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Navigating redesign and market desirability implications when considering increased product variety

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Current engineering change and market analysis tools provide discipline-specific feedback about the ramifications associated with offering increased product variety for an existing product. Engineering change tools provide ways to calculate and manage the risks associated with change propagation due to product modification, while strides in market research enable the modelling of consumer preferences for individual respondents. Yet, outcomes from these tools have not been adequately combined to explore the trade-off between engineering rework and consumer acceptance of the modified product. This work integrates the Change Prediction Method (CPM) and discrete choice analysis to simultaneously consider the engineering and business-side ramifications of offering increased variety by adding new product options. Outputs from the CPM are used to create a tradeoff plot between estimated market share gains and product cost when redesign effort is considered. This approach is applied to a gas grill problem to demonstrate how such trades can be considered when determining if a product option should be offered to increase product variety.

Keywords: Change Prediction Method; discrete choice theory; product redesign; product feature determination

1. Introduction

A firm's decision to adopt a design strategy that embraces increased product variety often occurs when there is an interest in satisfying the heterogeneous needs of a market. Product family design is a popular approach for achieving this goal by offering a set of related products from one or more product platforms (Simpson and Jiao 2014). Increased variety can be offered at controlled costs, and customers can select the product that maximises their preferences from the set of standardised products (Piller, Moeslein, and Stotko 2004). When combined with assemble-to-order strategies, consumers can play an active role in determining their final product.

Pursuing expanded product variety requires the development of a solution space (Slavador, de Holan, and Piller 2009), and two significant issues are the redesign effort needed to modify the existing product and the market desirability of the modification. Desirability is measured from the customer perspective, while engineers are concerned with the amount of redesign effort required. If these considerations are viewed separately by each discipline, the result is a highly iterative and likely inefficient design process.

To illustrate this point, consider a hypothetical scenario where four possible modifications are being considered for an existing product. Figure 1(a) shows the market desirability of

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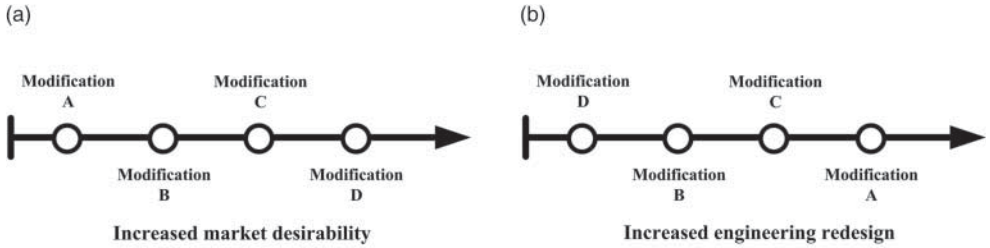


Figure 1. Exploring the (a) desirability and (b) engineering redesign effort associated with a product modification.

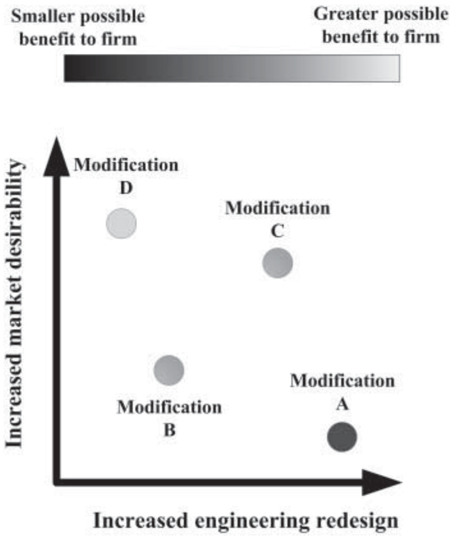


Figure 2. Identifying the trade-off between market desirability and engineering redesign effort for a proposed product modification.

each modification. Advances by the market research community have led to the development of approaches capable of modelling customer preferences for product characteristics and the creation of simulators to predict market response to new products. The amount of engineering redesign associated with each of these four modifications is shown in Figure 1(b). Previous work by Eckert, Pulm, and Jarratt (2003) and Eckert, Clarkson, and Zanker (2004) identified two types of product changes: emergent and initiated. While emergent changes are unexpected and occur during the design process, initiated changes arise from new requirements. Exploring the ramifications of these initiated changes allows engineering designers to understand the change propagation and rework costs associated with a product modification.

When both criteria are considered, it is possible that there is a distinct trade-off between market desirability and the engineering redesign effort required. As shown in Figure 2, Modification A not only requires the most redesign effort of the four modifications, but also has the least amount of market desirability. Modification D, conversely, is advantageous from both the engineering and marketing perspectives. Modifications B and C show how trade-offs between the two criteria must be explored and navigated when determining which opportunities to pursue.

The objective of this work is to create a stronger connection between the engineering and market domains. Currently, no approach exists that simultaneously explores the trade-off between engineering redesign effort and market desirability. This limitation is addressed by demonstrating how the Change Prediction Method (CPM) (Clarkson, Simons, and Eckert 2004) can be used to determine the cost of engineering rework, and discrete choice analysis (DCA) (Ben-Akiva and Lerman 1985; Train 2003) can be used to determine changes in market share of preference (MSP). Combining analyses from these different domains will allow for a better understanding of the trade-offs between engineering effort and market desirability when exploring product modification as a means towards increased product variety.

2. Background

Assessing the engineering and marketing ramifications associated with a potential product modification requires the synthesis of research from distinct areas. The following subsections provide insight into the current state-of-the-art and limitations of customer preference modelling and engineering change management in the context of modifying a product for increased variety.

2.1. *Customer preference modelling*

Though there are many different approaches discussed in the engineering design literature capable of identifying customer needs (Urban and Hauser 1993; Dieter 1999; Otto and Wood 2001; Pahl et al. 2006), there are significantly fewer approaches capable of quantifying customer preferences. Experimental research has shown increased consumer satisfaction when product customisation is offered (Huffman and Kahn 1998; Bauer 2009), and that these customers also demonstrate an increased willingness to pay (Merle, Chandon, and Roux 2010). Other works have explored the role of product styling and the role of multicultural factors (Chen, Khoo, and Yan 2003; Fung, Chong, and Wang 2004). Surveys have been used to build ontology-based semantic representations of preferences (Cao, Li, and Ramani 2011) and to generate utility functions, specifically when hypothetical alternatives are considered (See, Gurnani, and Lewis 2004; See and Lewis 2006). Finally, data mining techniques have used customer reviews and social media entries to quantify customer preferences (Tucker and Kim 2009).

A significant amount of attention has also been paid to conjoint analysis (Urban and Hauser 1993; Orme 2006) and DCA (Ben-Akiva and Lerman 1985; Train 2003) as a means for estimating quantifiable customer preferences. Arguably, this challenge has been best met by research in DCA. Wassenaar first integrated DCA into decision-based design (Wassenaar and Chen 2003; Wassenaar et al. 2004), and Michalek, Feinberg, and Paplambros (2005) and Michalek, Ceryan, and Paplambros (2006) used DCA to design both a single product and a product line. Nested logit models were used by Kumar, Chen, and Simpson (2009) to represent heterogeneity in the development of product families, and the advantages and challenges of using a Hierarchical Bayes (HB) multinomial logit (MNL) model (Train 2003) were explored by Sullivan, Ferguson, and Donndelinger (2011). HB models were also used to quantify the sacrifice made by a consumer when choosing a non-ideal product (Porterfield 2012) and to strategically seed the initial population of a multi-objective genetic algorithm for product line design (Foster et al. 2014).

Research using DCA has demonstrated that a designer must consider quantifiable consumer preferences when designing a product rather than solely focusing on engineering considerations. This work uses DCA to assess the market desirability impact of a proposed product modification and to further integrate engineering and market research analysis into product design problems.

