoing work

We introduced an integrated approach to product family redesign that combines GVI, PCI, and DSM in order to prioritize components for redesign based on variety and commonality needs. While all three of these tools exist in the literature and have been used extensively to support product family design as discussed in this paper, the novelty of our approach lies in using them in concert to help establish a redesign strategy for platform architectures that achieves a better balance between the commonality and variety needs within a product family. This is accomplished by plotting the PCI values versus GVI values for each component so that designers can quickly determine where to focus their redesign efforts and then use a DSM to redesign the platform architecture and/or interfaces between components. When plotting PCI versus GVI, components that lie below the diagonal are not as common as they could be, indicating that the company may be leaving money on the table due to unvalued uniqueness. Conversely, components above the diagonal may not be as distinctive as the customer wants, which may be adversely impacting sales due to confusing commonality. Finally, components that lie on the diagonal have achieved a good balance between commonality and distinctiveness by offering valued variety and competitive commonality. Once components in the product family are identified as candidates for redesign, the DSM can be invoked to establish a redesign strategy for interfaces in the platform architecture.

After applying the proposed approach to the example of wireless computer mice, we observed that the change for the family of the mice released in 2013–2014 was similar to the expected result for the family. In a more complex family of dishwashers, we also determined a suitable platform strategy for the components and interfaces based on the customer needs, commonality, and underlying architecture. Consequently, the components and interfaces for the family of dishwashers in 2009–2010 were more balanced and improved, similar to the redesign strategy recommended for the family in 2006–2007.

As part of our ongoing work, we are investigating an advanced PCI-GVI plot to determine the priority of component's redesign and facilitate product family benchmarking. One could imagine situations where lack of distinctiveness, for example, is much more important than cost savings through improved commonality, which would skew the linear relation that is currently exploited when plotting PCI versus GVI. Such emphasis would make the PCI-GVI relationship nonlinear, and the two metrics would need to be adjusted and weighted accordingly. We also plan to study the use of redesign cost and technical risk to help prioritize components in the family that should be redesigned. This information will provide additional insight into the benefits (or potential pitfalls) that may be achieved during redesign. This information could also be used for phasing the introduction of upgraded modules or redesigned components within an existing product family, a frequent concern for companies struggling to maintain multiple product lines in the marketplace. Finally, if we define interfaces in the DSM using more objective interface representation methods as discussed in (Asikoglu and Simpson 2012), then we can establish a better redesign strategy for interfaces in the platform architecture.

Appendix 1: PCI calculations for each family of dishwashers

Table 7 Family of dishwashers released in 2006–2007

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI$_k$
1	Cabinet	Top plate	4	0.50	1	1	2	49.2
2		Left side cabinet	4	0.50	1	1	2	
3		Right side cabinet	4	0.50	1	1	2	
4	Upper rack	Middle nozzle	4	1.00	1	1	4	57.5
5		Guide 1	4	1.00	1	1	4	
6		Upper rack 1	4	0.50	1	1	2	
7		Upper rack 2	4	0.50	1	1	2	
8		Rack handle deco-1	2	1.00	1	1	2	
9		Rack handle 1-1	2	1.00	1	1	2	
10		Rack handle 2-1	2	1.00	1	1	1	
11		Rack holder 1	3	1.00	1	1	3	
12		Upper rack 3	4	0.25	1	1	1	
13		Rack guide 1	2	1.00	1	1	2	
14		Rack guide 2	2	1.00	1	1	2	
15	Lower rack	Rack handle deco-2	2	1.00	1	1	2	56.3
16		Rack handle 1-2	2	1.00	1	1	2	
17		Rack handle 2-2	2	1.00	1	1	2	
18		Spoon basket	4	0.75	1	1	3	
19		Lower rack 1	4	0.25	1	1	1	
20		Rack roller	4	1.00	1	1	4	
21		Lower rack 2	3	0.33	1	1	1	
22		Rack holder 2	4	1.00	1	1	4	
23		Rack holder 3	4	1.00	1	1	4	
24		Lower rack 3	2	0.50	0.5	1	0.5	
25		Rack holder 4	2	1.00	1	1	2	
26	Tub	Tub	4	1.00	1	1	4	89.8
27		Balance weight	4	0.50	1	1	2	
28		Frame holder	3	1.00	1	1	3	
29		Upper nozzle	4	1.00	1	1	4	
30		Top frame	4	1.00	1	1	4	
31		Hinge spring	4	1.00	1	1	4	
32		Connector	4	0.75	1	1	3	
33		Rail 1	4	1.00	1	1	4	
34		Roller stopper 1	4	1.00	1	1	4	
35		Roller	4	1.00	1	1	4	
36		Roller stopper 2	4	1.00	1	1	4	
37		Roller stopper 3	4	1.00	1	1	4	
38		Tub packing	4	1.00	1	1	4	
39		Locker	4	0.50	1	1	2	
40		Guide 2	4	1.00	1	1	4	

