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Over-Design Versus Redesign as a Response to Future Requirements

Though little research has been done in the field of over-design as a product development strategy, an over-design approach can help products avoid the issue of premature obsolescence. This paper compares over-design to redesign as approaches to address the emergence of future requirements. Net present value (NPV) analyses of several real world applications are examined from the perspective of manufacturers (i.e., defense contractors, automobile, pharmaceutical, and microprocessor manufactures) and customers (i.e., purchases of vehicles, televisions, cell phones, washing machines, and buildings). This analysis is used to determine the conditions under which an over-design approach provides a greater benefit than a redesign approach. Over-design is found to have a higher NPV than redesign when future requirements occur soon after the initial release, discount rates are low, initial research, and development cost or price is high, and when the incremental costs of the future requirements are low. [DOI: 10.1115/1.4042335]

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1 Introduction

Products are often designed with capabilities to meet a specific set of current customer requirements. If a future requirement is added during the service life of the product, the current capabilities of the design may not be sufficient. Two approaches to address the emergence of future requirements are (i) redesigning the product after a new requirement emerges and (ii) over-designing the product, during initial development, in anticipation of a future requirement. While over-design occurs during the original design period, and hence takes advantage of the original design team's momentum and design awareness, it nevertheless requires additional engineering, qualification, and production costs. Since a redesign project occurs sometime after the original design period and dispersement of the original team, it requires a rethinking of the product's capabilities and their mutual interactions. Updating even one part of a product (through redesign) can have a ripple effect throughout the entire product. As such, redesign can cost more than is originally planned. Additionally, redesign necessitates the allocation of resources that could be used in more cost effective activities. There are, however, advantages to both over-design and redesign approaches. In this paper, over-design and redesign are analyzed to determine the conditions under which one provides a greater benefit than the other.

While there are limited examples of over-designed products, two examples do exist: (1) buildings and (2) production systems. Buildings have been over-designed in terms of space, power, and heating, ventilation, and air conditioning in anticipation of future needs. As the business expands the space is consumed or as the business evolves the need for increased power or heating, ventilation, and air conditioning may arise. Likewise production systems are often over-designed, in terms of space (depth, width, and height), speed/performance, power, cleanliness, and electrostatic isolation, to accommodate the production of future products. Thus, the significant cost of designing and implementing the production system can be mitigated to a degree.

In contrast, there are numerous examples of products, which are redesigns of previous products. These products are sometimes referred to as families or evolutions. Examples include generations of cell phones or computer peripherals. The C-130 Hercules aircraft is an excellent example of a product which has undergone numerous redesigns. It was originally conceived as a cargo plane. Subsequent redesigns include troop carrier, aerial refueling tanker, airborne command and control center, and gunship to name just a few of its more than 70 redesigns.

Methods to reduce the impact of a redesign have been extensively explored in the engineering literature. Some of these methods include product family platforms [1–3], modularity [4–6], flexibility [7–9], reconfigurability [10,11], transformability [12], and adaptability [13,14]. These methods do not remove the need for multiple designs or redesigns. However, the impact of the additional designs is reduced by minimizing the number of components to redesign, by manipulating components in the product to address new requirements, or by other means. Martin and Ishii [15] have presented a technique to quantify the variability provided by the above methods. These methods have focused on reducing the impact of the redesign costs, while avoiding over-design.

Over-design is an additional approach to address the impact associated with the emergence of future requirements, but has not been explored as thoroughly as approaches related to redesign. A review of four prominent journals (i.e., Journal of Mechanical Design, Journal of Design Engineering, Research in Engineering Design and Management Science) provides insight into the treatment of over-design in existing literature (Table 1).