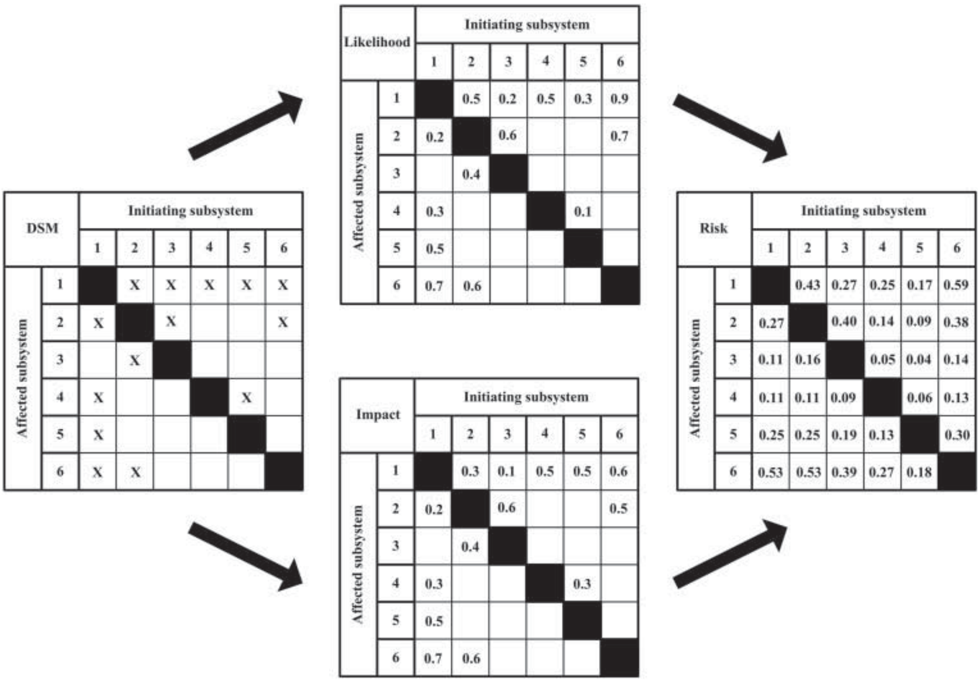
2.2. *Assessing product change*

There exist two categories of change: emergent and initiated (Eckert, Pulm, and Jarratt 2003; Eckert, Clarkson, and Zanker 2004). Emergent changes are unexpected changes that arise during the product design process. Initiated changes are expected changes that arise from new requirements. To account for the ramifications associated with these initiated changes, research in the design community has explored many aspects of engineering change management, as highlighted by the comprehensive literature review presented by Jarratt et al. (2011).

Component-based Design Structure Matrices (DSMs) (Browning 2001) decompose a product into subsystems, where columns represent initiating subsystems and rows map to the affected subsystems (Steward 1981). By identifying change relationships between subsystems with a DSM, subsystems can be classified as multipliers, absorbers, carriers, or constants (Eckert, Clarkson, and Zanker 2004).

Multiple methods have been proposed to quantitatively analyse design dependencies and change propagation including RedesignIT, Change Favourable Representation (C-FAR), a matrix-based method, and the CPM. RedesignIT is a software tool that requires designers to input a model and then evaluates the potential knock-on effects of a proposed change and presents possible remedies (Ollinger and Stahovich 2004). Instead of a model, C-FAR assigns linkage values to attributes of a product to produce a matrix consisting of risk values for potential changes to a system (Cohen, Navathe, and Fulton 2000). Like C-FAR, the matrix-based algorithm (Hamraz, Caldwell, and Clarkson 2013) and CPM (Clarkson, Simons, and Eckert 2004) produce a combined risk matrix, but rely on impact and likelihood values between directly connected subsystems instead of single linkage values.

The CPM (Clarkson, Simons, and Eckert 2004) uses a series of DSMs and propagation tree structures to calculate the risk of change propagation in terms of (1) the likelihood – defined as the average probability that a change in one subsystem leads to a design change in another subsystem – of a change propagating and (2) the impact – a representation of the average predicted amount of rework that results from a change propagating – of such an event. To calculate the risk of change propagation (likelihood of a change occurring times the impact of the ensuing change),



DSM		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	X	X	X	X	X
	2	X	■	X			X
	3		X	■			
	4	X			■	X	
	5	X				■	
	6	X	X				■

Likelihood		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.5	0.2	0.5	0.3	0.9
	2	0.2	■	0.6			0.7
	3		0.4	■			
	4	0.3			■	0.1	
	5	0.5				■	
	6	0.7	0.6				■

Impact		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.3	0.1	0.5	0.5	0.6
	2	0.2	■	0.6			0.5
	3		0.4	■			
	4	0.3			■	0.3	
	5	0.5				■	
	6	0.7	0.6				■

Risk		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.43	0.27	0.25	0.17	0.59
	2	0.27	■	0.40	0.14	0.09	0.38
	3	0.11	0.16	■	0.05	0.04	0.14
	4	0.11	0.11	0.09	■	0.06	0.13
	5	0.25	0.25	0.19	0.13	■	0.30
	6	0.53	0.53	0.39	0.27	0.18	■

Figure 3. Generic CPM model.

information from the likelihood and impact matrices is combined to create a risk matrix. This matrix displays the risk of a change propagating from an initiating to an affected subsystem regardless of a direct connection between the subsystems, as shown in Figure 3.

This process can also be enabled by using the Cambridge Advanced Modeller (CAM) with the CPM toolbox, because it is capable of representing one or more changes propagating throughout a system by considering indirect and direct connections (Clarkson, Simons, and Eckert 2004; Keller, Eckert, and Clarkson 2009, 2010; Koh, Caldwell, and Clarkson 2012; Ahmad, Wynn, and Clarkson 2013).

Originally, the CPM only handled changes initiated by one subsystem (Clarkson, Simons, and Eckert 2004), but Ahmad, Wynn, and Clarkson (2013) suggested a modification that allowed the method to accommodate changes initiated by multiple subsystems. Upon suggesting this modification, Ahmad, Wynn, and Clarkson (2013) proposed a framework using the CPM and cross-domain DSMs to consider the effects of multiple changes on product requirements, functions, components, and detailed design processes. Lastly, the effect of multiple change options on product requirements combined the work of Ahmad, Wynn, and Clarkson (2013) and the House of Quality (Koh, Caldwell, and Clarkson 2012). This paper builds on these developmental efforts by linking CPM outcomes with customer preference models for the first time.

3. Proposed approach

This work begins with the assumption that a base product exists and that product modifications are being explored to bring additional variety to the market. These modifications can be physical/functional changes to a product subsystem, emotion-focused changes (such as colour), or changes to the accessory items that are bundled with the base product.

The following subsections describe the proposed approach, shown in Figure 4, to enable the combination of CPM and DCA outputs to explore the market-engineering space trade-offs associated with different product modifications. First, the potential subsystems of the product are identified. Once potential options are generated, a change analysis is conducted to determine the cost of engineering rework. Market desirability is then assessed using DCA to determine the amount of market share captured from the competition and cannibalisation of share from existing product offerings. This information is then aggregated with the engineering rework analysis to explore the trade-off between market desirability and redesign effort for each option.

3.1. *Explore risk associated with changing product subsystems*

The first step of this approach is to explore the risk resulting from the modification of different product subsystems. The CPM output is a combined risk matrix. However, as shown in Figure 3, this combined risk matrix can be difficult to interpret when the number of subsystems is large. An alternative approach is to create a risk portfolio plot to explore whether a subsystem has a low risk for propagating changes to other systems (Keller, Eckert, and Clarkson 2009).

A risk portfolio plot is created by first calculating each subsystem's combined outgoing risk, which is the average of the column values of the combined risk matrix in Figure 3. These values are plotted on the x-axis. The combined incoming risk values are calculated by averaging the row values of the risk matrix. These values are plotted on the y-axis, as shown in Figure 5. The top left quadrant of a risk portfolio plot contains change absorbers, while the bottom right quadrant contains change multipliers. The diagonal line represents change carriers, or subsystems that have the same amount of incoming risk as outgoing risk.

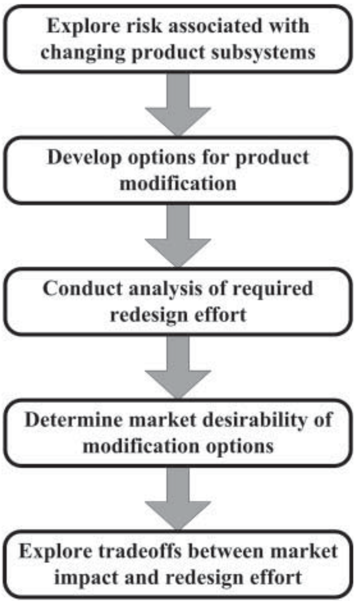


Figure 4. Major steps of the proposed approach.

