Design for variety: developing standardized and modularized product platform architectures

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Abstract Developing a robust, product platform architecture brings an important competitive advantage to a company. The major benefits are reduced design effort and time-to-market for future generations of the product. This paper describes a step-by-step method that aids companies in developing such product platform architectures. Using the concept of specification "flows" within a product development project, the design for variety (DFV) method develops two indices to measure a product's architecture. The first index is the generational variety index (GVI), a measure for the amount of redesign effort required for future designs of the product. The second index is the coupling index (CI), a measure of the coupling among the product components. The design team uses these two indices to develop a decoupled architecture that requires less design effort for follow-on products. This paper describes the DFV method and uses a water cooler example to illustrate the method.

Keywords Product platform, Architecture, Design, Modularity, Coupling

1
Introduction

1.1
Related literature

Design for variety (DFV) is a series of structured methodologies to help design teams reduce the impact of variety on the life-cycle costs of a product (Martin and Ishii 1996, 1997). In addition, various authors have explored

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issues dealing with the strategic benefits of developing product platforms and the management of families.

Pine (1993) discussed the need for product variety in today's marketplace. Sanderson and Uzumeri (1995) used a case study of the Sony Walkman to show how understanding the market, the use of "strong" design, the effective division of labor, and manufacturing flexibility aid in rapid model development. Sanderson (1991) considered how design management strategy affects design costs.

Robertson and Ulrich (1998) discussed planning for product platforms. They encouraged the use of platform development early on and stated that it must include consideration of marketing, design, and manufacturing issues. Maier and Fadel (2001) looked at the early stages of product family design to help designers choose appropriate manufacturing and design strategies. Claesson et al. (2001) modeled product platforms using configurable components.

Galsworth (1994) describes the variety effectiveness program (VEP), a methodology to help companies decrease the complexity of variety. She used six analysis tools in VEP to help guide companies, covering the areas of: unique versus shared parts, modularity, reduction of part count, design for assembly, range of component specifications, and trends in product and component specifications.

Dahmus and Otto (2001) considered the effect of serviceability costs on developing a product architecture. Blackenfelt (2000) used the quality loss function to help optimize the degree of variety within a product platform.

Fujita et al. (1998) used optimization techniques to estimate the best architecture for a family of aircraft. Adler et al. (1995, 1996) considered design as a stochastic processing network with engineering resources as workstations, and projects as jobs that flow between the workstations. Their process model provides a useful framework for understanding bottlenecks in designs and how changes may be made to reduce the bottlenecks.

Erens (1996) characterized development under functional, technology, and physical domains. He used this characterization to help develop product platforms. Gonzalez-Zugasti et al. (1998) used a metamodel of the technical performance requirements and costs to optimize the design of a family of spacecraft based on a common platform. Tseng and Jiao (1998) developed the product family architecture (PFA) model to handle the tradeoffs between diversity of customer requirements and reusability of design and process capabilities.

The literature review shows a growing interest in the area of product platform architectures. It also shows an

opportunity for a more detailed and prescriptive approach to developing product platforms. In Martin (1999), a detailed method was developed that aids the development team in creating a product platform architecture, which is easily updated in future generations. From this came the research presented in this paper. It gives a detailed, step-by-step approach to help a design team develop a product platform and applies the method to the example of a water cooler.

1.2
Definition of architecture

Ulrich (1995) referred to product architecture as the "scheme by which the function of a product is allocated to physical components." He defined it more precisely as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specification of the interfaces among interacting physical components. By definition, any product design meets all three of Ulrich's requirements for architecture. A design must have an arrangement of functional elements, a mapping between function and structure, and specified interactions among components. Thus, any design for a single product has an architecture.

A product family can also have an architecture. A family architecture implies that the different products have a common arrangement of elements, common mapping between function and structure, and common interactions among components. A product family architecture only exists if this commonality is present.

Our method seeks a structured approach that aids in developing the arrangement of functional elements, the function–structure mapping, and the interface specifications for a product family. In essence, the DFV method gives operational detail to Ulrich's architecture concept.

1.3
What is the goal of developing an architecture?

An architecture is developed for a product line to maximize the profit potential for the company. Our work seeks to aid engineers in creating designs that build on current design effort for future products and thus reduce development costs. These products will have architectures that require minimal changes to meet future marketplace needs. Meeting these future needs would be relatively simple in a deterministic world. However, the uncertainty in future customer needs, technology changes, competitor responses, and so on complicate the planning of a product that can build on, or leverage, current design efforts.

To develop a method that helps leverage the design effort, we first look at the factors external to the company that will cause a design to change over time. By understanding these "drivers" of change, we can begin to plan the product line such that it isolates components that are likely to change. This understanding will help minimize design effort for future products and make design structures common across generations. Section 2 discusses the generational variety index (GVI). Section 3 covers the coupling index (CI). Section 4 discusses how these indices are applied in the DFV method.

1.4
Product variety: spatial and generational

Two types of variety should be considered when developing the architecture of a product: variety within the current product line being designed, and variety across future generations of the product. We refer to the variety in the current product being designed as "spatial" variety. The variety across generations is referred to as "generational" variety. These terms are illustrated in Fig. 1. This paper focuses on developing a design that can be easily applied to future products (generational variety). However, the concepts can also be applied to spatial variety considerations.

2
Generational variety index

The generational variety index (GVI) is an indicator of which components are likely to change over time. The GVI is defined as:

The generational variety index (GVI) is an indicator of the amount of redesign required for a component to meet the future market requirements.

After reading this section the reader should understand and be able to duplicate the generational variety index. Figure 2 shows the process for calculating the GVI.

2.1
Drivers of generational changes

The GVI is based on an estimate of the required changes in a component from external (i.e. noncontrollable) factors. Examples of such external drivers are customer needs, reliability requirements, reduced prices, and so on. A more detailed listing is shown in Table 1. The changes in these external drivers can cause changes in the components over time. In this paper the external drivers are measured in the form of engineering metrics (EM).

Estimating the GVI is the first step, followed by the generation of the coupling index (described in Sect. 3). These two indices are then used in the DFV method. This method helps the team develop an architecture that can be easily applied to future generations. To demonstrate the DFV process, the example of a water cooler is used throughout this document. Only the major subsystems
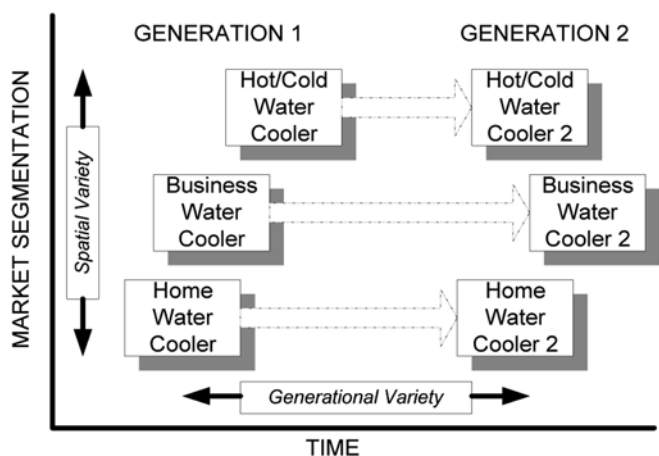

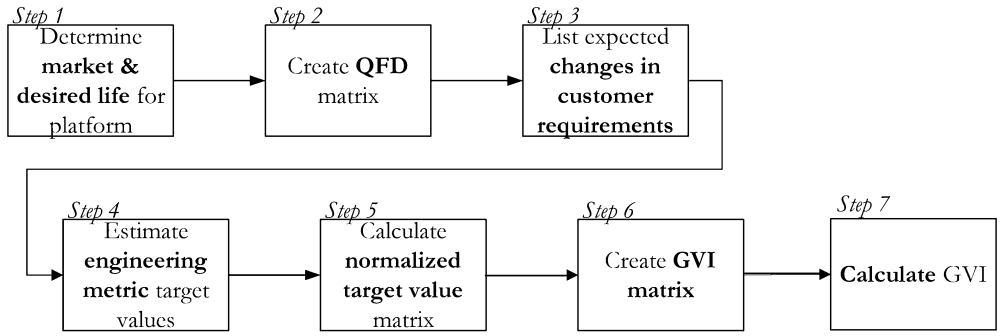**Fig. 1.** Spatial and generational variety

Fig. 2. Flow chart of generational variety index development

Table 1. External drivers of generational change

Customer requirements
Changing performance needs (including size, style, weight, etc.)
New environmental constraints (temperature, humidity, vibration, etc.)
New functions (due to new markets or new enabling technologies)
Reliability improvements
Reduced prices (cost reductions required)
Reduce amount of material
Change material type
Remove redundant components
Reduce assembly time
Use lower cost technology
Reduce serviceability requirements
Reduce serviceability time
Improve component manufacturing process
Regulations, standards, and so on
Changing government/industry regulations or standards
Competitor introduction of improved product (higher quality or lower price)
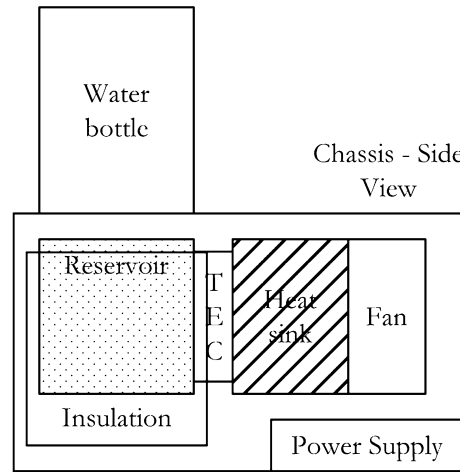Obsolescence of parts

Fig. 3. Schematic view of water cooler indicating component sub-systems

(referred to as "components" from here forward) of the cooler will be considered.

The components considered for the water cooler are the fan, heat sink, thermoelectric cooler (TEC),[1] power supply, chassis, plumbing, reservoir, insulation, and fascia (the plastic coverings). These basic components are outlined in Fig. 3.