Table 7 continued

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI_k
41	Air guide	Sensor	4	0.75	1	1	3	93.7
42		Air guide	4	1.00	1	1	4	
43		Common nut	4	1.00	1	1	4	
44		Guide gasket	4	1.00	1	1	4	
45	Door	Left hinge 1	4	1.00	1	1	4	70.3
46		Right hinge 1	4	1.00	1	1	4	
47		Bracket 1	4	0.50	1	1	2	
48		Dispenser	4	0.50	1	1	2	
49		Bracket 2	4	1.00	1	1	4	
50		Front cover	4	0.50	0.5	1	1	
51		Door liner	4	0.50	1	1	2	
52		Blower	4	0.50	0.5	1	1	
53		Blower gasket	4	1.00	1	1	4	
54		Blower cover 1	4	1.00	1	1	4	
55		Blower cover 2	4	1.00	1	1	4	
56		Vent	3	0.67	1	1	2	
57	Control panel	Control panel	4	0.50	0.5	0.5	0.5	27.3
58		Control button 1	4	0.50	1	1	2	
59		Panel decoration	2	0.50	1	1	1	
60		Window 1	4	0.50	0.5	1	1	
61		Window 2	2	0.50	1	1	1	
62		Damper	2	1.00	1	1	2	
63		Power switch Knob	4	0.50	0.5	1	1	
64		Control button 2	2	1.00	1	1	2	
65		Control button 3	2	1.00	1	1	2	
66		Control plate	2	0.50	1	1	1	
67		Main PCB	4	0.50	0.5	1	1	
68		Display PCB 1	4	0.25	0.5	0.5	0.25	
69		Locker	4	0.50	0.5	1	1	
70		Handle	4	0.50	0.5	1	1	
71	Sump	Main nozzle	4	0.75	0.75	1	2.25	91.0
72		Multi harness	4	0.25	0.5	0.5	0.25	
73		Sump holder 1	4	1.00	1	1	4	
74		Motor damper	4	1.00	1	1	4	
75		Sump gasket	4	1.00	1	1	4	
76		Sump	4	1.00	1	1	4	
77		Damper 1	4	1.00	1	1	4	
78		Motor gasket	4	1.00	1	1	4	
79		Sump guide cover	4	1.00	1	1	4	
80		Check valve	4	1.00	1	1	4	
81		Stepping motor	4	1.00	1	1	4	
82		Micro switch	4	1.00	1	1	4	
83		Switch cam	4	1.00	1	1	4	
84		Sump holder 2	4	1.00	1	1	4	
85		Sump packing	4	1.00	1	1	4	
86		Pump motor	4	1.00	1	1	4	
87		Washer motor	4	1.00	1	1	4	
88		Motor case	4	1.00	1	1	4	