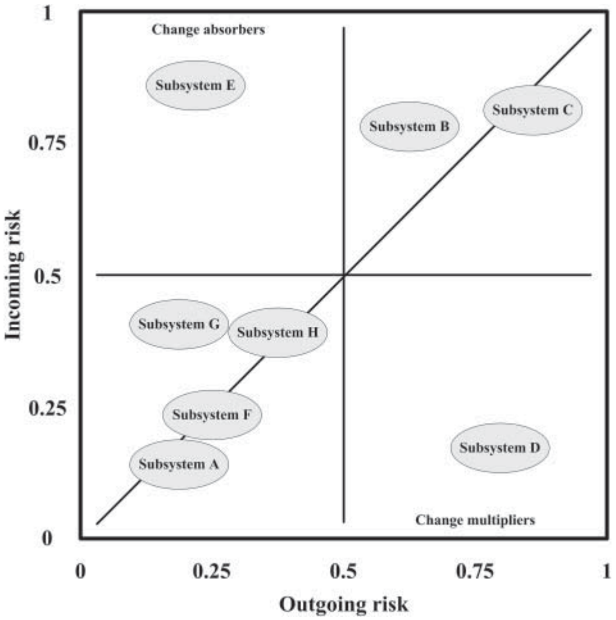


Figure 5. Example of a risk portfolio plot.

Considering only change propagation, subsystems in the lower left quadrant of the plot are good candidates for modification because of the low incoming and outgoing risk. Conversely, subsystems in the upper-right quadrant may pose challenges worth avoiding because of their high-risk nature when both incoming and outgoing risks are considered. Change absorbers can also be an attractive subsystem to investigate as there is minimal resultant risk. The subsystems selected for further investigation must be chosen by the design team when considering the costs, time, and effort required to make changes to the system.

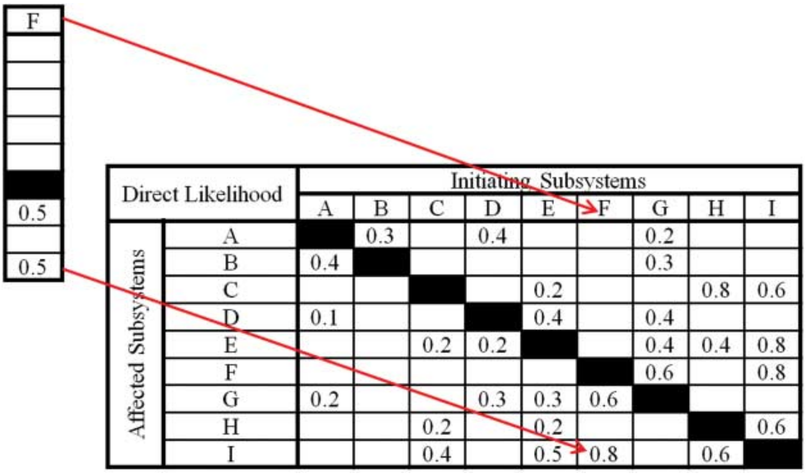
3.2. *Develop options for product modification*

For the subsystems chosen in the previous step, conceptual-level options for product modification must be created. If available, this brainstorming process could be aided by existing customer feedback for the base product. Without this information, concept generation tools such as the gallery method or the 6-3-5 method could be used (Otto and Wood 2001). This step is not unique to the design process, and significant research has been done in the area of concept generation. Once completed, the options developed in this step should exist at a level of detail that allows a designer to understand how one or more subsystems might be impacted or changed.

3.3. *Conduct analysis of required redesign effort*

Having generated options for product modification in the previous step, the goal here is to understand the amount of engineering redesign effort needed to integrate this option into a particular subsystem. Options explored during this step might be selected to (1) broaden the scope of modifications considered by the design team, (2) consider modifications requiring little engineering rework, or (3) assess modifications expected to have significant market desirability. In this work, only modification options that have a 1-to-1 mapping to a single subsystem are considered. This restriction is due to current limitations of the CPM approach, and can be relaxed as extensions to CPM are proposed and verified. Initial efforts in this direction have explored how the likelihood matrix is impacted by multiple changes (Ahmad, Wynn, and Clarkson 2013).

To begin this analysis, options for product modification are mapped to the corresponding subsystem of the base product. If necessary, extra information gained from a specific option under consideration can be used to update the impact and likelihood values in the DSM. Since each option relates to a single subsystem, only the column relating to the specific option being considered requires updating, as shown in Figure 6. This update is possible, and perhaps necessary, because average change values were originally considered in Section 3.1. From the updated direct impact and likelihood values, an updated combined risk matrix is then generated.



Direct Likelihood		Initiating Subsystems								
		A	B	C	D	E	F	G	H	I
Affected Subsystems	A	■	0.3		0.4			0.2		
	B	0.4	■					0.3		
	C			■		0.2			0.8	0.6
	D	0.1			■	0.4		0.4		
	E			0.2	0.2	■		0.4	0.4	0.8
	F						■	0.6		0.8
	G	0.2			0.3	0.3	0.6	■		
	H			0.2		0.2			■	0.6
	I			0.4		0.5	0.8		0.6	■

Figure 6. Replacing average values with specific values for a modification option.

Total redesign effort of an option is calculated by estimating the total cost to produce the base product with the considered option. For modifications initiated by changing an existing subsystem, the total cost should include the redesign effort associated with changing the initiating subsystem and the effects on other subsystems. Equation (1) uses the cost framework introduced in Keller, Eckert, and Clarkson (2010) as a basis to calculate estimated total cost, $\mathrm{ETC}_{k,i}$, to produce a product with modification, k, initiated by changing subsystem, i.

$$\mathrm{ETC}_{k,i} = \mathrm{rework}_{k,i} + \sum_{j=1}^{N} \mathrm{fix}_j + \sum_{\substack{j=1 \\ j\neq i}}^{N} \mathrm{rework}_j (E_{k,i\to j})(r_k(i \to j)), \tag{1}$$

In this equation:

- fix_j is the total cost for subsystem j of the base product,
- $\mathrm{rework}_{k,i}$ is the estimated cost to change subsystem i to offer modification k,
- rework_j is the estimated average cost to change subsystem j,
- $E_{k,i\to j}$ is the expected number of changes initiated by subsystem i on subsystem j for modification k,
- $r_k(i \to j)$ is the risk of initiating subsystem i affecting subsystem j for modification k, and
- N is the total number of subsystems.

The term fix_j includes all design, material, and manufacturing costs associated with subsystem j of the base product and the terms $\mathrm{rework}_{k,i}$ and rework_j capture any changes to these costs as a result of offering modification k. Note, the total cost of the base product can be obtained by holding $\mathrm{rework}_{k,i}$ and rework_j at zero for all subsystems. Estimates for these values can be obtained by considering the specific change made to a subsystem and historical change data or opinions from engineering experts. Estimates for total costs can also include changes to the manufacturing process, such as additional costs due to new machinery, increased workforce, and production process complexity.

3.4. *Determine market desirability of modification options*

DCA is a well-established marketing method that allows a quantitative measure of customer preference for the different features comprising a product. When respondents complete a suite of choice-task questions by selecting the product most preferred in each question, it is possible to estimate the part-worth utility for each attribute level (Ben-Akiva and Lerman 1985; Train 2003). It is often assumed that overall product utility can be calculated as a sum of one part-worth value from each attribute. When this is done for multiple products, the likelihood of one product being chosen over the others in a competitive market can be estimated. The utility that decision-maker i receives from product l is often expressed as a function of alternative attributes (x_{il}), the coefficients of the alternative attributes (β), and consumer attributes (s_i), as in Equation (2). Alternative attributes correspond to performance, price, and other system characteristics, and are statistically estimated using the data gathered from the various choice-task questions fielded.

$$V_{il} = f(x_{il},\ \beta, s_i). \tag{2}$$

A mathematical model commonly used to estimate attribute-level part-worths is MNL regression (Ben-Akiva and Lerman 1985; Train 2003). However, in their standard form these models do not capture market heterogeneity. HB mixed logit demand models extend the random utility model to allow for the estimation of part-worths (β) for each individual respondent.