In a literature survey of articles in the Journal of Mechanical Design, over the last 37 years, there are 12 articles that speak about over-design. Eight of these articles speak negatively about over-design while three are neutral and only one is positive [16]. Similar results are observed when other popular engineering design journals are surveyed. Since 1992, there have been eight articles in the Journal of Engineering Design that speak about

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Table 1 Survey of over-design in the recent literature including: Journal of Mechanical Design (JMD), Journal of Engineering Design (JED), Research in Engineering Design (RED), and Journal Management Science (MS)

	JMD	JED	RED	MS
Timeframe	1980–2017	1991–2017	1988–2017	1994–2017
Articles mentioning over-design	12	8	3	8
Negative	8	7	2	7
Neutral	3	0	0	1
Positive	1	1	1	0

over-design. All but one of these speak negatively about over-design. Again the one article that does not speak negatively about over-design only acknowledges the value of over-design as it relates to safety factors [17]. There have been three articles in Research in Engineering Design that discuss over-design. Of these three articles only one refers to over-design in a positive manner [15]. In the past 23 years, there were eight articles that speak about over-design in the journal Management Science. All but one article reference over-design in a negative manner. The one non-negative article did not emphasize the positive attributes of over-design, but did refer to it as a potential product design approach [18]. As a result of the research opposing over-design, much of the engineering community may not consider over-design as a valuable design approach. The impression that over-design is to be avoided has perhaps unnecessarily influenced those who might benefit from its implementation.

The value of over-design versus redesign changes depending on the perspective from which it is viewed. To analyze the value of over-design as compared to redesign, two points-of-view are discussed in this paper: the manufacturer and customer. Addressing these two points-of-view is important because the benefits to the manufacturer can be different than the benefits to the customer. Both manufacturer and customer must incur upfront and recurring costs independent of whether an over-design or redesign approach is used. The difference in the value realized by an over-design or redesign approach, from a manufacturer's or a customer's perspective, lies in the timing and relative values of these costs. The purpose of this paper is to analyze the relative value of the approaches and determine under what conditions over-design or redesign provides the greater benefit. Following a literature review in Sec. 2, Sec. 3 presents the theoretical approach used in this paper to evaluate the relative value of over-design and redesign approaches. In Sec. 4, conditions in which an over-design approach provides a higher net present value (NPV) than a redesign approach are presented (e.g., low discount rates, early emergence of future requirements). The authors concluding remarks are contained in Sec. 5.

2 Literature Review

Redesign is sometimes seen as an opportunity for new product sales, but it can also add complexity and risk to existing products. Reasons for a product redesign include adding product capabilities, improving safety, correcting errors, and resolving product quality problems [19]. Additionally, companies redesign products to entice customers to buy more products [20]. In an effort to capitalize on new products, Lobel et al. [21] detail how and when successive products should be released. Though launching new products can be rewarding, a trade-off must be made between the increased revenue and cost required by the redesign. The costs of redesign are dependent on the changes involved in the redesign. The design changes frequently propagate throughout other components in the design. These propagated changes are often unforeseen and can result in a substantial increase in the cost of the redesign [22]. Though redesigning a product can be valuable, it often carries high unanticipated costs [23].

There are many design tools that attempt to reduce the negative impact that results from a redesign. Some of these approaches try to decrease the amount of components redesigned or decrease the costs of redesign [7,24]. Adaptable design is a design method used to make products easily upgradeable by using a similar design in multiple products [25]. The ability to use a design in more than one product saves time and resources [26]. A design theory similar to adaptable design is product families. Together the members of a product family have more capabilities than a single product does [27,28]. Like adaptable design, the products in a product family share a common architecture. This means that fewer components are designed for each new product [18,28]. In addition, manufacturing production efficiency improves when the products produced are similar, as in a product family [29]. While these approaches do not eliminate redesign they do decrease the cost of redesign by sharing similar architecture across several products.