2.2
Using quality function deployment for input

To generate the GVI, the team must first estimate what external drivers might require the product to change over time. Note that the time period considered is based on how long the team wishes the architecture to last.

To generate the GVI we use a modified quality function deployment (QFD, Hauser and Clausing 1988) structure. For this water cooler example, we consider customer requirements and cost to be the drivers of change. Changing regulations, standards, and so on could also be added to the matrix, if desired.

QFD phase I QFD phase I lists the customer needs and their relationship to engineering metrics. Items such as

"fast cool down," "cold water," "high capacity," and "low energy usage" are a few examples of the customer needs for this product. The engineering metrics for the various needs are measurable items such as "cool-down time," "water temperature," "cold water volume," and "power consumption." These are a translation of the subjective customer requirements into quantifiable engineering specifications (Fig. 4).

QFD phase II QFD phase II maps the engineering metrics to the components used in the design. The mapping for the water cooler example is shown in Fig. 5. An "X" indicates that the component can affect the engineering metric. In this example, the fan, heat sink, TEC, power supply, reservoir, insulation, and fascia all have an impact on the "cool-down time" metric. The fan also has an impact on the "power consumption" metric.

2.3
GVI steps

QFD phase II helps in developing the GVI. The GVI is used to estimate how much component redesign effort is required to meet the future engineering metrics. The GVI number will be different for different architectures.

A number of different approaches for determining the GVI were considered and tried, with the goal that it be easy to understand and to use. In the end, direct input from the team members was determined the best process. The method for determining the GVI is described below.

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[1] A thermoelectric cooler is a solid-state heat-pumping device. A current moving through an alternating series of *p*- and *n*-type semiconductor materials moves heat from one location to another, which is the reverse eect of a thermocouple.

Engineering Metrics

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

Fig. 4. GVI QFD phase I

Components

Engineering Metrics	Fan	Heat Sink	TEC	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

Fig. 5. QFD phase II

Table 2. Markets and introduction dates

Market	Description	Introduction date
–	Development Start	Jan-99
Current	Home (low water usage)	Sep-00
Future 1	Home (reduced energy usage)	Jun-01
Future 2	Business (high water usage)	Oct-01
Future 3	Home (reduced cost and smaller footprint)	Apr-02

GVI step 1: determine market and desired life of product platform An understanding of where the market is headed is critical to the DFV method. Also, the team must determine how long they would like the product platform to last. For the water cooler example, the period is two and a half years, and four different products are envisioned. Methods to map the future product plans were discussed by Wheelwright and Sasser (1989) and Wheelwright and Clark (1992). The markets that this water cooler platform is attempting to satisfy are shown in Table 2.

GVI step 2: create QFD matrix If not already available, create a simplified phase I and phase II QFD. See Figs. 4 and 5 for an example.

GVI step 3: list expected changes in customer requirements Add a column to phase I, estimating qualitatively (high/medium/low) the range of change for the customer requirements (Fig. 6). This simple step gets the develop-

ment team to think about how the customer needs are changing. "High" indicates that this is a rapidly changing customer need and that large changes will be required.

GVI step 4: estimate engineering metric target values In this step the engineering metric target values (EMTV) are determined for the period for which the product platform is being developed. The target values could be based on information from conjoint analysis, trend analysis, expected new markets, or expected competitor introduction of products. For this example, the estimated target values are estimated based on previous trends and marketing data. Formal methods, such as Yu et al. (1998), give a more detailed approach to estimating future target values. The estimated future values for the water cooler are shown in Fig. 7.

GVI step 5: calculate normalized target value matrix The GVI step 4 target values can be normalized (based on the current market target values) and plotted to visually represent the changes. This is an optional step and is shown in Fig. 8.

GVI step 6: create GVI matrix The GVI matrix is based on the QFD phase II matrix. To determine the GVI matrix the team uses its engineering expertise and judgment to estimate the cost of changing the component to meet the most stringent future EM target values. The GVI matrix uses a 9/6/3/1 rating system for these estimates (Table 3). For each EM/component node in the matrix, the team estimates the component redesign costs (including design effort,

Engineering Metrics

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 ($)	Expected range of change over platform life
Fast cool down	X										M
Cold water		X									L
High capacity			X								M
Low energy usage				X							M
Compact					X	X	X				L
Fill cup quickly								X			M
Reliable									X		L
Low cost										X	M

Fig. 6. QFD phase I with expected changes in customer requirements

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Engineering Metrics

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 ($)	Expected range of change over platform life
Fast cool down	X										M
Cold water		X									L
High capacity			X								M
Low energy usage				X							M
Compact					X	X	X				L
Fill cup quickly								X			M
Reliable									X		L
Low cost										X	M
EM Target Values	**CDT**	**WT**	**CWV**	**P**	**W**	**H**	**D**	**VFR**	**MTBF**	**$**	
Current Market	120	10	0.5	75	12.5	12.5	12.5	0.5	15,000	100	Sep-00
Future Market 1	120	10	0.5	50	12.5	12.5	12.5	0.5	15,000	100	Jun-01
Future Market 2	90	10	0.75	75	12.5	12.5	12.5	0.75	15,000	125	Oct-01
Future Market 3	120	10	0.5	75	10	12.5	10	0.5	15,000	80	Apr-02

Fig. 7. QFD phase I with EM target values added
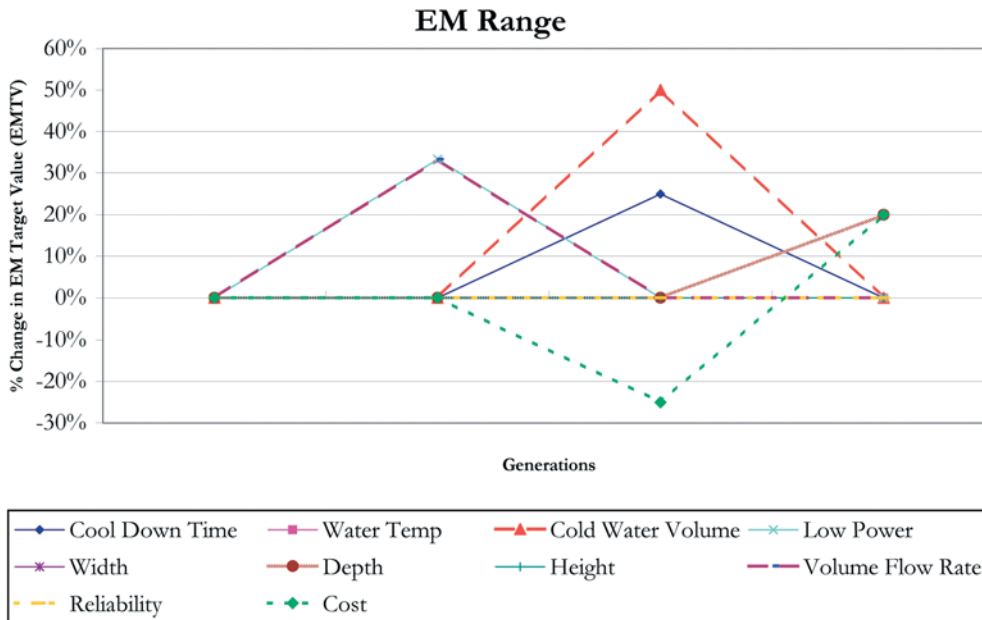
Fig. 8. Percentage change in EM normalized target values

tooling, and testing) required to meet the future target value for that engineering metric. These costs are expressed as a percentage of the original cost to design.

For instance, the "cool-down time" engineering metric starts at 120 min for the first generation and has its most stringent requirement of 90 min in future market 2. From QFD phase II, the team knows which components affect that EM. The team then decides which of these components require a major or partial redesign in order to meet the more stringent EM of 90 min. This is based on the

Table 3. GVI matrix rating system

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

engineering expertise and judgment of the team. An example of the phase II matrix with GVI input is shown in Fig. 9.

GVI step 7: calculate GVI The GVI for each component is calculated by summing each of the columns of the GVI matrix. The GVI calculation is shown in Fig. 10. The application of measurement theory concepts (Krantz and Suppes 1971) to the GVI shows that it maintains ordinal and ratio relationships. The GVI is an indicator of the level of component redesign that may be required to meet the future engineering metrics. For the water cooler example, the fascia (GVI=24) and reservoir (GVI=19) are the components that have higher percentage levels of redesign required to meet the future specifications.

3
Coupling index

As discussed in Sects. 2 and 3, there are various external drivers for changing a design. The changes created by

these external drivers may in turn require other changes within the design. Such changes do not directly enhance the value of the product, except to the extent that they support the initial changes. These changes are created by the interaction, or "coupling," within the design. It quickly became apparent that understanding coupling within a design was crucial for developing architectures robust to future changes in customer requirements. The definition of coupling (Ulrich 1995) used in this paper is:

> Two components are considered coupled if a change made to one of the components can require the other component to change.

This section develops our coupling index (CI), which is defined as:

> The coupling index indicates the strength of coupling between the components in a product. The stronger the coupling between components, the more likely a change in one will require a change in the other.

Developing the coupling index is done by considering the "specification flows" among components. These specification flows are defined as the design information that must be passed between designers to design their respective components. By mapping out the specification flows early in the design process, the team explicitly describes the relationships that couple the parts. Figure 11 shows the process for calculating the coupling index.

Components

Engineering Metrics	Fan	Heat Sink	TEC	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

Fig. 9. Phase II matrix with GVI input

Components

Engineering Metrics	Fan	Heat Sink	TEC	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

Fig. 10. GVI calculation

CI step 1: develop basic physical layout for the product In order to generate the CI for a product, the basic technology to be used and the general layout of the product must be known. Without this, it would be difficult to determine how subsystems, subassemblies, or parts are coupled.

Once this basic information is determined, development of the CI can begin. As more detail is brought to the design, the CI will evolve as new linkages between components are added and deleted. An example of the initial water cooler layout to be considered is found in Fig. 3.