When the utility for multiple products in a competitive market is calculated, the probability of a decision-maker choosing one of those products can be determined. Equation (3) is used to calculate the probability of the ith respondent selecting the lth product from a set of products considered in the market k, where $k \in \{1 \cdots K\}$. The number of product attributes is given by j, and the utility of not selecting any of the product is given by $V_{i,\text{none}}$. The MSP for a given product (l) is then given by Equation (4).

$$p_i^l = \frac{\mathrm{e}^{\sum_j X_{ijk}\beta_J}}{\sum_{k=1}^{K} \mathrm{e}^{\sum_j X_{ijk}\beta_J} + \mathrm{e}^{V_{i,\text{none}}}}. \tag{3}$$

$$\mathrm{MSP}_l = \frac{\sum_{i=1}^{N} p_i^l}{N} \times 100. \tag{4}$$

In Equation (4), N is the total number of respondents who took the survey and i is an individual respondent. This equation can then be used to evaluate a product's estimated likelihood of purchase at the market level. To do this, the following products are considered in the market:

- the modified base product,
- the original base product(s) offered by the manufacturer,
- the competitor's products, and
- the outside good (none, or walk-away, option).

Changes in MSP can then be calculated for the firm and the competition. This is done by comparing MSP values from the original market scenario (original good, competitor products, and none option) to the results from the new market scenario. Table 1 demonstrates a hypothetical example of these calculations for a scenario with four different proposed product modifications. Note that in this form, only one modified base product is considered in the market at a time. Also, the competitor product calculations include the None option.

In Table 1, a negative change in MSP for the competition or the base product indicates that share of preference has been diverted to the modified product. Ideally, a firm would adopt a modification that diverts no share of preference from the base product and a large negative change in MSP for the competition. In the aforementioned example, Option 2 reflects this idealised case. This makes it more desirable than Option 1 or 3. Options 1 and 3 divert little, if any, share from the competitor and instead divert share from the firm's base product. Options 2 and 4 both produce changes in competitor MSP. Option 4 also produces a loss in MSP for the base product, while Option 2 does not. However, Option 4 does lead to an overall positive change in MSP for the firm. Selecting the best product modifications to pursue requires both market desirability and the engineering redesign effort to be considered. This is done in the next section by combining the results of Sections 3.3 and 3.4.

Table 1. MSP values for market scenarios.

Market scenario	Base product(s) MSP (%)	Modified product MSP (%)	Competitor product(s) MSP (%)	Change in base product(s) MSP (%)	Change in competitor product(s) MSP (%)
Original	30	0	70	–	–
Option 1	15	16	69	– 15	– 1
Option 2	30	20	50	0	– 20
Option 3	25	5	70	– 5	0
Option 4	20	25	55	– 10	– 15

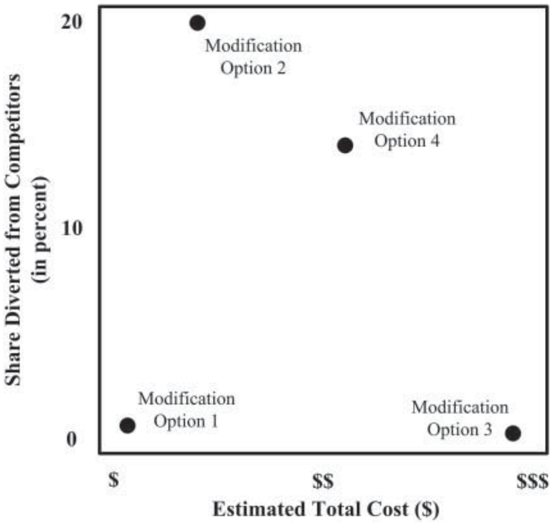


Figure 7. Product modification decision support tradeoff plot.

3.5. *Explore trade-offs between market impact and redesign effort*

The final step of this approach considers the trade-offs between the engineering and marketing domains to determine which product modification should be further developed. A tradeoff plot, such as that presented in Figure 7, provides a way to visually consider the engineering and marketing trade-offs associated with estimated total cost ($\mathrm{ETC}_{k,i}$) and the negative change in competition MSP for each considered modification. Proposed product modifications located in the upper-left corner are most desirable as they divert the largest amount of share from the competitor with minimal engineering rework cost. Options located in the bottom right corner have the highest estimated total cost and result in the lowest loss in MSP for the competition. These options are less desirable and a firm may want to avoid them since they offer limited value.

4. Demonstration of approach

To demonstrate this approach, a gas grill study is presented. The grill chosen as the base product is a Master Forge 2-burner gas grill with the following relevant characteristics:

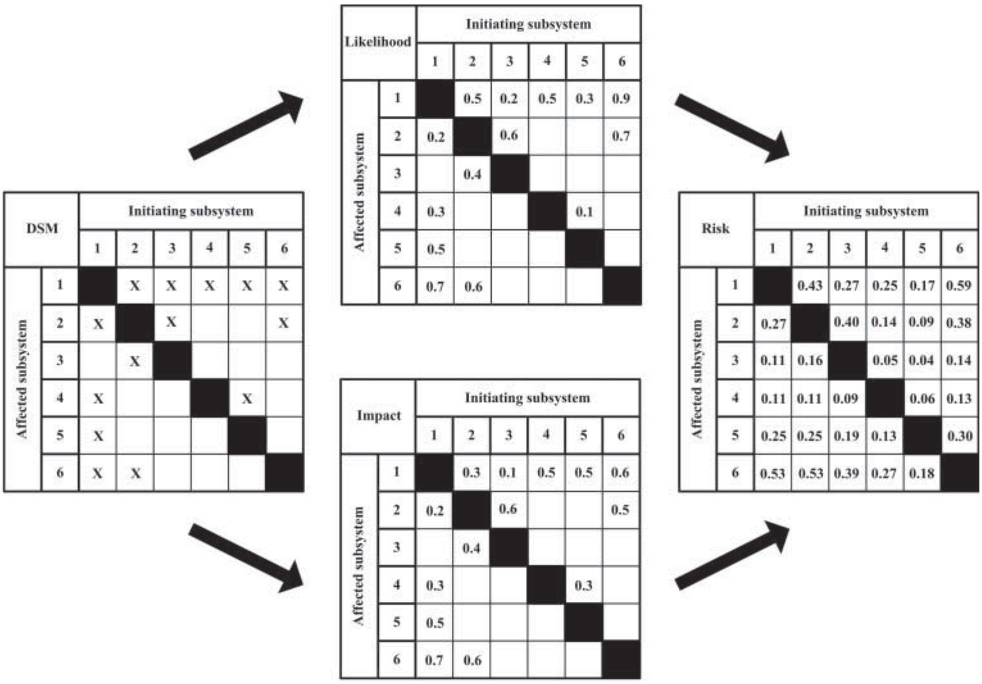
- 2 gas burners requiring liquid propane and electronic ignition button;
- 2 cast-iron cooking grates with a warming rack attached to the grill lid (cooking area of 455 square inches);
- Cabinet storage underneath the grill to hold 1 liquid propane tank;
- 2 foldable side tables with no tool hooks (THs) or side burners;
- 1 analog thermometer on the grill lid with no grill lights or cover;
- Painted steel construction with black finish, 4 casters, and 44 inches in height;
- Price: $237.

4.1. *Explore risk associated with changing product subsystems*

Using the assembly manual (Master Forge 2008), the grill is first decomposed into six subsystems as shown in Table 2. Subsystem 1 contains the grill body, which consists of the firebox, lid, and

Table 2. Description of grill subsystems.