Other design approaches reduce the cost of redesign by dividing the redesign into more manageable pieces. Some of these approaches include modularity and flexible product design. Modularity is a method whereby many of these design approaches can be completed. Modularity adds capabilities by physically adding or changing a module that carries a capability [30,31]. Module redesign can also be easier than a redesign of the whole product [31,32]. Flexible products often employ modularity to facility changes [7,33,34]. The ability of flexible products to change during the service life can make them last longer than other products [35]. Flexible designs can accommodate some future requirements without knowing the necessary capabilities by allowing the addition of capabilities in the future [9]. One goal of these design approaches is to simplify changes of the product by allowing them to apply to all or portions of the product. Redesign may still be necessary with these design approaches, but is simplified by not doing a full system redesign.

Moreover, other design approaches attempt to avoid redesign entirely by manipulating the product. Reconfigurability allows for a product to adapt to new requirements without redesign [10,36]. Reconfigurability allows a design to have the specific capabilities needed for one set of requirements, and after the product is rearranged, it can have different capabilities for a different set of requirements [37]. Transformability is another design strategy that allows the product to change [12]. Transformability is similar to reconfigurability in that the product can have many transformations that allow it to have several different sets of capabilities [38]. These two design approaches, reconfigurability, and transformability, attempt to add new capabilities by allowing the product to change itself.

Design approaches related to redesign are prominent in the literature, but over-design approaches and analysis are not. Coman and Ronen [39] give approaches to avoid over-design and say that over-design results from designers who try to assess and address all possible customer needs. Shmueli et al. [40] indicate that a designer's emotional attachment to a design can motivate them to add all possible capabilities. Additionally, Thompson et al. [41] and Rust et al. [42] have found that extra product features, can detract from the main product capabilities. Rust et al. [42] further determined that adding nonsensical capabilities to products can also damage customer trust in the product brand. This research suggests that over-designing a product is an inefficiency that must be avoided. However, an over-designing approach, with purpose, can be beneficial by extending the life of a product.

Over-design has not been explored, but, as is shown in this paper, it can be a viable design approach to avoid redesign. Products that are able to adapt to new environments and new customer needs will outlast products that have a narrow focus on a few customer requirements [26]. New products can have issues with reliability when they are used in an unintended manner [43]. Therefore, if both the intended use and unintended use capabilities are built into a product, this shortcoming can be avoided. In addition, the worth of a product to a consumer increases when more features are added, as long as the features are congruent [44]. This is especially true when a feature is unique to one product [45]. The principle of usable excess quantifies the value of individual elements of excess capability, thus directing designers toward incorporating the most usable excess capabilities in their designs [46].

The purpose of this paper is to objectively evaluate over-design versus redesign approaches. Various tests are carried out, and the conditions under which one approach is more beneficial that the other is discovered.

3 Models of Over-Design and Redesign

Over-design and redesign are two distinct approaches to address the emergence of future requirements. For the purposes of this paper over-design and redesign are defined based on initial and future product requirements. By definition, an optimal design meets all product requirements without excess or margin. A redesigned product is based on an initial product optimally designed to meet the initial requirements. It is later redesigned to optimally meet both the initial and future requirements. Thus, two product designs (initial and redesigned) are involved in a redesign approach. An over-designed product is initially designed to optimally meet both the initial and future requirements. It is over-designed with respect to the initial requirements, but optimally designed to meet both the initial and future requirements. Only one product is involved in an over-design approach.

The evaluation of each of these approaches is more complete if it includes an analysis from two different perspectives: manufacturer's and customer's, because the benefits to the customer can be different than the benefits to the manufacturer. To perform this analysis, the benefits and costs to the manufacturer or customer must be understood and quantified. From the manufacturer's perspective, this can be accomplished by observing a company's financial performance. A manufacturer derives benefit in the form of revenue received from the sale of a product. The benefit (revenue) is enabled by an initial research and development investment and is sustained by paying the ongoing manufacturing cost of goods sold (COGS). Cost of goods sold includes the direct materials included in the product, direct labor required to produce the product, factory overhead, and production supplies required by production to produce the product. For example, automobile companies, such as Ford [47], Toyota [48], Honda [49], and General Motors [50] which publish their financial performance indicate that as a percentage of revenue (1) R&D costs are 4–5% and (2) COGS are 77–83%. Therefore, the costs of a hypothetical or typical automobile includes approximately 4.5% for R&D costs and 82.5% for COGS. Other companies and hence their products can be evaluated in a similar manner. Data for several companies is discussed in further detail in Sec. 4.