CI step 2: draw control volume around components A control volume (CV) is a boundary around a system indicating the flows into and out of that system. For the DFV method, the control volumes are "drawn" around each component. If possible, these control volumes should be approximately at the same level of complexity (i.e. do not list a "screw" as one component and a "power supply" as another). In the water cooler example, CV's are drawn around the chassis, fascia, heat sink, and so on.

CI step 3: list specification flows required between components For each control volume, have the engineers list the specifications they need to *receive* from each of the other control volumes. Also have the engineers list the specifications that they expect to *supply* to each of the other control volumes. Do not assume any precedence among the components during this stage.

Reconcile the differences between these specification flows. Put the specification flows into matrix form. The top row of the matrix lists the components *supplying* the information; the left column lists the components *receiving* (or requiring) the information. Figure 12 shows the specification flows between the fan, heat sink, and TEC. For example, the team has determined that changes in the "pressure curve" and "*X/Y*-dimension" specifications for the fan can cause changes in the design of the heat sink.

CI step 4: build a graphical representation of the specification flows The next step is to build a graphical representation of the flows. This is optional but is useful in visualizing the flows between components (Fig. 13). The listing of supplied and required information is useful for both spatial and generational variety. Those components that supply numerous specifications to other components are items that the design team would like to keep static in order to minimize redesign effort. The next steps are to determine a quantification index for the specification flows.

CI step 5: estimate sensitivity of components to changes For each specification, the team estimates the sensitivity of each component to a small change in that
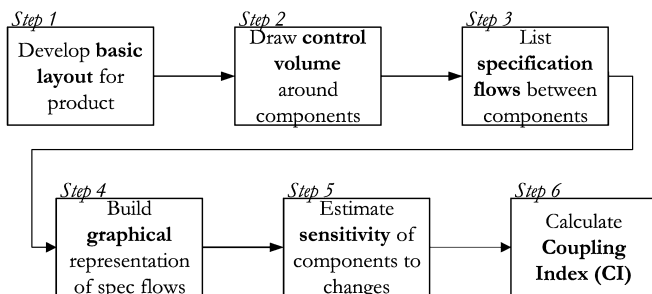

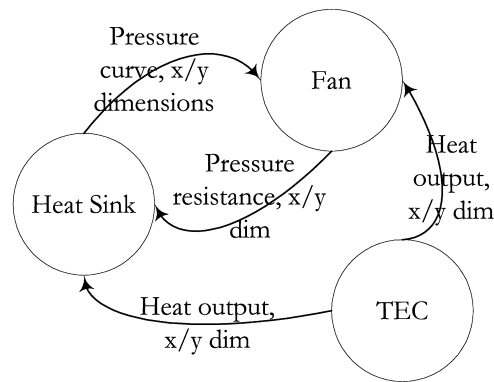**Fig. 12.** Partial CI matrix showing specification flows

Fig. 13. Graphical representation of specification flows

specification. If a small change in the specification requires a change in the component, then the component has a high sensitivity. If the specification requires a large change to create a change in the receiving component, then it has a low sensitivity. The high sensitivity specifications are given a rating of 9, and the low sensitivity specifications are given a rating of 1. Table 4 lists the descriptions of the numerical ratings.

For this rating system, it is assumed that the "impact" caused by a specification change is equivalent and linear across all components. Figure 14 shows the sensitivity rating applied to a portion of the water cooler example. For example, even a small change in the heat sink "pressure resistance" requires a change in the fan, since the pressure resistance is a critical specification in determining which fan will be used. Therefore the heat sink pressure resistance specification has a high (9) sensitivity.

CI step 6: calculate coupling index From the coupling matrix, two indices are derived. The sum for a column indicates the strength of the information supplied by that component to other components and is referred to as the

Fig. 11. Flow chart of coupling index development

Table 4. CI rating system for sensitivity of specifications

Rating	Description
9	Small change in specification impacts the receiving component (high sensitivity)
6	Medium-high sensitivity
3	Medium-low sensitivity
1	Large change in specification impacts the receiving component (low sensitivity)
0	No specifications affecting component

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Components SUPPLYING Information

	Fan	Heat Sink	TEC
Fan		Press resist 9 x dim 3 z dim 3	Heat output 3 x dim 1 z dim 1
Heat Sink	Pressure curve 3 x dim 3 z dim 3		Heat output 3 x dim 3 z dim 3
TEC		Heat sink cond 3 Effective HS area 3	

(Components REQUIRING Information — left axis label)

Fig. 14. Partial CI matrix of specification flows showing sensitivity ratings

Components SUPPLYING Information

	Fan	Heat Sink	TEC	CI-R
Fan		Press resist 9 x dim 3 z dim 3	Heat output 3 x dim 1 z dim 1	20
Heat Sink	Pressure curve 3 x dim 3 z dim 3		Heat output 3 x dim 3 z dim 3	18
TEC		Heat sink cond 3 Effective HS area 3		6
CI-S	9	21	14	44

(Components REQUIRING Information — left axis label)

Fig. 15. Partial CI matrix showing coupling indices

coupling index–supply (CI–S). The sum for a row is information being received by each component and is referred to as the coupling index–receive (CI–R). These indices are defined below:

The coupling index–receiving (CI–R) indicates the strength (or impact) of the specifications that a component receives from other components.
The coupling index–supplying (CI–S) indicates the strength (or impact) of the specifications that a component supplies to other components.

For each column and row, the sensitivities are summed (Fig. 15). In this example, the CI–S for the TEC is 21, which means that its design has a relatively strong impact on other components in this matrix. The fan has a relatively high CI–R, indicating the other components have a strong impact on it.

The CI–S and CI–R indicate how tightly coupled a component is. A high CI–S indicates that the component supplies a great deal of necessary information to other components. If that component is changed, it has a higher likelihood of causing changes in other components. A high CI–R for a component indicates a higher likelihood it will require changes because other components were changed. The full coupling index results for the water cooler example are shown in Fig. 16.

As shown in Fig. 16, the reservoir has the largest CI–S, indicating that it is very tightly coupled within the design. Under the current architectural concept, a change in this component has a strong potential for requiring changes in other components. The drivers of this large CI–S are: (1) the reservoir supplies many specifications to other components, and (2) many of the components requiring these specifications are sensitive to any changes.

4
Design for variety method

The mechanics of developing the generational variety index (GVI) and coupling index (CI) are in themselves important processes, which give the project team a more explicit understanding of the external drivers of change and of how changes may propagate throughout the design. This section describes how these indices are further used to develop a product platform architecture that is more robust to changes from the external environment. The generation of the GVI and CI and their application to architecture development constitutes the design for variety (DFV) method. The method uses the indices to focus on the most critical areas in developing the architecture.

Sections 2 and 3 looked at the reasons a component changes over time. As discussed, there are two causes for a component to change: external drivers (measured by the GVI), and internal drivers (measured by the CI–R). The external drivers come from areas outside the design team's control (changing customer requirements, regulations, competitor introductions, and so on). The internal drivers come from the coupling between the product components. These drivers are illustrated in Fig. 17.

4.1
DFV method steps

DFV step 1: generate GVI and CI for the design As described in Sects. 2 and 3, the generational variety index and coupling indices are generated for the product.

Components SUPPLYING Information

Components REQUIRING Information	Fan	Heat Sink	TEC	Power Supply	Chassis	Plumbing	Reservoir	Insulation	Fascia	CI-R
Fan		Press resist 9; x dim 3; z dim 3	Heat output 3; x dim 1; z dim 1	Voltage 9; P-P voltage 1	Strength 1; Mounting points 3; x dim 1; y dim 9; z dim 1		Volume 3		Vent area 3; Thickness 1	52
Heat Sink	Pressure curve 3; x dim 3; z dim 3		Heat output 3; x dim 3; z dim 3		Strength 1; Mounting points 3; x dim 6; y dim 6; z dim 1		Absorptivity 1; Volume 6	y dim 3	Vent area 3; Vent location 3	51
TEC		Heat sink cond 3; Effective HS area 3		Voltage output 9; P-P voltage 3			Conductivity 3; x dim 1; z dim 1; Volume 6	y dim 3; Conductivity 3		35
Power Supply	Voltage 9		Imax 3; Resistance 3		Strength 1; Mounting points 1; x dim 1; y dim 1; z dim 1				Vent area 1; Vent location 3	24
Chassis	Weight 1; x dim 1; y dim 3; z dim 1; Mounting holes 9; x location 1; y location 3; z location 1	Weight 3; x dim 1; y dim 9; z dim 1; Mounting holes 9; x location 3; y location 3; z location 1		Weight 3; x dim 1; y dim 1; z dim 1; Mounting holes 9; x location 1; y location 1; z location 1			Weight 3; x dim 9; y dim 9; z dim 3; Mounting holes 9; x location 9; y location 9; z location 3	x dim 1; y dim 3; z dim 1	Weight 1; x dim 3; y dim 3; z dim 3; Mounting holes 9; x location 3; y location 3; z location 3	155
Plumbing							Water height 1; x location 3; y location 3; z location 3; Hole diameter 3	z dim 3	Hole x loc 3; Hole z loc 3; Hole radius 3	25
Reservoir		Radiance 1	Heat pumping 3; x dim 1; z dim 1		Strength 3; Mounting points 9; x dim 6; y dim 6; z dim 3	Diameter 3; Fitting type 9		x dim 3; y dim 3; z dim 3; Conduct. 3		57
Insulation	Airflow direction 3		y dim 1				x dim 9; y dim 9; z dim 9; Conduct. 1; Volume 3			35
Fascia	Flow rate 3; Airflow direction 3; x dim 1; y dim 3; y location 3	Max temp 1		Max temp 1; Heat output 3	Strength 3; Mounting points 9; x dim 9; y dim 6; z dim 9	Diameter 3; x location 6; z location 6		Thickness 1		70
CI-S	54	53	26	44	100	27	119	30	51	504

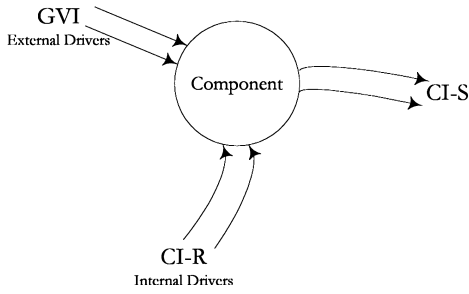**Fig. 16.** Complete CI matrix including indices

Fig. 17. Illustration of drivers of component change

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DFV step 2: order the components

- Rank order the GVI: based on the GVI, rank order the components from highest to lowest. These are the components that are most likely to change over the product platform time period due to external drivers. The results for the water cooler are shown in Table 5.
- Include coupling indices: add coupling indices for each of the components as shown in Table 6.