Subsystem id	Subsystem description
1	Grill body
2	Control system
3	Fuel transport system
4	Side tables
5	Cart system
6	Cooking zones



DSM		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	X	X	X	X	X
	2	X	■	X			X
	3		X	■			
	4	X			■	X	
	5	X				■	
	6	X	X				■

Likelihood		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.5	0.2	0.5	0.3	0.9
	2	0.2	■	0.6			0.7
	3		0.4	■			
	4	0.3			■	0.1	
	5	0.5				■	
	6	0.7	0.6				■

Impact		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.3	0.1	0.5	0.5	0.6
	2	0.2	■	0.6			0.5
	3		0.4	■			
	4	0.3			■	0.3	
	5	0.5				■	
	6	0.7	0.6				■

Risk		Initiating subsystem					
		1	2	3	4	5	6
Affected subsystem	1	■	0.43	0.27	0.25	0.17	0.59
	2	0.27	■	0.40	0.14	0.09	0.38
	3	0.11	0.16	■	0.05	0.04	0.14
	4	0.11	0.11	0.09	■	0.06	0.13
	5	0.25	0.25	0.19	0.13	■	0.30
	6	0.53	0.53	0.39	0.27	0.18	■

Figure 8. Original CPM for gas grill.

grease drip pan and cup. Subsystem 2 consists of the controls and housing for each burner and the electronic ignition button. Subsystem 3 is the fuel line extending from the propane tank to the control system and travels through the firebox. Note that the propane tank itself is not included in this breakdown. Subsystem 4 comprises the side tables and their connections to the grill body. Subsystem 5 contains everything stored underneath the grill body. Finally, Subsystem 6 is the cooking zone. This includes the area inside the grill body in which the amount of heat reaching the food can be controlled through the amount of fuel burned and/or the height above the burning fuel. Subsystem 6 contains the burners, cooking grates, warming rack, and the heat tents.

Following decomposition of the grill into subsystems, the DSM can be created. Identification of these dependencies and values for direct likelihood and impact were defined by a group of graduate and undergraduate engineering students in the Department of Mechanical and Aerospace Engineering at North Carolina State University. The CPM toolbox within CAM (Wynn et al. 2010) is then used to calculate the combined impact, likelihood, and risk matrices. The DSM and values for the direct impact, direct likelihood, and risk matrices are shown in Figure 8.

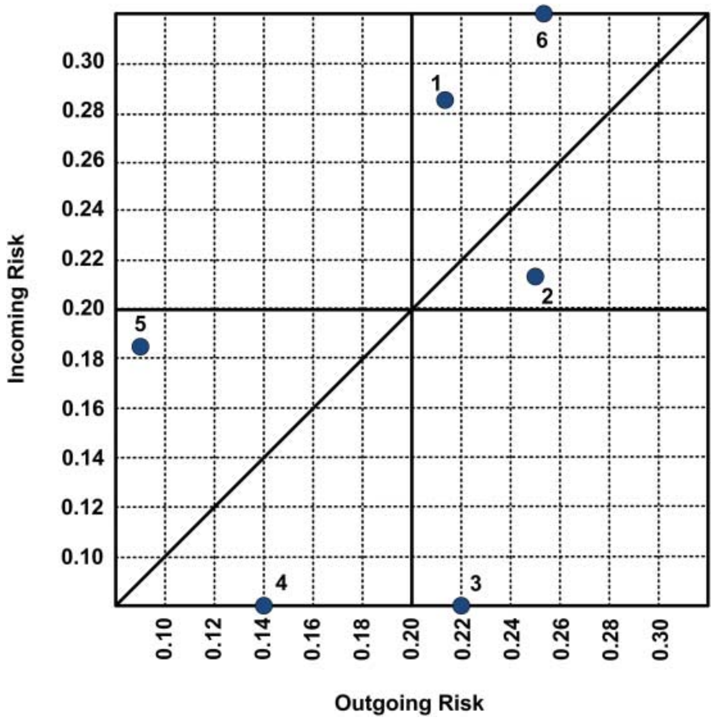


Figure 9. Gas grill scaled risk portfolio plot.

To further explore the risk of change propagation, a scaled risk portfolio plot is shown in Figure 9. Subsystems closer to the bottom left corner, such as Subsystems 4 and 5, are desired, as they have a very small incoming and outgoing risks. In contrast, Subsystems 1, 2, and 6 are closer to the top right corner of the scaled plot. At least in comparison to the other subsystems, these three have much larger risks associated with them.

4.2. *Develop options for product modification*

Before proposing possible product modifications using conceptual generation techniques commonly found in the literature (Goel 1997; Otto and Wood 2001; Pahl et al. 2006; Linsey, Markman, and Wood 2012), the authors fielded two surveys that asked respondents to comment on the likes and dislikes of their current grill(s). Five common suggestions were (1) 'add side burner', (2) 'add grill light', (3) 'change under-grill storage configuration', (4) 'add grill cover', and (5) 'offer customisation options'. The final suggestion, 'offer customisation options' was added as a result of a comment suggesting grill manufacturers 'provide options for add-ons such as take one side [table] off to add on a warmer or other feature'.

These customer suggestions were then mapped to the subsystems identified in Table 2. Additional concepts were generated by the authors and students in a senior/graduate-level design class offered at North Carolina State University. Nine student groups with 3–5 students each were given the grill's assembly manual and asked to generate as many possible modifications as possible. In total, over 200 changes were identified using techniques such as mind-mapping and the gallery method. As Subsystem 4 is identified in Figure 9 as being a 'low-risk' option for change, concepts related to this subsystem received particular attention. Beyond the suggestion of 'add side burner', other options identified involved adding

- 2 THs per side table,
- 4 THs per side table,
- 1 side burner and no THs,
- 1 side burner and 2 THs, and
- 1 side burner and 4 THs.

Other possible modifications identified included changing the

- lid opening mechanism from a manual open,
- height of the grill,
- grill colour,
- grill cover,
- under-grill cabinet storage configuration,
- cooking zone specifications from three zones (two main burners and a warming rack),
- analog thermometers, and
- lack of grill light.

Almost all of the options listed are related to only one subsystem. Exceptions include the grill colour (Subsystems 1, 2, 4, and 5) and grill cover (none of the subsystems directly). The full list of change options is presented in the Appendix (Table A1).

4.3. *Conduct analysis of required redesign effort*

To begin this step, new direct likelihood and impact values are defined for each product modification, as in Table 3. As an example, consider Subsystem 4 with the addition of a single side burner. When the dependency DSM was first created, as shown in Figure 8, the only interaction identified because of an initiated change in Subsystem 4 was with Subsystem 1. As more detail about the change is known, a dependency relationship with Subsystem 2 is identified because it is perceived to control the amount of fuel going to the new side burner. However, if a designer is simply to add THs to each side table, no interaction occurs with either Subsystem 1 or Subsystem 2.

Once experts define updated direct likelihood and impact values, the columns in Figure 8 are updated so that the combined risk matrix for each product modification can be calculated. These values become the $r_k(i \rightarrow j)$ values in Equation (1).

Since historical change data and cost information were unavailable for this product, the average rework costs were estimated for each subsystem. These costs were estimated by assuming that (1) the base cost of the product is 50% of the market price, (2) each subsystem cost (fix_j) is a percentage of the total cost, and (3) the average rework costs for each subsystem (rework_j) are 2/3 of the original cost (fix_j). Table 4 shows the average rework cost estimates for each subsystem.

Table 3. Updated direct likelihood values for two product modifications.

	Options	Baseline	1 Side burner	2 Tool hooks per table
Direct likelihood	Initiating subsystem	4	4	4
Affected subsystems	1 – Grill body	0.5	0.8	0
	2 – Control system		1	
	3 – Fuel transport system			
	4 – Side table			
	5 – Cart system			
	6 – Cooking zone			

Table 4. Average subsystem rework cost estimates.