Table 7 continued

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI$_k$
89		Motor bracket	4	1.00	1	1	4	
90		Mesh filter 1	4	0.75	1	1	3	
91		Mesh filter 2	4	1.00	1	1	4	
92		Mesh filter 3	4	1.00	1	1	4	
93		Mesh filter 4	4	0.75	1	1	3	
94		Sump case 1	4	1.00	1	1	4	
95		NTC thermistor	4	1.00	1	1	4	
96		Micro switch	4	1.00	1	1	4	
97		Safety switch	2	1.00	1	1	2	
98	Base	Cabinet base 1	4	0.50	1	1	2	75.5
99		Lower cover	4	0.50	1	1	2	
100		Drain hose 1	4	1.00	1	1	4	
101		Inlet hose	4	0.50	0.5	0.5	0.5	
102		Connector hose	2	1.00	1	1	2	
103		Damper 2	4	1.00	1	1	4	
104		Inlet valve	2	1.00	1	1	2	
105		Power cord	4	1.00	1	1	4	
106		Capacitor	4	1.00	1	1	4	
107		Cabinet base 2	4	1.00	1	1	4	
108		Leg	4	1.00	1	1	4	
109		Leg bush	4	1.00	1	1	4	

Table 8 Family of dishwashers released in 2009–2010

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI$_k$
1	Cabinet	Top plate	4	0.75	1	1	3	74.6
2		Cabinet 1	4	0.75	1	1	3	
3		Cabinet 2	4	0 75	1	1	3	
4	Upper rack	Middle nozzle	4	0.75	0.75	1	2.25	71.3
5		Guide 1	4	1	1	1	4	
6		Upper rack 1	4	0.5	1	1	2	
7		Upper rack 2	2	0.5	1	1	1	
3		Rack handle deco-1	3	1	1	1	3	
9		Rack handle 1-1	3	1	1	1	3	
10		Rack handle 2-1	3	1	1	1	3	
11		Rack holder 1	3	1	1	1	3	
12		Rack holder 2-1	4	1	1	1	4	
13		Rack holder 3-1	4	1	1	1	4	
14		Upper rack 3	4	0.5	1	1	2	
15		Upper rack 4	2	1	1	1	2	
16		Rack guide 1	4	1	1	1	4	
17		Rack guide 2	4	1	1	1	4	
18		Upper rack 5	2	1	1	1	2	

Table 8 continued

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI$_k$
19	Lower rack	Rack handle deco-2	3	1	1	1	3	71.2
20		Rack handle 1-2	3	1	1	1	3	
21		Rack handle 2-2	3	1	1	1	3	
22		Spoon basket	4	0.75	1	1	3	
23		Lower rack 1	4	0.5	1	1	2	
24		Rack roller	4	0.75	0.75	1	2.25	
25		Lower rack 2	4	0.75	1	1	3	
26		Rack holder 2-2	4	1	1	1	4	
27		Rack holder 3-2	4	1	1	1	4	
28		Lower rack 3	3	0.667	0.667	1	1.333	
29		Rack holder 4	3	1	1	1	3	
30	Third rack	Tray	2	1	1	1	2	46.7
31		Third rack	2	1	1	1	2	
32		Rack guide 3	2	1	1	1	2	
33		Rack guide 4	2	1	1	1	2	
34		Rack holder 5	2	1	1	1	2	
35	Tub	Tub	4	0.5	0.75	0.75	1.125	74.7
36		Balance Weight	4	0.75	0.75	1	2.25	
37		Frame holder	4	1	1	1	4	
38		Bushing	3	1	1	1	3	
39		Upper nozzle	4	0.75	0.75	1	2.25	
40		Top frame	4	0.5	1	1	2	
41		Hinge spring	4	0.75	1	1	3	
42		Connector	4	1	1	1	4	
43		Rail 2	3	1	1	1	3	
44		Rail l	3	1	1	1	3	
45		Roller stopper l	4	1	1	1	4	
46		Roller	3	1	1	1	3	
47		Roller stopper 2	4	1	1	1	4	
48		Roller stopper 3	4	1	1	1	4	
49		Tub packing	4	0.75	1	1	3	
50		Locker	4	1	1	1	4	
51		Guide 2	4	0.5	0.75	1	1.5	
52		Nozzle guide	3	1	1	1	3	
53		Rail 3	3	1	1	1	3	
54	Air guide	Sensor	4	1	1	1	4	100.0
55		Air guide	4	1	1	1	4	
56		Common nut	4	1	1	1	4	
57		Guide gasket	4	1	1	1	4	
58	Door	Left hinge 1	4	0.75	1	1	3	64.2
59		Right hinge 1	4	0.75	1	1	3	
60		Bracket 1	4	0.75	1	1	3	
61		Dispenser	4	1	1	1	4	
62		Bracket 2	4	1	1	1	4	
63		Front cover	4	0.5	0.5	1	1	
64		Door liner	4	0.5	0.75	1	1.5	
65		Blower	4	0.5	0.75	1	1.5	
66		Blower gasket	4	0.75	0.75	1	2.25	
67		Blower cover 1	4	0.75	0.75	1	2.25	
68		Vent	4	0 75	1	1	3	