Graphical aids A useful task is to plot the indices from the DFV method as a visual aid. Figure 18 shows the CI–R plotted against the GVI. Since the GVI is a measure of the strength of the external drivers of change, and the CI–R is a measure of the internal drivers, this graph is an overall indicator of how much a component is expected to change.

The "bubble" graph in Fig. 19 adds CI–S to the graph, represented as the size of the bubble. The GVI and CI–R are compared against the CI–S because they are indicators of how much the component is expected to change, and the CI–S is a measure of how likely those changes are to propagate. Figure 19 shows the reservoir with a relatively large CI–S bubble, which means changes to the reservoir have a relatively high strength of propagation.

Table 5. Rank ordering of GVI

Component	GVI
Fascia	24
Reservoir	19
Chassis	15
Plumbing	9
Heat sink	7
TEC	6
Power supply	5
Fan	4
Insulation	1

Table 6. GVI and CI, and design costs

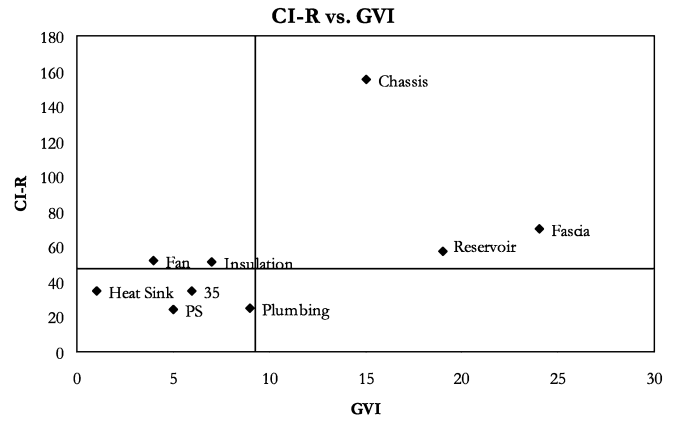| Component	GVI	CI–R	CI–S
Fascia	24	52	51
Reservoir	19	42	101
Chassis	15	155	34
Plumbing	9	25	33
Heat sink	7	32	53
TEC	6	29	26
Power supply	5	21	44
Fan	4	38	54
Insulation	1	32	30

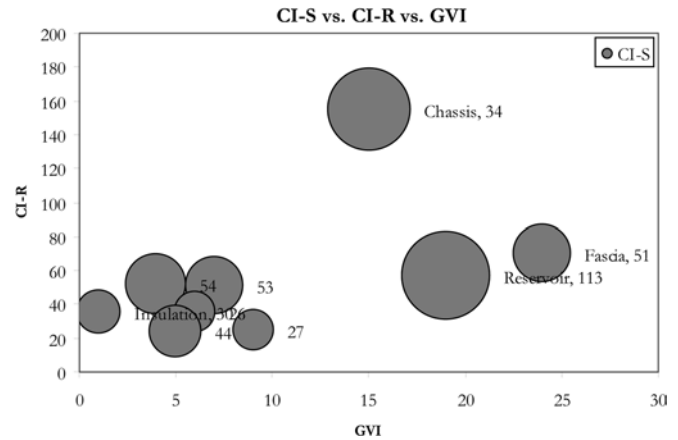Fig. 18. CI–R versus GVI (water cooler)

Fig. 19. CI–S versus CI–R versus GVI (water cooler)

DFV step 3: determine where to focus efforts (ie. where to standardize and/or modularize) After the generation of the GVI and CI, the team is ready to begin making changes to the product architecture to develop a product platform that can be more easily applied to future product generations. Before continuing, it is important to remember the significance of each of the indices. The GVI is an indicator of the expected amount of redesign required for a component to meet the future market requirements. The coupling index–receiving (CI–R) is an indicator of the likelihood that a component will change when other components are redesigned. The coupling index–supplying (CI–S) is an indicator of the likelihood that changing a component will require redesign of other components.

In order to visually aid the ranking of the components on which we should focus, the components are categorized into high/low categories. For the water cooler, there are four components (fascia, reservoir, chassis, and plumbing) that have GVI greater than 9, meaning an estimated 50% redesign is required. These we denote as high (H) GVI. For the CI, we demarcate the high/low based on the average of the CI, which is approximately 50 for the water cooler. This gives the categorizations shown in Table 7. Note that the categorization process is not necessary and is only used to visually help in the ranking. If used, the demarcation line between high/low can be

Table 7. Component categorization for water cooler, including NRE costs

Component	GVI	CI–R	CI–S	NRE $
Fascia	H	H	H	200,000
Reservoir	H	L	H	10,000
Chassis	H	H	L	40,000
Plumbing	H	L	L	1000
Heat sink	L	L	H	10,000
TEC	L	L	L	3000
Power supply	L	L	L	3000
Fan	L	L	H	2000
Insulation	L	L	L	2000

Table 8. Rank ordering of components based on GVI, CI–R, CI–S, and NRE costs

Component	GVI	CI–R	CI–S	NRE $	Rank
Reservoir	H (24)	H (52)	H (51)	10,000	3
Fascia	H (19)	L (42)	H (101)	200,000	1
Chassis	H (15)	H (155)	L (34)	20,000	2
TEC	H (9)	L (25)	L (33)	3000	6
Plumbing	L (7)	L (32)	H (53)	1000	8
Fan	L (6)	L (29)	L (26)	2000	7
Heat sink	L (5)	L (21)	L (44)	10,000	4
Power supply	L (4)	L (38)	H (54)	3,000	5
Insulation	L (1)	L (32)	L (30)	2,000	9

modified as necessary. The team could choose the median, the top quartile, and so on as the demarcation.

Note that the nonrecurring engineering (NRE) costs for designing the difference components have been included. One of the assumptions made in developing the component categorizations was that the components were of equivalent design complexity (and thus, cost). For the water cooler example, this is not the case. Components such as the fascia and chassis have high development and tooling costs that overshadow the NRE costs of the other components. For such products, these costs must be considered in determining the components to focus on for architectural changes.

In Martin (1999) a detailed heuristic is shown to help the team decide which components should be standardized or modularized to create a robust product platform architecture. For this paper, a much-condensed description is given. In general, the team would like to standardize all the components. This translates into a product that can meet all the market requirements without having to be redesigned. Since this is generally not possible from a technical standpoint, or because the unit cost becomes prohibitively expensive, some method to decide which components to standardize is needed. Note that standardization involves reducing the GVI and CI–R to zero. This means that no external (GVI) or internal (CI–R) couplings will require the component to change in the future, thus assuring standardization.

For standardization, those components that have high design costs and high GVI should be focused on first, since these are the components that are most likely to require expensive changes due to the (uncontrollable) changing customer requirements. Another consideration is to standardize high CI–S components since they have a high potential for causing changes in other components. Based on this general approach, the components for the water cooler example are ranked in Table 8.

DFV step 4: develop product platform architecture Up to this point, the DFV method has covered descriptive measures of the design. This fourth and final step of DFV applies a prescriptive approach to improve the architecture of the product. It will help the team make decisions on both how to rearrange the mapping between the physical components and functions, and how to define interfaces. These are points 2 and 3 of Ulrich's definition of architecture. We do not address point 1 since we assume a decision has been made on the basic functions of the design.

4.2
Standardization and modularization

In general terms, the goal of the team is to design the product platform architecture so that as much of the design as possible is standardized across generations. For the parts of the design that cannot be standardized, the team would like to modularize them. Definitions of these terms follow.

1. Standardized (GVI and CI–R related)

- *Fully standardized: it is expected that the component will not change across generations. This implies that the GVI and CI–R are equal to zero.*
- *Partially standardized: the component is expected to require minor changes across generations. The higher the GVI and CI–R, the less standardized is the component.*

2. Modularized (CI–S related)

- *Fully modularized: the geometry, energy, material, or signal (GEMS) of the component can be changed to meet expected customer requirements without requiring other components to change. This implies that the CI–S of the component is zero.*
- *Partially modularized: changes in the GEMS of the component may require changes in other components. The higher the CI–S, the more changes expected, and thus the component is considered less modular.*

In the DFV method, standardization and modularization are focused on those components that are most likely to cause major redesign efforts in later generations. This ranking of the components was done in DFV step 3. As stated in the definitions above, reducing the GVI, CI–R, and CI–S of the components drives these standardization and modularization efforts.

The next sections describe two major approaches to redesigning the architecture such that the GVI and CI of a component are reduced, which in turn should lower the future redesign efforts. In this paper, these approaches are demonstrated on the top-ranked component from step 3, the fascia. The Appendix also gives some detail of these approaches applied to the chassis.

4.2.1
Approaches to reducing GVI

The GVI is determined based on the engineers' estimates of the redesign costs required to meet the future customer

needs. The ratings for the GVI were previously displayed in Table 3. Underlying each number in the GVI matrix are specifications that link the component to the particular engineering metric. For instance, the EM "cool-down time" changed from 120 min to 90 min. The team ranked this time change as causing a moderate change (rating of 3) to the fan. The explicit specifications behind this number are that the "flow rate" and "pressure curve" specifications of the fan would have to be changed to meet this new cool-down time. These specifications were only implicit when the team developed the GVI earlier. To help change the architecture, it is necessary to explicitly list the specifications linking the EM to the components. These EM/component specifications are substituted into the GVI matrix for each node. Specifications for the water cooler are shown in Fig. 20.