Subsystem	Percentage of total product price (%)	Fix_j	Rework_j
1	33	\$39.60	\$26.40
2	14	\$16.80	\$11.20
3	5	\$6.00	\$4.00
4	10	\$12.00	\$8.00
5	22	\$26.40	\$17.60
6	16	\$19.20	\$12.80

For each specific product modification, $\text{rework}_{k,i}$ is estimated by Equation (5). Values for $E_{k,i\to j}$ are set to 1 or greater if $r_k(i \to j)$ is not zero, and are 0 otherwise. In this work, a majority of non-zero $E_{k,i\to j}$ values were set to 1. However, when considering the change to two main burners and three warming racks, $E_{k,2\to 3}$ is set to 2 because it is expected that Subsystem 1 will add two interfaces to accommodate the two new warming racks. With all elements of Equation (1) defined, the estimated total cost for each modification can be calculated as follows:

$$\text{Rework}_{k,i} = \text{rework}_j * \text{impact} + \tfrac{1}{3}\,\text{fix}_j. \tag{5}$$

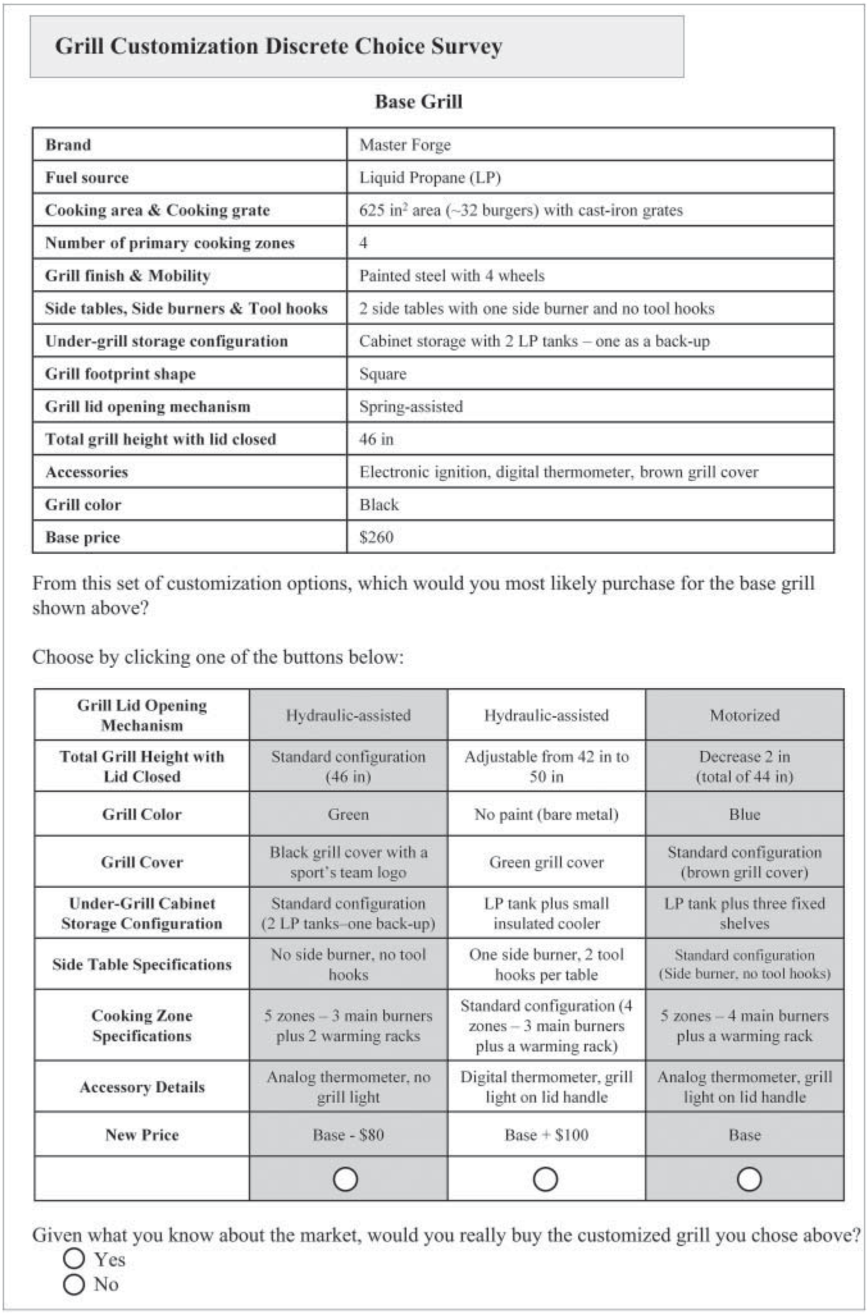
Product modifications focused on colour do require significant rework. Therefore, 5% of the total manufacturing and material cost of the base product is added to or subtracted (subtract 5% for the no paint option) from the overall cost of the base product. When considering accessory changes, a 100% markup is assumed for an existing base product and this value is added to the total cost of the base grill. A black cover with a logo is assumed to be 25% more cost due to possible copyright royalties. The outcome for each product modification is shown in the Appendix (Table A1).

If focused solely on pursuing options with the lowest estimated total cost, the best product modification to pursue is the no paint option with an estimated cost of \$116.84. Following this, the ‘2 Tool Hooks per Table’ option has an estimated total cost of \$120.90.

4.4. *Determine market desirability of modification options*

To create the choice tasks for the discrete choice surveys, the attributes and levels defined had to cover the entire range of product modifications considered. Additionally, levels that reflect the base product must also be considered in the scope of the survey’s design space. To capture price preferences of the survey respondents, a price attribute must also be created. For the survey fielded in this paper, the price attribute levels are defined with respect to dollars taken away from, or added to, the price of the base grill (e.g. ‘Base − \$20’, ‘Base’, and ‘Base + \$30’). Additional criteria used when defining the attributes and levels include ensuring that attributes are independent, that attribute levels are mutually exclusive, and that, where possible, the number of levels should be balanced across all attributes. The full listing of product levels and attributes defined for the survey is presented in the Appendix (Table A2).

The choice tasks were designed and created using Sawtooth Software’s SSI Web module (Sawtooth Software, Inc. 2008). Each respondent was shown 12 choice tasks, of which two were used as holdout tasks. Three full product profiles were shown in each task question, a balanced overlap survey design scheme was chosen, and a dual-response none option was selected. The survey was fielded online and respondents were first asked to choose from one of three base grills. Those respondents who chose the base grill associated with this problem were used to gather customer preference data. In total, data from 29 respondents were obtained. While this number of respondents may be appropriate for the investigative analysis conducted in this work, practitioners



Grill Customization Discrete Choice Survey

Base Grill

Brand	Master Forge
Fuel source	Liquid Propane (LP)
Cooking area & Cooking grate	625 in^2 area (~32 burgers) with cast-iron grates
Number of primary cooking zones	4
Grill finish & Mobility	Painted steel with 4 wheels
Side tables, Side burners & Tool hooks	2 side tables with one side burner and no tool hooks
Under-grill storage configuration	Cabinet storage with 2 LP tanks – one as a back-up
Grill footprint shape	Square
Grill lid opening mechanism	Spring-assisted
Total grill height with lid closed	46 in
Accessories	Electronic ignition, digital thermometer, brown grill cover
Grill color	Black
Base price	$260

From this set of customization options, which would you most likely purchase for the base grill shown above?

Choose by clicking one of the buttons below:

Grill Lid Opening Mechanism	Hydraulic-assisted	Hydraulic-assisted	Motorized
Total Grill Height with Lid Closed	Standard configuration (46 in)	Adjustable from 42 in to 50 in	Decrease 2 in (total of 44 in)
Grill Color	Green	No paint (bare metal)	Blue
Grill Cover	Black grill cover with a sport's team logo	Green grill cover	Standard configuration (brown grill cover)
Under-Grill Cabinet Storage Configuration	Standard configuration (2 LP tanks–one back-up)	LP tank plus small insulated cooler	LP tank plus three fixed shelves
Side Table Specifications	No side burner, no tool hooks	One side burner, 2 tool hooks per table	Standard configuration (Side burner, no tool hooks)
Cooking Zone Specifications	5 zones – 3 main burners plus 2 warming racks	Standard configuration (4 zones – 3 main burners plus a warming rack)	5 zones – 4 main burners plus a warming rack
Accessory Details	Analog thermometer, no grill light	Digital thermometer, grill light on lid handle	Analog thermometer, grill light on lid handle
New Price	Base - $80	Base + $100	Base
	○	○	○

Given what you know about the market, would you really buy the customized grill you chose above?

○ Yes
○ No

Figure 10. Sample choice-task question.

would want to have choice-task results from more respondents. Guidelines for an appropriate number of respondents needed as a function of survey design can be found in Orme (2006). A screenshot of a typical choice-task question used in this survey is shown in Figure 10, where a description of the base grill is also given as a reminder.