Table 8 continued

No.	Assembly	Component	n_i	f_1	f_2	f_3	$n_i * f_1 * f_2 * f_3$	PCI_k
69	Control panel	Handle deco	3	0.667	0.667	1	1.333	31.5
70		Control panel	4	0.25	0.5	0.5	0.25	
71		Control button 1	4	0.5	1	1	2	
72		Window 1	4	0.25	0.5	1	0.5	
73		Window 2	2	1	1	1	2	
74		Power switch knob	3	0.667	1	1	2	
75		Control button 2	4	0.5	0.5	0.5	0.5	
76		Control button 3	4	0.25	1	1	1	
77		Main PCB	4	0.25	0.25	1	0.25	
78		Display PCB 1	4	0.5	0.5	0.5	0.5	
79		Locker	4	1	1	1	4	
80		Handle	4	0.5	0.75	1	1.5	
81	Sump	Main nozzle	4	0.75	0.75	1	2.25	67.3
82		Multi harness	4	0.25	0.75	0.75	0.563	
83		Sump holder 1	4	0.75	1	1	3	
84		Sump gasket	4	1	0.75	1	3	
85		Sump	4	0.75	0.75	0.75	1.688	
86		Check valve	4	0.75	1	1	3	
87		Stepping motor	4	0.5	0.75	1	1.5	
88		Micro switch	4	1	1	1	4	
89		Switch cam	4	0.75	1	1	3	
90		Sump holder 2	4	0.75	0.75	1	2.25	
91		Sump packing	4	1	1	1	4	
92		O-Ring	2	1	1	1	2	
93		Pump motor	4	1	1	1	4	
94		Washer motor	4	0.75	0.75	0.75	1.688	
95		Mesh filter 1	4	0.75	1	1	3	
96		Mesh filter 2	4	0.75	1	1	3	
97		Mesh filter 3	4	0.75	1	1	3	
98		Mesh filter 4	4	0.75	1	1	3	
99		Heater	3	1	1	1	3	
100		Sensor	3	0.667	1	1	2	
101		Cover	3	1	1	1	3	
102		Sump case 2	3	1	1	1	3	
103		Sump case 3	3	1	1	1	3	
104		Impeller	3	1	1	1	3	
105		Drain hose 2	3	1	1	1	3	
106	Base	Cabinet base 1	4	0.75	0.75	0.75	1.688	73.7
107		Lower cover	4	0.75	1	1	3	
108		Drain hose	4	0.75	1	1	3	
109		holder	4	0.75	1	1	3	
110		Filter	3	1	1	1	3	
111		Inlet hose 1	4	0.75	1	1	3	
112		Lower frame	2	1	1	1	2	
113		Damper 1	4	1	1	1	4	
114		Damper	4	0.75	0.75	1	2.25	
115		Safety switch	4	1	1	1	4	
116		Power cord	4	1	1	1	4	
117		Cabinet ease 2	4	0.75	0.75	0.75	1.688	
118		Leg	4	1	1	1	4	