There are two major approaches to reducing or eliminating the GVI created by these specification flows. In the first, the EM/component specifications are removed by 1) rearranging the mapping of functionality to components, or by 2) "freezing" the specification. In the second approach, the sensitivity of the component to a change in the specification is reduced by 1) reducing the internal coupling within the component (i.e. within the component control volume), or by increasing the 2) "headroom" of the specification. Further descriptions of these approaches along with examples are shown below, followed by a detailed application of the approaches to the fascia of the water cooler.

Approach 1: Remove EM/component specifications

1a. *Rearrange the mapping of functionality to components:* one approach to reducing the GVI is to change the architecture of the product to remove EM/component specifications. Rearranging the mapping of the functionality to the components can do this. An

example of this would be to decouple the "volume flow rate" EM from the reservoir height component specification by rearranging the architecture so that a pump is used to create the head pressure, rather than the height of the water. Also, the "cold water volume" specification could be partially decoupled from the reservoir volume by creating an architecture where water would be frozen to cool the room-temperature water down to specification rather than requiring a large volume of reservoir cooled water.

1b. *"Freeze" the specification*: a pseudomethod for removing a specification is to standardize or "freeze" it. By freezing the specification, the team dictates that it will not be modified. An example is to remove the "power consumption" EM/power supply voltage specification by fixing the voltage at 12 V for the current and future designs.

Note that it will be difficult to freeze a specification that is tightly linked with customer needs because it will constrain the team's ability to meet future needs. Also, there is always uncertainty in this method since while the team can state the specification will not change, there is always a possibility it will. Before freezing a specification, the team needs to fully understand the specification's relationship to the customer needs as well as how it is internally coupled within the component.

Approach 2: Reduce sensitivity of the components to changes in the specifications

2a. *Reduce internal coupling (within the component CV)*: one reason a component may require a great deal of redesign is its own internal coupling. A small modification to a component can ripple throughout that

Engineering Metrics	Fan	Heat Sink	TEC	Power Supply	Chassis	Plumbing	Reservoir	Insulation	Fascia
Cool Down Time (min)	Flow rate Pressure curve (3)	Heat sink resistance (6)	Qmax (3)	Voltage Max current (1)			Volume (6)	Conductance (1)	Vent area (6)
Water temperature (C)									
Cold Water Volume (gal)							Volume (9)		
Power consumption (W)	Efficiency (1)		Imax Resistance (3)	Efficiency (3)					
Width (in)					Width (6)				Width (6)
Height (in)									
Depth (in)					Depth (6)				Depth (6)
Volume flow rate (gal/min)						ID Friction coeff (9)	Water height (1)		
MTBF (hrs)									
Cost ($)		Material Assembly (1)		Unit cost (1)	Material cost Material amount Assembly cost (3)		Material cost Material amount Coating cost (3)		Material cost Material amount Yield (6)
GVI	4	7	6	5	15	9	19	1	24

Fig. 20. Explicit listing of GVI EM/component specifications (water cooler)

component if the individual parts or features comprising it are highly coupled. For example, a change in the "power consumption" EM might require a reduced "voltage" specification for the TEC. Because of the high internal coupling of the TEC, this is not a simple change. New *p*- and *n*-type semiconductor material shapes will need to be specified, which will require a different solder pad configuration, different ceramic sizes, etc. Thus, the high internal coupling of the TEC requires a major change to the TEC design. If the TEC could be designed to have a lower internal coupling, then a change in the voltage specification might be accommodated without major design changes.

2b. *Increase the "headroom" of the specification*: another method to reduce sensitivity is to increase the "headroom" of the EM/Component specifications. This implies designing the product so the component can absorb a large change in the specification before requiring redesign. This might be referred to as "overdesign." For the water cooler, designing and incorporating a larger reservoir volume to meet future "cold water volume" requirements could do this. While the volume of the reservoir would be overdesigned for the current customer needs, it would be able to meet future needs without any design changes.

A possible disadvantage of increasing specification headroom is that material costs may be increased. Also, it may not be possible to increase the headroom due to technological challenges for the current product.

4.2.2
Example of GVI reduction applied to fascia
Cool-down time (vent area)→fascia The specification linking the fascia and cool-down time (CDT) is "vent area." The vent area makes it possible for the fan to bring in cooler air with minimum pressure drop. Removing this specification link (using approach 1a) would be difficult since there has to be some method of removing the heat. Other conceivable architectures such as radiant heat dissipation, or using conduction through the fascia and then free or forced convection from the fascia external walls, would be technologically difficult to accomplish and would add a great deal to cost and development time. Having a vent area is the best architecture choice for removing the heat.

Another approach is to minimize the strength of the linkage by increasing the headroom of the vent area (approach 2b). This increased headroom implies that the current vent area will accommodate future changes in CDT. To do this the team will need to do some quick analysis to determine what the expected vent area will need to be for the future requirements. They can then design the fascia with this increased vent area, and thus headroom. This allows standardization of the vent area (for this engineering metric) across generations.

Of course, standardizing the vent area may not be possible. This could occur if one of the markets for the product would not accept the increased vent area, possibly because of aesthetics. In such a case, standardizing the whole fascia is not possible and a third approach is considered.

Approach 2a involves reducing the internal coupling of the component so that changing the vent area does not require major redesign or retooling. One possible design to separate a change in the vent area from larger modifications to the tool is to have a fascia panel with a large cutout for insertion of vent panels with different vent areas. This architecture design is shown in Fig. 21.

Another way to modularize the fascia is to design the injection-molding tool with a removable insert. By inserting or removing the tool insert, different vent areas can be molded. A possible difficulty with both these methods is making the design aesthetically pleasing. Also, they do not completely standardize the fascia. However, they do allow upgrading without a major design change, which will reduce the GVI.

Width (width) and depth (depth)→fascia Changes in the customer requirements for width and depth are heavily linked to the fascia. A change in the overall width and depth of the water cooler will require a change in the fascia under the current architecture being considered (that of a chassis with front and back fascia panels attached to it). Thus, under the current architecture these specifications cannot be removed. Other architectures may be able to break this link. For instance, if the fascia consisted of many modular building blocks (e.g. like a Lego set), these blocks could be built up during the assembly process to create different widths and depths. Thus, no redesign of the fascia and its tooling would be needed. Of course, the difficulties in making this architecture meet other requirements such as aesthetics and cost make such an architecture unlikely.

Since the width and depth specifications cannot be removed, a top priority is to reduce the impact of the fascia width and depth to changes in the product's width and depth. By approach 2b, the current product and fascia could be designed to meet the future customer requirements for footprint. This means that all the products in the platform would have footprints of 10×10 in.^{2} versus the 12.5×12.5 in.^{2} footprint allowed for some of the generations. This extra "headroom" in the fascia width and depth allows the future customer requirements of product width and depth to be met without any fascia changes.

The final possibility is to decrease the internal coupling of the fascia (approach 2a) so that it can be updated without major redesign and retooling costs. Again, while this does not standardize the component, it helps alleviate some of the impact of the change. The internal coupling may be reduced
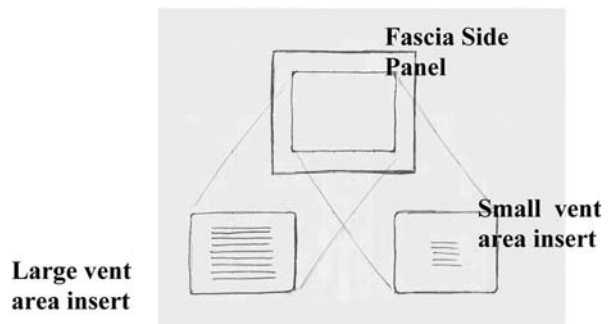

Fig. 21. Concept for reducing the GVI for the fascia vent area (water cooler)

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by modularizing the fascia so it can be updated to the smaller size by removing some parts. For instance, the depth of the water cooler could be modularized by placing an extender between the front and back panels (Fig. 22). The panels would be designed to meet the shorter depth requirement of 10 in. Where the 12.5-in depth is allowed, the extender would be inserted. While this method works for the depth, it would be very difficult to apply to the width due to the aesthetic curves on the front and panel.

A different architecture for the panels could be considered to allow the modularization of the width. Using five fascia panels (front, back, top, and two sides), the team could modularize the architecture by using corner connectors. The four vertical panels would be designed so they could be used with or without the connectors. For the smaller footprint products, just the panels would be used. On the larger footprint products, the corner connectors would be used to extend the width and depth of the product. This means that only the top panel would need to be redesigned, but not the vertical panels. Also, since the same connector design could be used at each corner, the design and tooling cost for this one-cavity tool could be minimized. The concept for this is shown in Fig. 23. The main disadvantage to this architecture is the limitation it places on the industrial design of the product. The water cooler would have more of a "flat" look versus the curves that can be incorporated into the integrated panels.

Cost (material amount, material cost, and yield) →fascia A major external driver for changing a component is cost reduction. The unit cost of a component may be targeted for cost reduction in future products. While cost driver specifications cannot be eliminated from the GVI matrix, they can be minimized. The team should design the product so that there is minimal opportunity to reduce the cost in future generations. Minimizing the unit cost is already a major focus of development teams. Sometimes, though, a decision is made to accept a higher unit cost while planning to cost-reduce during the next generation. These future cost reductions can create more costs because of the propagation effect of coupling.

For the fascia, the main drivers of the unit cost (not including amortized design and tooling costs) are the type of material used, the amount of material, and the yields from the tooling. Because of time constraints and structural concerns, the team may not spend the time to optimize the type or amount of material in the fascia. When pressure to cut costs arrives, this is a potential target for unit cost reduction. When this occurs, the team will generally do a cost analysis to determine if the unit cost savings will outweigh the costs of redesign and tooling. The coupling index matrix is useful in this case to point out how changing a component can create other costs.

The team will need to determine the cost drivers for the fascia with the most potential for reduction. This potential may lie in a feature that may cause a low yield, or one that has the potential for a reduction in the material amount. Another possibility is that lower cost materials may become available in the future, or may exist now but can only be used for one of the future products due to lower aesthetic requirements for that market (e.g. water coolers in a factory setting). The team should consider if and how they can isolate the fascia from these possible changes to increase yields or reduce material amounts and costs.