After collecting the survey responses, Sawtooth Software's CBC/HB module was used to estimate customer preferences at the level of the respondent (Sawtooth Software, Inc. 2009).

Table 5. Product pricing scheme for gas grill problem.

Attribute levels	Product attributes Lid opening	Total height	Colour	Cover	Storage configuration	Side table	Cooking zone	Accessory details
1	+ \$0	+ \$0	+ \$0	+ \$0	+ \$0	+ \$0	+ \$0	+ \$0
2	+ \$5	+ \$2	+ \$0	+ \$25	+ \$20	+ \$1	+ \$5	+ \$2
3	+ \$10	+ \$4	+ \$0	+ \$25	+ \$10	+ \$2	+ \$10	+ \$6
4	+ \$15	– \$2	+ \$0	+ \$25	+ \$15	+ \$30	+ \$10	+ \$2
5		– \$4	+ \$0	+ \$25	+ \$10	+ \$31	+ \$15	+ \$4
6		+ \$15	– \$10	+ \$30	+ \$30	+ \$32	+ \$20	+ \$8
7								

Table 6. Subset of market scenarios when considering product modifications.

Market scenario	Base product(s) MSP (%)	Modified product MSP (%)	Competitor product(s) MSP (%)	Change in base product(s) MSP (%)	Change in competitor product(s) MSP (%)
Original	48.1	0	51.9	N/A	N/A
3 Main burners and 2 warming racks	47.9	0.5	51.6	– 0.2	– 0.3
Motorised lid opening	44.2	6.3	49.5	– 3.9	– 2.4
Red gas grill	12.4	38.6	49.0	– 35.7	– 2.9
LP tank + trash can	26.2	33.5	40.3	– 21.9	– 11.6

Part-worths on the price levels were constrained so that a lower price is preferred to a higher price, and 20,000 burn-in iterations were used to stabilise the estimation. With part-worths for each individual respondent obtained, Equations (3) and (4) are used to obtain the MSP values for the current and potential market scenarios. To maintain a consistent product pricing scheme across all respondents, the values shown in Table 5 were added to the price of the base product. These values were chosen after considering the rework$_{k,i}$ numbers determined in Equation (5) and shown in the Appendix (Table A1). With this price scheme a competitive market was created that contained the base product and the outside good (the None option). The MSP for the base product was 48.1%, while the MSP for the None option was 51.9%.

To complete this step, each proposed product modification is considered independently. Now, the competitive marketplace is assumed to contain the modified product, the base product offered by the manufacturer, and the outside good. A subset of results from different market scenarios is shown in Table 6. These results suggest that adding an additional main burner and a warming rack has little impact on the market and is generally ignored from a share of preference perspective. A motorised lid captures 6.3% of the MSP; however, a majority of the share is diverted from the base product. Similarly, offering the grill in red captures the most share of preference of any of the options, but is done by cannibalising share from the base product. Conversely, adding a trash can to the storage area diverts share from both the base product and the competitor product. This option is also the one that captures the largest amount of share from the outside good.

4.5. *Explore trade-offs between market impact and redesign effort*

The previous sections calculated two important measures for each product modification: the total estimated cost of the product and the amount of MSP captured. When considered simultaneously,

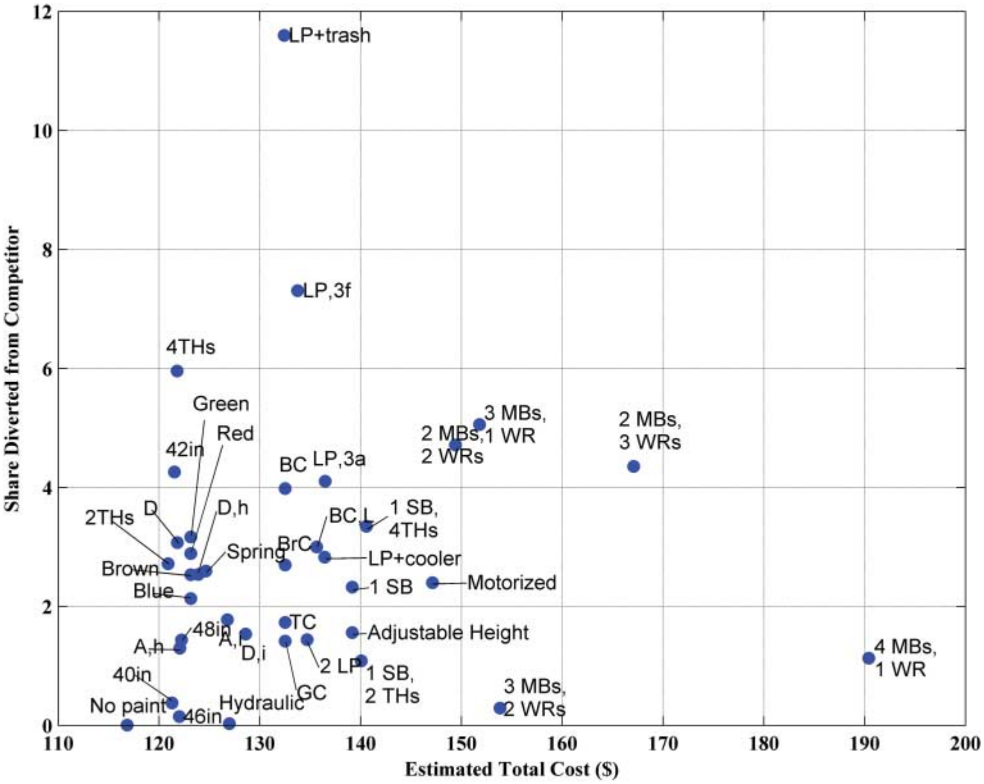


Figure 11. Gas grill tradeoff plot for product modification options.

these two measures provide insight into the interaction between the engineering rework necessary to make the modification possible and an estimation of market response. As suggested in Section 3.5, a tradeoff plot can be created to visualise the interplay between estimated total cost and the market share diverted from the competition for each option. This plot is shown in Figure 11 for the 38 product modifications considered.

This tradeoff plot allows a designer, and a firm, to explore the ramifications associated with pursuing different product modifications. Final decisions about which option(s) to pursue must take into account the multiple criteria that comprise a company's business goals. The results shown in Figure 11 can be used to help filter out concepts that should not be explored in greater detail. For example, the 'no paint' modification required the least rework and had the smallest risk of change propagation. Yet, this option results in essentially no MSP loss for the competition. Other product modifications that should not be pursued include options that require the addition of a side burner or a main burner. These options have larger estimated costs and small changes in competitor MSP.

The 'LP (Liquid Propane) + trash can' option adds over $20 to the estimated total cost of the product, but diverts significantly more share from the competition than other product modifications. Other options such as changing the colour of the grill or adding THs tend to result in very small cost increases while capturing new elements of the market. Yet a firm may not want to offer all possible colours, as the red and green options outperform the blue and brown colour options. The goal of this step is to consider the trade-offs between rework cost and diverted market share and identify which modification options should be developed further.

Table 7. Comparison of ETC values using different DSM values.

Combined risk case	Average ETC	Standard deviation of ETC
Original	\$135.60	\$16.10
Updated	\$138.53	\$17.94

As stated in Section 3.3, the results presented in Figure 11 correspond to the combined risk matrix calculated using modification-specific values for the direct likelihood and impact matrices. If the original DSM shown in Figure 8 is used, the estimated total cost remains unchanged for 13 options (those without change propagation), increases for 6 options, and decreases for 9 options. The data shown in Table 7 show that using the updated DSM and associated impact and likelihood values increases the average estimated total cost from \$135.60 to \$138.53. Additionally, the standard deviation increases by \$1.84. These results suggest that the combined risk values from the original DSM will group costs more tightly since 'average' impact and likelihood values are being used. With the additional detail that comes with defining a specific product modification, application-specific values of likelihood and impact should lead to larger distributions of estimated total cost. By doing so, a designer is able to 'add' risk to designs that will require greater rework than average (as in the 'LP + trash can' option) or 'subtract' risk from designs that will require less rework than average (4 main burners and 1 warming rack).