Appendix 2: DSM of the platform architecture for each family of dishwashers

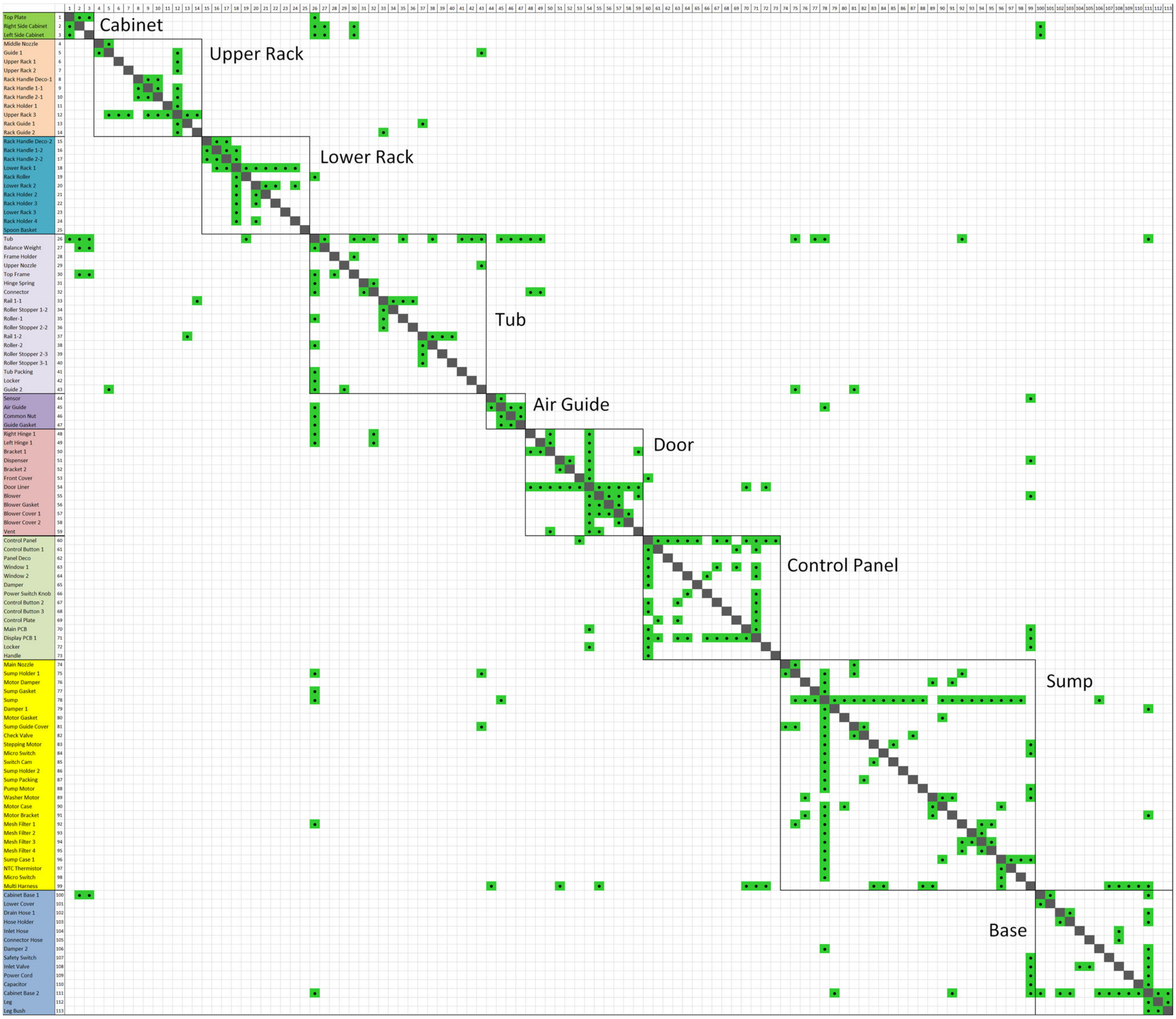


Fig. 11 Family of dishwashers released in 2006–2007: DSM with only direct connections between components