This completes the brainstorming on possible architecture changes to the fascia to reduce the GVI. A summary of these possible architecture changes is shown in Table 9. In the next section, the brainstorming approaches to reduce the CI are covered.

4.2.3
Approaches to reducing the coupling indices

Reducing coupling follows the same basic approaches as those of reducing the GVI. The team focuses on removing component/component specifications, or on reducing their sensitivity. The complete CI matrix was displayed in Fig. 16. The approaches are described below.

Approach 1: Remove component/component specifications

1a. *Rearrange the mapping of functionality to components*: removing component/component specifications is one method to reduce the CI. Specifications can be removed to help reduce coupling and thus slow the propagation of changes throughout the product. For instance, the heat sink to chassis "mounting point" specification could be removed by changing the architecture to mount the heat sink to the chassis. Of course, such a new architecture arrangement will create new coupling specifications, which have to be considered as well.

1b. "Freeze" the specification: freezing the specification also works for removing the component/component specifications. In the case of the "mounting points," mounting locations for the current and future products could be at fixed locations.
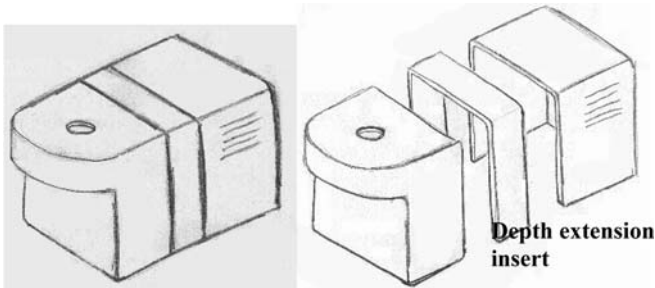

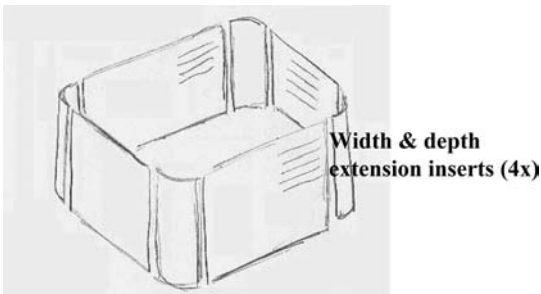**Fig. 22.** Concept for reducing GVI of the fascia depth (water cooler)

Fig. 23. Concept for reducing GVI of fascia width and depth (water cooler)

Table 9. Summary of possible architecture changes to reduce GVI (water cooler fascia)

Engineering metrics	Specs received (fascia)	Approach 1a (rearrange F/S mapping)	Approach 1b (freeze specifications)	Approach 2a (reduce internal coupling)	Approach 2b (increase headroom)
Cool-down time (min)	Vent areas	Architecture change not requiring vents	–	Modular vent piece Insert in tooling to change vent area	Design to meet most stringent future CDT spec requirement
Water temperature (°C)	–	–	–	–	–
Cold water volume (gal)	–	–	–	–	–
Power consumption (W)	–	–	–	–	–
Width (in.)	Width	Modular plastic building blocks	–	Architecture change to use four fascia panels instead of two. Use corner inserts to extend width	Design to meet most stringent future width spec
Height (in.)	–	–	–	–	–
Depth (in.)	Depth	Modular plastic building blocks	–	Architecture change to use four fascia panels instead of two. Use corner inserts to extend width For current two-panel design, use modular insert to increase depth	Design to meet most stringent future width spec
Volume flow rate (gal/min)	–	–	–	–	–
MTBF (h)	–	–	–	–	–
Cost ($)	Material cost Material amount Yield	–	–	Develop tooling to allow use of different material types	Reduce material amount Use lowest-cost material Develop tooling with no difficult-to-form features

Approach 2: Reduce sensitivity of the components to changes in the specifications

2a. Reduce internal coupling (within the component CV): reductions in the internal coupling of a component can also help reduce the sensitivity of that component to shifting specifications, just as with the GVI.

2b. Increase the "headroom" of the specification: one component/component specification that could benefit from extra headroom is the chassis strength. Since the chassis must be able to hold the reservoir (and the water in it), it would be best to design the chassis with extra "headroom" such that it can hold the future expected reservoir sizes. These approaches to reducing the CI are applied in the next section to the fascia CI–R reduction.

4.2.4
Example of CI–R reduction applied to fascia

Fan (airflow rate, airflow direction, X/Y dimension, Y-location)→fascia The fan airflow, geometry, and location can cause changes to the fascia. The fascia allows the air to flow out of the unit through vents. Thus, changes in the fan can affect the design of the venting. It is difficult to remove these linkages (approach 1a) without a major architectural change. However, it is possible to freeze some of the specifications, such as the X/Y-dimensions and location of the fan, to effectively eliminate them. The types of fans being considered are catalog items and are often called "muffin" fans (Fig. 24). These fans are built in standard sizes, which have various levels of performance for each size. Freezing the X/Y-dimensions of the fan used in the water cooler is feasible since future performance upgrades can be handled by using higher performance fans of the same size. The team also decides that the location and airflow direction of the fan can be frozen without constraining future requirements.

The airflow rate of the fan cannot be frozen, since it is expected that future products will require higher flow fans. This increased airflow may require changes in the design of the vents. The team may choose approach 2b and give the fascia the headroom to handle the future requirements. If it is feasible to incorporate a vent design now that will

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Fig. 24. Example of muffin-type fan (water cooler)

handle the future vent requirements, this is a way to reduce the Cl-R.

Heat sink (maximum temperature)→fascia For the heat sink, the surface temperature reached could conceivably cause damage to the fascia plastic. However, since high glass-transition temperature plastics are used, there is plenty of headroom for the heat sink temperature specification to increase without any problems.

Power supply (maximum temperature, heat output)→fascia The temperature of the power supply could also damage the plastic, similar to the heat sink. As with the heat sink, there is significant headroom in this

specification. A change in the heat output of the power supply may require additional cooling capacity for the interior in the form of more venting. However, the relatively small increase in future power supply changes is adequately covered by the currently planned venting configuration.

Chassis (strength, mounting points)→fascia A significant decrease of the chassis strength could affect its ability to support the fascia. However, the strength of the chassis has significant headroom, plus no major changes to its basic design are expected.
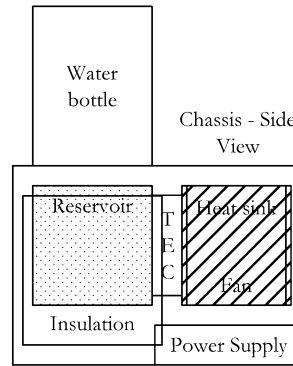
Fig. 25. Example of water cooler with fan on side

Table 10. Summary of possible changes to reduce CI–R (water cooler fascia)

Components supplying specifications	Fascia specifications received	Approach 1a (rearrange F/S mapping)	Approach 1b (freeze specifications)	Approach 2a (reduce internal coupling)	Approach 2b (increase headroom)
Fan	Airflow rate Airflow direction X/Y-dimension Y-location	–	Freeze size of fan and airflow direction	–	Design vent area to meet expected future requirements
Heat sink	Max. temperature	–	–	–	Design distance between heat sink and fascia to give headroom
TEC	–	–	–	–	–
Power supply	Max. temperature	–	–	–	Plastic damage temp. is well above expected maximum PS temp.
	Heat output				Design vent area to meet future heat output requirements
Chassis	Strength Mounting points	Change architecture to use flexible bracket between chassis and fascia	Freeze the location of the mounting points	–	Chassis strength will have significant headroom in accommodating fascia weight
Plumbing	Diameter X/Z-location	–	Freeze X/Z-location of plumbing	–	Increase diameter of fascia hole to accommodate expected future requirements
Reservoir	–	–	–	–	–
Insulation	Thickness	–	Freeze thickness of insulation	–	Reduce width of reservoir to allow headroom for insulation thickness
Fascia	–	–	–	–	–

Table 11. Approaches chosen to reduce GVI to zero (water cooler fascia)

Engineering metrics	Fascia GVI specifications	Approach chosen to reduce GVI
Cool-down time (min)	Vent areas	Design to meet most stringent future CDT spec requirement (approach 2b)
Water temperature (°C)	–	–
Cold water volume (gal)	–	–
Power consumption (W)	–	–
Width (in.)	Width	Design to meet most stringent future width spec (approach 2b)
Height (in.)	–	–
Depth (in.)	Depth	Design to meet most stringent future width spec (approach 2b)
Volume flow rate (gal/min)	–	–
MTBF (h)	–	–
Cost ($)	Material cost	Reduce material amount
	Material amount	Use lower cost material
	Yield	Use tooling with easy-to-form features

Table 12. Approaches to reducing the CI–R to zero (water cooler fascia)

Components supplying specifications	Fascia CI–R specification	Approach chosen
Fan	Airflow rate	Freeze size of fan and airflow direction (approach 1b)
	Airflow direction X/Y-dimension Y-location	Design vent area to meet expected future requirements (approach 2b)
Heat sink	Max. temperature	Choose plastic with sufficiently high melt temperature (approach 2b)
TEC	–	–
Power supply	Max. temperature	Choose plastic with sufficiently high melt temperature (approach 2b)
	Heat output	Design vent area to meet future heat output requirements (approach 2b)
Chassis	Strength	Freeze location of mounting points (approach 1b)
	Mounting points	Design chassis to have significant strength headroom (approach 2b)
Plumbing	Diameter	Freeze X/Z-location of plumbing (approach 1b)
	X/Z-location	Increase diameter of fascia hole to accommodate expected future requirements (approach 2b)
Reservoir	–	–
Insulation	Thickness	Freeze thickness of insulation (approach 1b)
Fascia	–	–

A change in the mounting points on the chassis may also require redesign of the fascia mounting points. This can be alleviated by freezing the location of the mounting points, or by using a bracket between the chassis and fascia points. This bracket could then be changed to accommodate small changes in the mounting points.