5. Conclusion and future work

The approach presented in this work introduces a strategy for simultaneously considering the engineering change and market response ramifications of a proposed modification. Tools such as the CPM have previously been introduced as ways to better understand and quantify the risks associated with change propagation. Gathering and modelling consumer preferences with DCA allow for the preference structure of a heterogeneous consumer population to be quantified. However, the outcomes from these approaches have not been previously combined to assist in the decision-making process when choosing which product modification(s) to offer.

To create the combined risk matrix for the CPM, a designer or design team must first define a DSM for the system and populate the direct impact and likelihood matrices. While creating a DSM for the system can be straightforward, defining values to populate the direct impact and likelihood matrices can be challenging and time-consuming. Since it is often unclear what changes might occur to a system when the DSMs are first created, a general assumption of the CPM is to use average values for an average redesign process. However, prior research has shown that variability in the direct impact and likelihood values can cause significant changes to the combined risk matrix (Jarratt, Clarkson, and Parks 2002; Von Hagel and Ferguson 2014). An update procedure is introduced in this work that replaces average direct impact and likelihood values for a system with impact and likelihood values specific to a proposed modification.

While updating the impact and likelihood values for each product modification can be laborious, results using original DSM values were shown to have more closely grouped estimated rework costs. This causes high-risk options to be shown as less risky. Using the updated values led to a combined risk matrix that returned a wider range of rework costs that may better represent estimates of the true design rework needed. If the CPM was not used to estimate combined risk and impact scores, a designer would be left to guess possible values without properly understanding the interacting nature between components as change propagates. Understanding the rework needed to change a product and the subsequent estimated cost can also be used as a first filter to remove product modifications that are obviously too costly or lead to unmanageable amounts of rework.

Rework provides an estimate of the challenges faced from an engineering perspective, but provides little insight into how the market will respond to the product. DCA is used to gather and quantifiably estimate the preference structure of a heterogeneous consumer population. This was accomplished by using changes in MSP to understand how a proposed modification would divert share from the product originally offered, and from the competition within the market. The data necessary for DCA can be easily gathered online once a representative sample of the expected consumer base is identified. In this work, the mean part-worth estimates from a HB mixed logit model were used to represent respondent preferences. While it is common practice to use holdout choice-task questions to verify the accuracy of the estimated model, sensitivity of market simulations could also be explored by accounting for the uncertainty in parameter estimation.

A non-trivial challenge associated with considering a large number of possible product modifications is managing the number of product attributes and attribute levels that appear in the choice-task questions. The ability to filter out modifications with extremely high risk and rework costs using the CPM outputs aids in reducing the scope of options considered. Furthermore, while the demonstrative problem in this paper used a simple market simulation to estimate shares of preference, market simulators can be easily expanded to handle additional products. The goal of this example was simply to demonstrate that the trade-offs between the engineering and marketing domains must be considered and can be navigated by this approach.

This work is a first step towards integrating these techniques. From a change management perspective, additional research is first needed to extend CPM to handle uncertainty analysis. Rather than using a single point value for the impact and likelihood matrices, combined risk scores should be calculated using probability distributions. This would move the estimates of rework cost away from a point estimate towards a range estimate. Additionally, future work should consider changes impacting multiple subsystems and multiple changes to a single product. Currently, the state of the art allows only a single change to a single subsystem.

Uncertainty must also be accounted for when estimating the MSP diverted from the competitor products. This would involve moving away from a point estimate of the part-worth values and using the mean and standard deviation of the part-worth coefficients determined during model estimation. Future work should also explore advancements in simulating a competitive market. While it is easy to add multiple competing products to a simulator, properly defining the scope and extent of this mix is not well understood for engineering design problems. Additionally, the fixed price structure used in Table 5 could be eliminated, allowing the price of the product to be treated as a design variable.

The results presented in Figure 11 provide insight into the interaction between market response and estimated rework costs that normally would not be available. There are also no discernible trends in the relationship between these factors for the different modifications. A designer could not reasonably state that as estimated costs of a change increase, the expected market response would increase or decrease. Therefore, this analysis is needed before modifications are further developed and resources committed. Significance of this work will be further enhanced by future validation efforts. One such approach towards validation would be to use a base product and rapid prototyping capabilities to simulate a product redesign effort.

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Appendix

Table A1. Complete set of product modifications considered.

Modification options	Subsystem	$\text{Rework}_{k,i}$	$\text{ETC}_{k,i}$
2 THs/table	4	\$0.90	\$120.90
4 THs/table	4	\$1.80	\$121.80
1 Side burner, 0 THs	4	\$5.20	\$166.08
1 Side burner, 2 THs/table	4	\$6.10	\$166.98
1 Side burner, 4 THs/table	4	\$6.60	\$167.48
Spring-assisted lid opening	1	\$4.64	\$124.64
Hydraulic-assisted lid opening	1	\$6.96	\$126.96
Motorised lid opening	1	\$11.60	\$137.60
40 inches height	5	\$2.00	\$122.00
42 inches height	5	\$2.24	\$122.24
46 inches height	5	\$1.52	\$121.52
48 inches height	5	\$1.28	\$121.28
Adjustable height	5	\$10.64	\$136.92
Brown gas grill	1, 2, 4, 5	N/A	\$123.16
Red gas grill	1, 2, 4, 5	N/A	\$123.16
Green gas grill	1, 2, 4, 5	N/A	\$123.16
Blue gas grill	1, 2, 4, 5	N/A	\$123.16
Bare metal gas grill	1, 2, 4, 5	N/A	\$116.84
Black grill cover	N/A	N/A	\$132.50
Brown grill cover	N/A	N/A	\$132.50
Tan grill cover	N/A	N/A	\$132.50
Green grill cover	N/A	N/A	\$132.50
Black grill cover with sport’s team logo	N/A	N/A	\$135.63
2 LP tanks	5	\$6.16	\$146.96
LP tank + 3 fixed shelves	5	\$5.22	\$138.35
LP tank + 3 adjustable shelves	5	\$7.96	\$141.09
LP tank + trash can	5	\$3.89	\$141.64
LP tank + small, insulated cooler	5	\$7.91	\$148.71
2 Main burners, 2 warming racks	6	\$2.68	\$136.42
3 Main burners, 1 warming rack	6	\$5.06	\$145.97
2 Main burners, 3 warming racks	6	\$4.72	\$156.94
3 Main burners, 2 warming racks	6	\$7.10	\$156.54
4 Main burners, 1 warming rack	6	\$8.20	\$186.68
Analog thermometer, lid handle grill light	1	\$2.07	\$122.07
Analog thermometer, inside lid grill light	1	\$6.78	\$126.78
Digital thermometer, no grill light	1	\$1.82	\$121.82
Digital thermometer, lid handle grill light	1	\$3.89	\$123.89
Digital thermometer, inside lid grill light	1	\$8.60	\$128.60

Table A2. Attributes and levels for choice-task questions.

Attributes	Levels						
	1	2	3	4	5	6	7
Lid opening	Manual	Spring-assisted	Hydraulic-assisted	Motorised			
Total height	44″	46″	48″	42″	Adjustable (40–48″)		
Colour	Black	Brown	Red	Green	Blue	No Paint	
Cover	Absent	Black (BC)	Brown (BrC)	Tan (TC)	Green (GC)	Black with logo (BC,L)	
Storage configuration	LP tank only	2 LP tanks	LP tank + 3 fixed shelves	LP tank + 3 adjustable shelves	LP tank + trash can	LP tank + small insulated cooler	
Side table	0 SB, 0 TH	2 THs/table	4 THs/table	1 SB, 0 TH	1 SB, 2 THs/table	1 SB, 4 THs/table	
Cooking zone	2 MB, 1 WR	2 MB, 1 WR	3 MB, 1 WR	2 MB, 3 WR	3 MB, 2 WR	4 MB, 1 WR	
Accessory details	A	A,h	A,i	D	D,h	D,i	
Price ($)	Base − 20	Base	Base + 30	Base + 60	Base + 90	Base + 120	Base + 150

LP, liquid propane; SB, side burner; TH, tool hooks; MB, main burner; WR, warming rack; A, analog thermometer; D, digital thermometer; h, lid handle grill light; i, inside lid grill light.