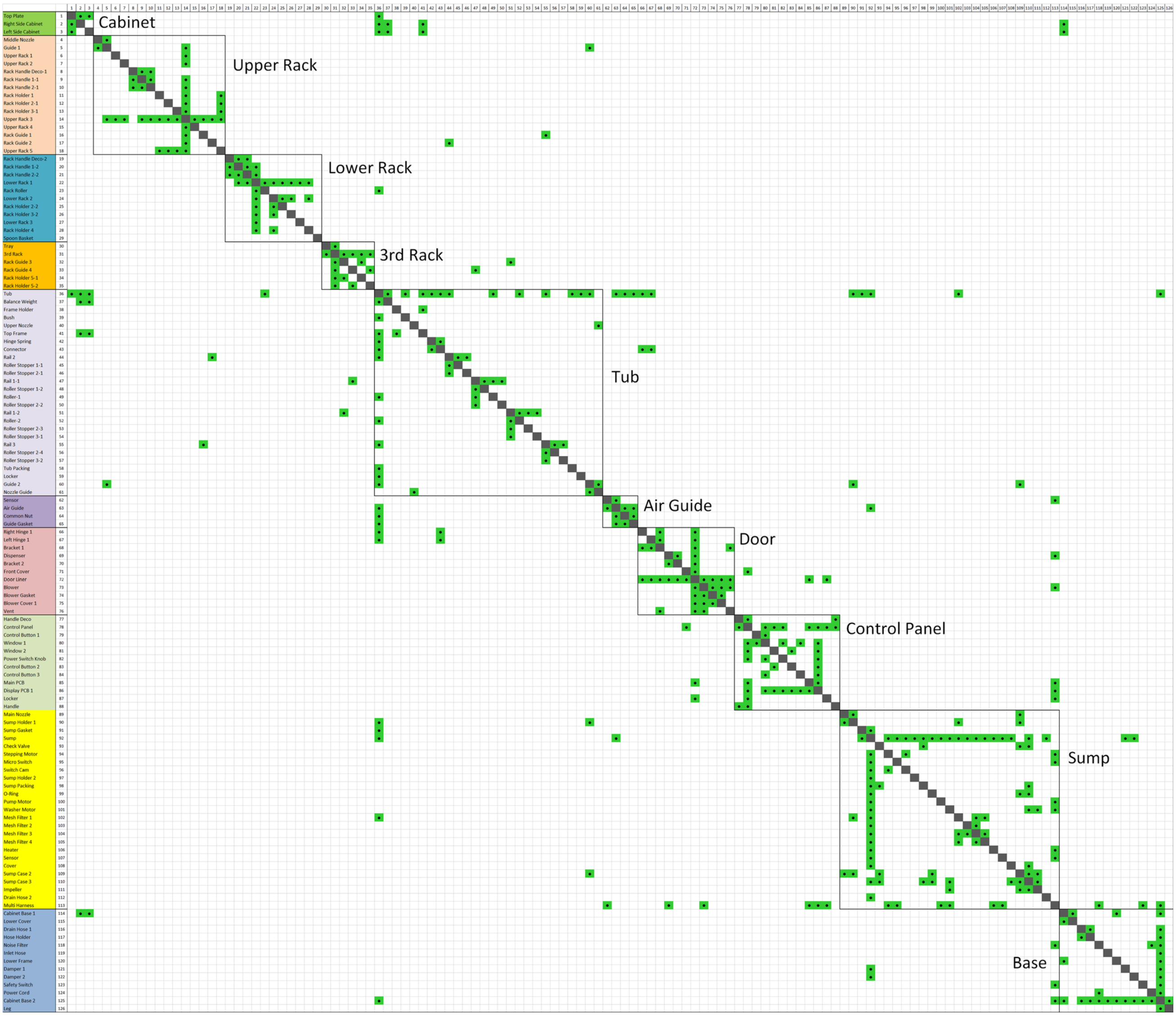


Fig. 12 Family of dishwashers released in 2009–2010: DSM with only direct connections between components