Plumbing (diameter, X/Z-location)→fascia The diameter and X/Z-location of the plumbing affects the fascia. If the location of the plumbing is moved in the X- or Z-axis, or if the plumbing diameter is increased, the outlet hole in the fascia will need to be modified. To keep these specifications from requiring a change in the fascia, the X/Z-location can be frozen, and the diameter of the hole can be increased to accommodate the expected future requirements for the plumbing.

Insulation (thickness)→fascia The insulation thickness can affect the fascia by increasing the overall width required for the water cooler, because the current architecture is highly constrained in this dimension. The team could freeze this specification, but only after an analysis to determine that increasing the thickness of the insulation will not be required to meet future design specifications. Another option is to reduce the width of the reservoir to allow some headroom for the insulation thickness specification.

This ends the brainstorming on approaches to reduce the CI–R of the fascia. A summary of the

Components SUPPLYING Information

	Fan	Heat Sink	TEC	Power Supply	Chassis	Plumbing	Reservoir	Insulation	Fascia	CI-R
Fan		Pressure 9 x dim 3 z dim 3	Heat output 3 x dim 1 z dim 1	Voltage 9 P-P voltage 1	Strength 0 Mounting points 0 x dim 0 y dim 0 z dim 0		Volume 3		Vent area 0 Thickness 0	33
Heat Sink	Pressure curve 3 x dim 3 z dim 3		Heat output 3 x dim 3 z dim 3		Strength 0 Mounting points 0 x dim 0 y dim 0 z dim 0		Absorptivity 1 Volume 6	y dim 3	Vent area 0 Vent location 0	22
										6
TEC		Heat sink conductance 3 Effective heat sink area 3		Voltage output 9 P-P voltage 3			Conductivity 3 x dim 1 z dim 1 Volume 6	y dim 3 Conductivity y 3		29
Power Supply	Voltage 9		Imax 3 Resist. 3		Strength 0 Mounting points 0 x dim 0 y dim 0 z dim 0				Vent area 0 Vent location 0	21
										0
Chassis	Weight 0 x dim 0 y dim 0 z dim 0 Mounting holes 0	Weight 0 x dim 0 y dim 0 z dim 0 Mounting holes 0		Weight 0 x dim 0 y dim 0 z dim 0 Mounting holes 0			Weight 0 x dim 0 y dim 0 z dim 0 Mounting holes 0	x dim 0 y dim 0 z dim 0	Weight 0 x dim 0 y dim 0 z dim 0 Mounting holes 0	0
Plumbing	x location 0 y location 0 z location 0	x location 0 y location 0 z location 0		x location 0 y location 0 z location 0			x location 0 y location 0 z location 0 Water height 1 x location 3	z dim 3	x location 0 y location 0 z location 0 Through-hole x loc 0 Through-hole z loc 0	7
							y location 3 z location 3 Hole diameter 3		Hole radius 0	9
CI-S	18	21	20	22	0	0	34	12	0	127

Fig. 26. CI matrix after standardizing fascia and chassis (water cooler)

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Reservoir is 8" x 6" x 4" (HxWxD) for effective capacity of 0.5 gal. Increase in width to 8" is accommodated by Chassis and gives effective capacity of 0.75 gal. Mounting holes for Heat Sink are fixed on Reservoir. Wall thickness of Reservoir can be increased some to accommodate any future changes in weight of Heat Sink and Fan.

Heat Sink (5" x 5" x 4.5") has space to grow in height, width and depth, although headroom is constrained by other components. The Fan will be mounted to Heat Sink and this will increase their coupling. However adding a Mounting Bracket as an interface between them should reduce this coupling.

Insulation will need to be redesigned when Reservoir width is increased.

Fan is placed on side of Heat Sink instead of on back. Allows room for Heat Sink Fin Length to increase. Fixed mounting on Heat Sink using Bracket.
A second fan can also be placed on other side of Heat Sink to increase cooling if future thermal specifications change.

Chassis designed for 11" x 11" footprint. Sufficiently strong to support future weight increases of other components. Mounting points for Reservoir, Fascia, Power Supply, and Fan are frozen.

Fascia designed for 11" x 11" footprint. Fixed mounting points to attach to Chassis. Hole for plumbing outlet is fixed and has oversized diameter for increases in size of plumbing. Vent areas are oversized to accommodate future requirements.

Power Supply mounted to Chassis. Mounting points are frozen. Future power supplies will use same points. Vent areas are designed large enough to sufficiently ventilate Power Supply.
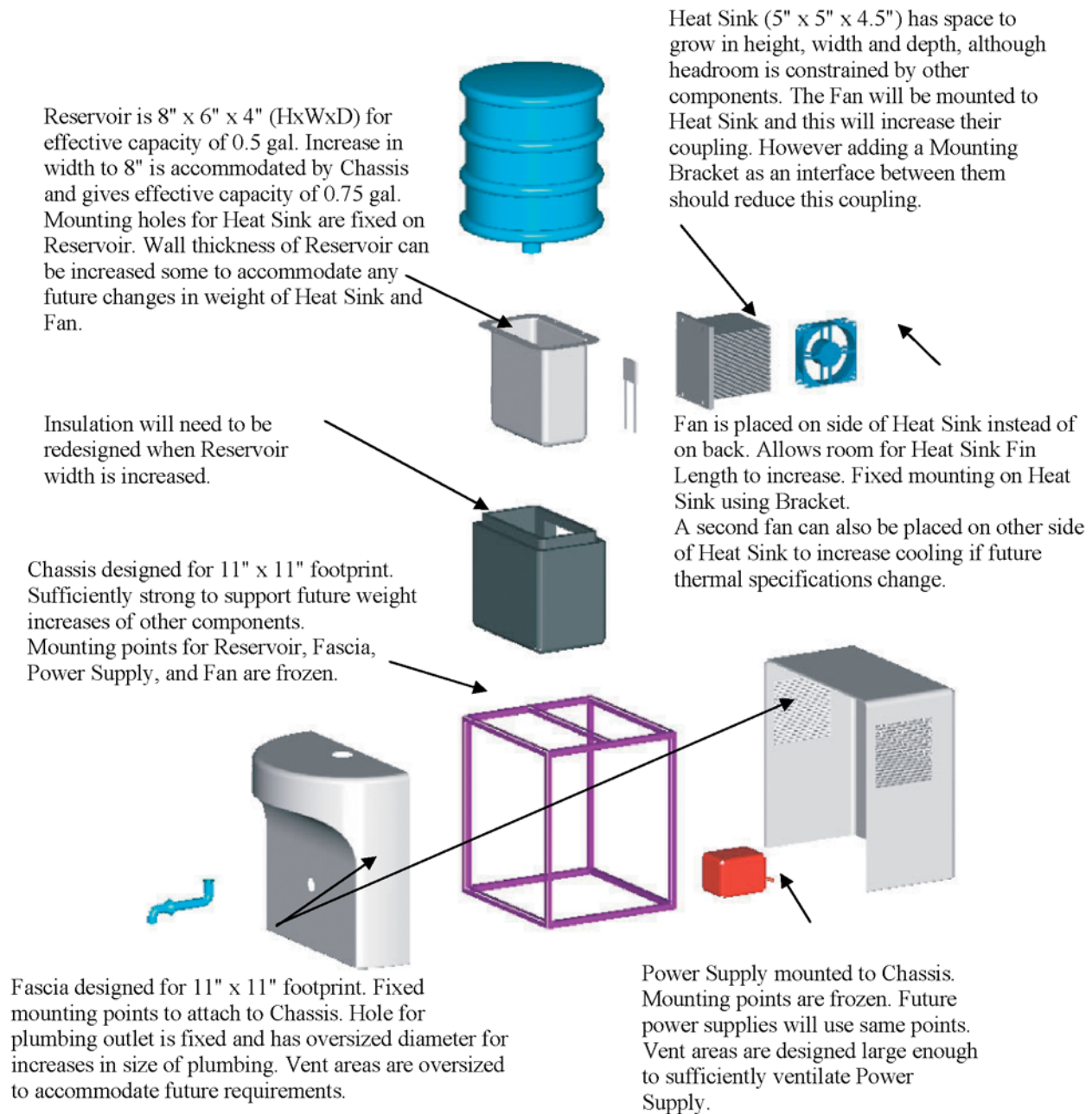
Fig. 27. TEC water cooler incorporating standardization of fascia and chassis

possible CI changes to the architecture are listed in Table 10.

Product platform architecture for the water cooler As discussed previously, standardizing the fascia and chassis components is economically attractive since the costs of redesign are expected to be high. The major hurdle in standardizing these components (as with many products) is the change in the size required for future generations. One approach to meeting the future requirements for size is to design the product such that it meets the future size requirement in the current design.

The most stringent footprint requirement is 10×10 in.[2] for the final home product (future market 3). In doing an analysis of using a 10×10 in.[2] size for the water cooler, it became evident that this size would not allow the

cooler to meet the cold water volume and cool-down time required for the cooler designed for offices (future market 2). This market does not require the smaller footprint, and if the 12.5×12.5 in.[2] footprint were used, the cooler would be able to meet the requirements.