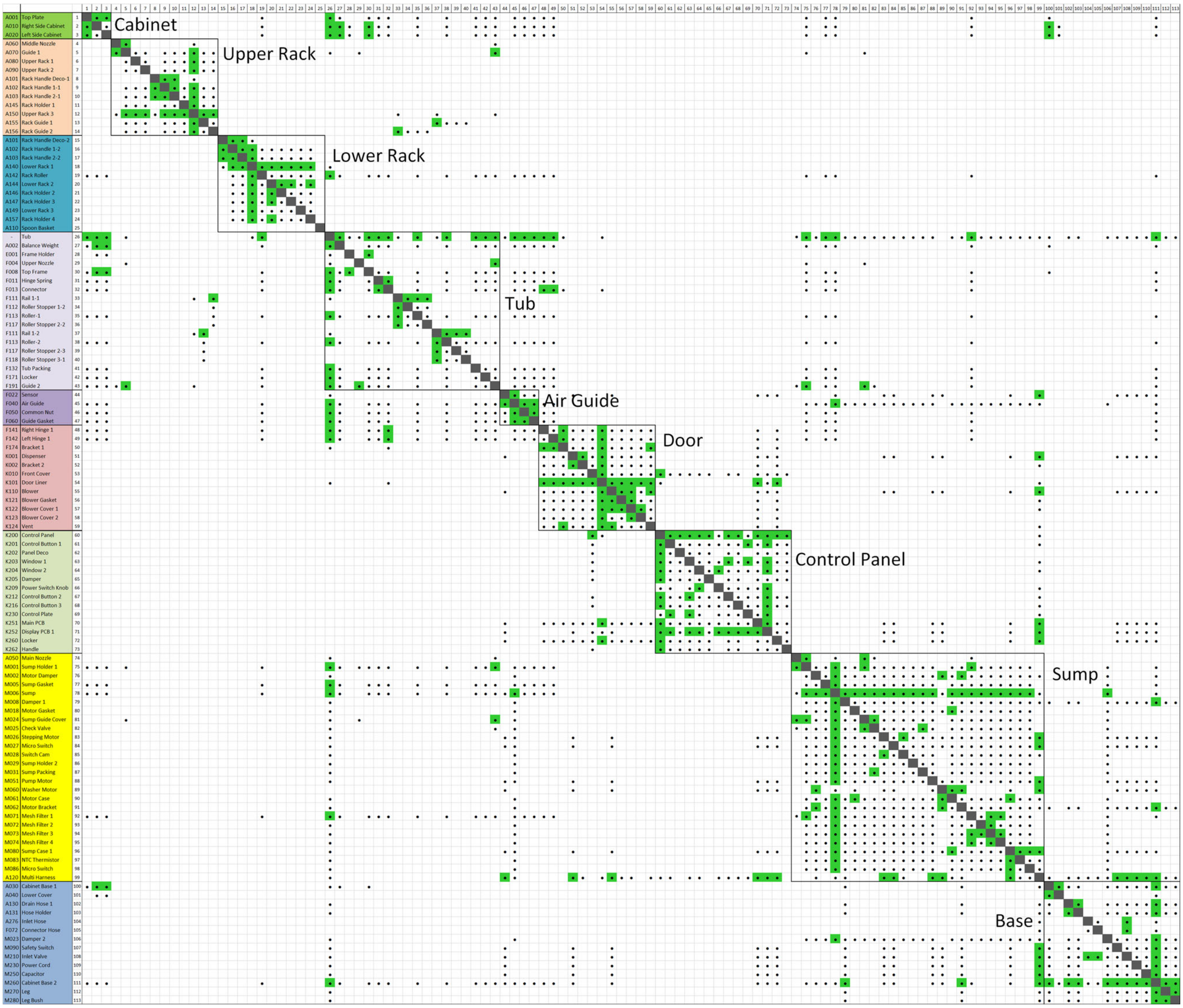


Fig. 13 Family of dishwashers released in 2006–2007: DSM with direct and indirect connections between components (the *dot* within a *green cell* indicates a direct connection between the corresponding components, and the *dot within a white cell* indicates that there exists an indirect connection between the two components)