However, analysis also shows that an 11×11 in.[2] footprint would allow the office water cooler to meet the cold water volume and cool-down time requirements. Of course, this footprint does not meet the home cooler requirement (future market 3). At this point, it becomes a point of discussion between marketing and engineering to decide which alternative is the most economically attractive. Marketing claims that the office cooler will not sell unless it meets all the specifications. They also would like the home cooler to have the smaller foot-

Table 13. Potential savings in redesign eort using DFV method (water cooler)

	No product platform design	Product platform design using DFV method
Indices		
GVI	90	51
CI	504	192
Initial design cost (%)	100	100
Redesign cost (% of initial design)		
From external drivers (GVI)	83	6
From internal drivers (CI)	16	1
Total redesign cost (%) *	98	6

* Note: Total redesign costs' do not add to external and internal numbers due to rounding

Table 14. Summary of architecture changes to reduce GVI (water cooler chassis)

Engineering metrics	GVI specs (chassis)	Approach 1a (remove specifications)	Approach 1b (freeze specifications)	Approach 2a (reduce internal coupling)	Approach 2b (increase headroom)
Cool down time (min)	–	–	–	–	–
Water temperature (°C)	–	–	–	–	–
Cold water volume (gal)	–	–	–	–	–
Power consumption (W)	–	–	–	–	–
Width (in.)	Width	Use modular building blocks (precut rods and corner connectors – similar to Tinker Toys)	–	Flexible fixturing to easily change over to different width and depths	Design to meet most stringent future width spec
Height (in.)	–	–	–	–	–
Depth (in.)	Depth	Use modular building blocks (precut rods and corner connectors – similar to Tinker Toys)	–	Flexible fixturing to easily change over to different width and depths	Design to meet most stringent future width spec
Volume flow rate (gal/min)	–	–	–	–	–
MTBF (h)	–	–	–	–	–
Cost ($)	Material cost	–	–	–	Reduce material amount
	Material amount Yield				Use lowest cost material

print. However, when confronted with the costs of having to redesign the cooler for this future market, they concede that the lost sales would not make up for the expected costs of the redesign. They feel that the 11×11 in.[2] size will still do well in the market. Thus, the choice is made to standardize the fascia and chassis to this size footprint.

In order to accommodate this smaller footprint of 11×11 in.[2], one architecture change is to move the fan from the back to the side of the heat sink (Fig. 25). This is needed because the 11-in depth specification cannot be met if the fan is placed in back. Placing the fan on the side of the heat sink where there is space allows the team to meet the more stringent depth requirement. The footprint is the more difficult specification of the fascia and chassis

to standardize. The approaches chosen to allow standardization of the other specifications are shown in Table 11. The approaches chosen to reduce the CI–R to zero for the fascia are given in Table 12. Besides the fascia, the chassis was also looked at for reduction of the GVI and CI. The results from the chassis are detailed in the Appendix.

After applying the design changes to the water cooler, the team reviews the GVI and CI matrices to determine if more changes should be made to the architecture. They will need to consider whether the GVI of the remaining components will cause significant redesign costs for those components, or if the changes will propagate, requiring significant redesign of other components. For the water cooler, standardizing the fascia and chassis causes a

Table 15. Summary of architecture changes to reduce CI–R (water cooler chassis)

Components supplying specifications	Chassis specifications received	Approach 1a (remove specs)	Approach 1b (freeze specs)	Approach 2 (increase headroom)	Approach 3 (reduce internal coupling)
Fan	Weight	Use separate mounting bracket between fan and chassis to mount fan ($X/Y/Z$-location, $X/Y/Z$-dimension, and mounting holes)	Freeze $X/Y/Z$-dimension	Chassis has plenty of headroom for weight	–
	$X/Y/Z$-dimension Mounting holes $X/Y/Z$-location	Mount fan to heat sink ($X/Y/Z$-location)	Freeze mounting holes		
Heat sink	Weight	Use separate mounting bracket between heat sink and chassis ($X/Y/Z$-location, $X/Y/Z$-dimension, and mounting holes)	Freeze $X/Y/Z$-dimension	Chassis has plenty of headroom for weight	–
	$X/Y/Z$-dimension Mounting holes $X/Y/Z$-location	Mount heat sink to reservoir ($X/Y/Z$-location)	Freeze mounting holes		
TEC	–	–	–	–	–
Power supply	Weight	Use separate mounting bracket between PS and chassis ($X/Y/Z$-location, $X/Y/Z$-dimension, and mounting holes)	Freeze $X/Y/Z$-dimension	Chassis has plenty of headroom for weight	–
	$X/Y/Z$-dimension Mounting holes $X/Y/Z$-location		Freeze mounting holes		
Chassis	–	–	–	–	–
Plumbing	–	–	–	–	–
Reservoir	Weight	–	Freeze $X/Y/Z$-dimension	Chassis has plenty of headroom for weight	–
	$X/Y/Z$-dimension Mounting holes $X/Y/Z$-location		Freeze mounting holes		
Insulation	$X/Y/Z$-dimension	–	Freeze $X/Y/Z$-dimension	Allow dimensional growth	–
Fascia	Weight	Use separate mounting bracket between fascia and chassis ($X/Y/Z$-location, $X/Y/Z$-dimension, and mounting holes)	Freeze $X/Y/Z$-dimension	Chassis has plenty of headroom for weight	–
	$X/Y/Z$-dimension Mounting holes $X/Y/Z$-location		Freeze mounting holes		

significant reduction in the expected future redesign costs (Fig. 26), and no other major architecture changes need to be made. The final architecture for the water cooler is shown in Fig. 27.

5
Estimating the benefits of the DFV method
The product platform architecture is developed in order to reduce the amount of redesign effort for future generations of the product. The DFV method offers a structured approach to accomplish this goal. The application of the method to the water cooler example resulted in reduced generational and coupling indices. This reduction was accomplished by standardizing the fascia and chassis and translates directly into lower redesign efforts.

Table 13 shows the potential savings from the application of the DFV method. It compares the estimated redesign costs for a design with no product platform consideration to one designed using the DFV method. The table shows a reduction in the total GVI from 90 to 51, and a reduction in the total CI from 504 to 192.

The redesign efforts for two different development approaches for the product are also shown in Table 13.

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Table 16. Approaches chosen to reduce the GVI to zero (water cooler chassis)

Engineering metrics	Chassis GVI specification	Approach chosen
Cool down time (min)	–	–
Water temperature (°C)	–	–
Cold water volume (gal)	–	–
Power consumption (W)	–	–
Width (in.)	Width	Design to meet most stringent future width spec (approach 2b)
Height (in.)	–	–
Depth (in.)	Depth	Design to meet most stringent future depth spec (approach 2b)
Volume flow rate (gal/min)	–	–
MTBF (h)	–	–
Cost ($)	Material cost	Reduce material amount
	Material amount	Use low-cost material
	Yield	Develop simple structure (approach 2a)

Table 17. Approaches chosen to reduce CI–R to zero (water cooler chassis)

Components supplying specifications	Chassis CI–R specification	Approach chosen
Fan	Weight	Design chassis to have headroom for weight (approach 2b)
	$X/Y/Z$-dimension	Freeze $X/Y/Z$-dimension of fan (approach 1b)
	Mounting holes $X/Y/Z$-location	Mount fan to heat sink instead of chassis (approach 1a)
Heat sink	Weight	Design chassis to have headroom for weight (approach 2b)
	$X/Y/Z$-dimension	Mount heat sink to reservoir (approach 1a)
	Mounting holes $X/Y/Z$-location	Allow space for growth of Heat Sink (approach 2b)
TEC	–	–
Power supply	Weight	Design chassis to have headroom for weight (approach 2b)
	$X/Y/Z$-dimension	Freeze mounting holes
	Mounting holes $X/Y/Z$-location	Allow space for growth (approach 2b)
Chassis	–	–
Plumbing	–	–
Reservoir	Weight	Design chassis to have headroom for weight (approach 2b)
	$X/Y/Z$-dimension	Freeze mounting holes (approach 1b)
	Mounting holes $X/Y/Z$-location	Allow space for growth (approach 2b)
Insulation	$X/Y/Z$-dimension	Allow room for growth in dimensions (approach 2b)
Fascia	Weight	Freeze weight
	$X/Y/Z$-dimension	Freeze $X/Y/Z$-dimension
	Mounting holes $X/Y/Z$-location	Freeze mounting holes (approach 1b)

Without using a product platform approach and by optimizing each generational individually, the "no product platform design" redesign efforts from external drivers are expected to be 83% of the initial design effort and 16% from internal drivers. Note that since redesign efforts occur in the future, these efforts need to be calculated in current dollars. Thus, the numbers shown in the table are based on the net present value with a 15% discount rate. By using the DFV method to standardize the fascia and chassis, the amount of redesign is reduced significantly. The cost required because of changing customer requirements (GVI) is reduced from 83% to 6%. The cost from internal coupling (CI) drops to 1% from 16%.

The savings shown in Table 13 represents the maximum potential. It assumes that the designers not using the DFV method would optimize each generation individually without considering any future changes. In any real design project, even if a product platform structured methodol-

ogy is not used, the designers will generally have a minimal knowledge of future changes and will consider them during the design process. Thus, these numbers are probably overstated to some extent.

The other assumption is that the initial design effort when using the DFV method will be the same as when the method is not used. The initial effort to design using the DFV method will probably increase because of extra design analysis in considering the different approaches to reducing GVI and CI. Also, some of the tooling costs and unit costs may increase depending on the solutions chosen.

While the cost benefits described in this section are rough estimates, they give an indication of the potential for developing well-planned product platform architectures. Of course, each project's potential cost savings in using the DFV method will vary depending on numerous factors, including tooling costs, previous considerations of product platform architectures, uncertainties around the changing customer needs, and so on. However, the DFV method is simple and inexpensive to use for determining potential design changes. Once these changes are determined, the team can then consider these other factors to decide if they should implement the recommendations.

6
Summary

Faster product development continues to be a major goal for many companies, and "architecting" is becoming crucial in helping companies accomplish this. This paper describes a structured methodology (DFV) to aid in developing a product platform architecture that incorporates standardization and modularization to reduce future design costs and efforts. The example of a water cooler was used to illustrate the method. The DFV method consists of a descriptive portion (GVI and CI) and a prescriptive approach to help standardize and modularize the architecture. Companies such as Sony, Nortel Networks, and InFocus have used the concepts and details of the DFV method in the design of desktop robots, network enclosure boxes, and rear-projection TV. In addition, the method is an integral part of the DFM curriculum at Stanford University. With the ability to develop the GVI and CI, and knowledge of the application of these indices through the DFV method, design teams now have a structured method to help them architect products for future generations.

Appendix

The possible architecture options for the fascia were described in detail to give the reader an idea of how the reductions in GVI and CI are made. For the chassis, the possible architecture changes are presented in Tables 14 and 15. The approaches chosen to reduce the chassis GVI are shown in Table 16, and the approaches chosen to reduce the CI–R are shown in Table 17. These changes are incorporated into the TEC water cooler to make it more robust to future market and design changes.

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