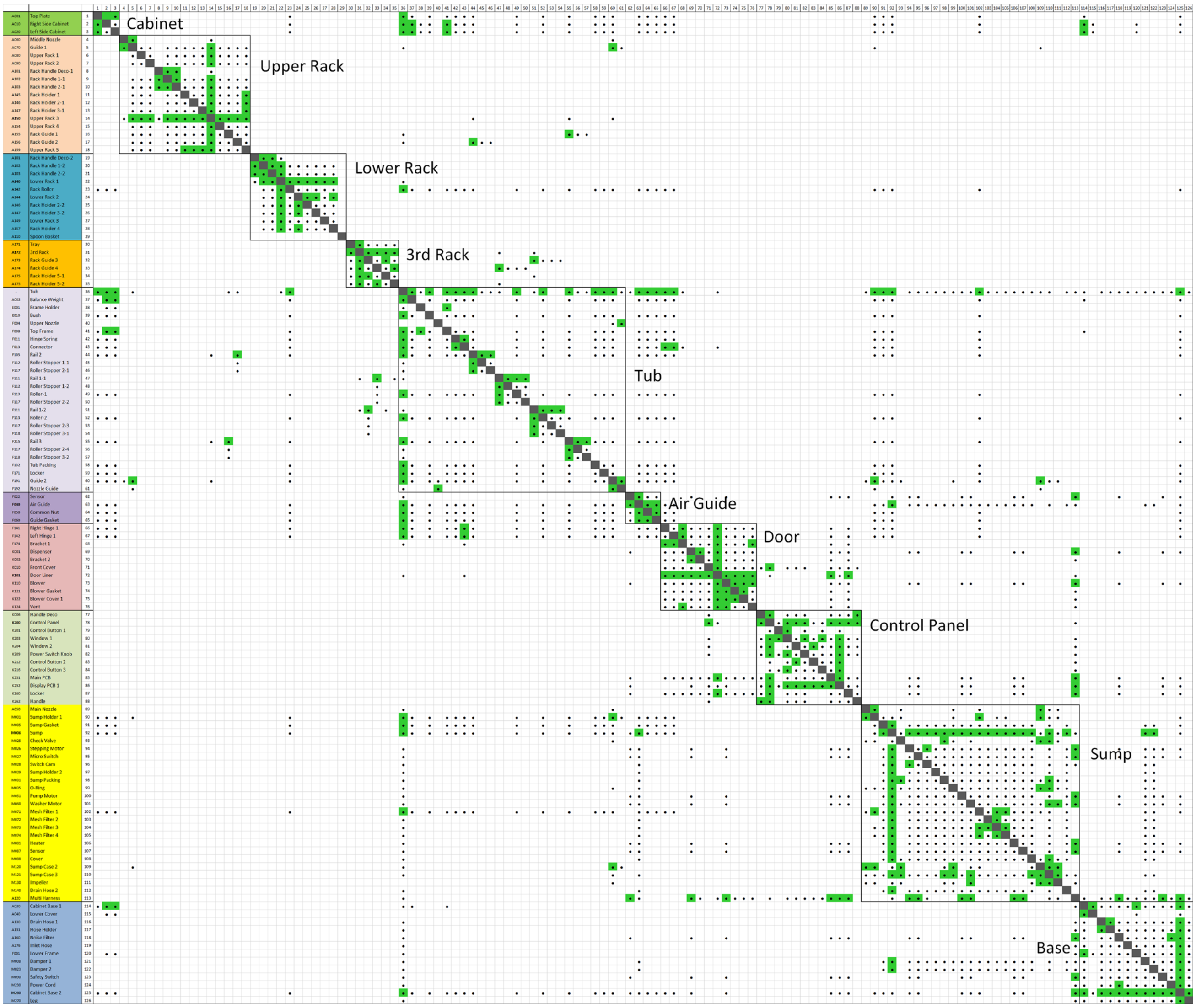


Fig. 14 Family of dishwashers released in 2009–2010: DSM with direct and indirect connections between components (the *dot within a green cell* indicates a direct connection between the corresponding components, and the *dot within a white cell* indicates that there exists an indirect connection between the two components)

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