A customer purchase can be evaluated in a similar manner. A customer derives benefit from the use of a product. The benefit is enabled by purchasing the product for a price and sustained by paying the associated in-service costs (i.e., maintaining the product, in some cases providing fuel or power, and paying any necessary fees or licenses). For example, the in-service costs of owning a home may include: (1) the cost of maintenance (e.g., repairs, new carpet, paint), (2) utilities (e.g., power, water, trash), (3) homeowners fees, and (4) taxes.

In essence both the manufacturer and the customer must make an upfront payment (R&D costs for the manufacturer and price for the customer) and pay ongoing costs (COGS for the manufacturer and in-service cost for the customer).

The initial product price relative to ongoing in-service costs that a customer must bear can be very different than the initial research and development (R&D) cost relative to the ongoing COGS that a manufacturer must bear. As will be shown, these ratios have a significant effect on the relative value of over-design versus redesign.

Each approach has strengths and weaknesses. The strength of the over-design approach is that only one product is designed and produced (or purchased and maintained); however, the weakness is that its R&D cost (or price) and its COGS (or in-service costs) are higher until the future requirements are demanded. Conversely, the strength of the redesign approach is that the ongoing manufacturing cost (or cost of ownership) are lower and more closely match the immediate demand, while the weakness is that two designs (or purchases) are required. The question then is: under what conditions is it more advantageous to produce or purchase an over-designed product with potentially higher initial costs than a pair of products that more closely match the immediate needs? To answer this question, a comparison is made of the costs and benefits of each approach. This comparison is made by calculating the difference in the NPV of each approach.

3.1 Evaluation of Over-Design Versus Redesign Based on Cash Flow.

The evaluation of an over-design versus a redesign approach can be performed by a financial analysis comparing the NPV of each approach. The NPV is based on cash flows representing the costs and revenue or customer benefit function for each approach. The relative value of the two approaches is calculated by taking the difference of each approach's NPV, as shown below:

$$\Delta \text{NPV} = \text{NPV}_{\text{Over-design}} - \text{NPV}_{\text{Redesign}} \quad (1)$$

where ΔNPV is the difference in the NPV of the over-design approach cash flow ($\text{NPV}_{\text{Over-design}}$) and redesign approach cash flow ($\text{NPV}_{\text{Redesign}}$).

Figure 1 is included as a simplified illustration of these cash flows. Figure 1(*a*) depicts the cash flows that a manufacturer experiences, while Fig. 1(*b*) depicts cash flows that a customer experiences. The horizontal axis is time, beginning at the point of the first expense and ending when the revenue or customer benefit is concluded. The vertical axis of each figure represents monetary value (revenue and benefit function above the horizontal axis and costs below it). Each figure depicts the cash flows constituting the respective cash flow. Revenue (or customer benefit function), R&D costs (or price), cost of goods sold (or in-service costs), and other costs associated with the design and manufacture (or purchase) of a product to address the initial requirements are included in each cash flow figure. The figures representing the redesign and over-design approaches also include incremental values, such as increment revenue, R&D costs (or price), COGS (or in-service costs), and other costs. These incremental values represent the additional benefits or cost resulting from the emergent requirements. In Figs. 1(*a*) and 1(*b*), these values are designated as follows:

Figure 1 is used throughout this paper as a pictorial aid to conceptualize the analysis and evaluation. This section reviews the models (terms and equations) used in the analysis of each approach.

From the manufacturer's perspective Eq. (1), the difference in NPV, is written more precisely as

$$\Delta \mathrm{NPV}_{\mathrm{Mfrs}} = \mathrm{NPV}_{\mathrm{Mfrs\,Over\text{-}design}} - \mathrm{NPV}_{\mathrm{Mfrs\,Redesign}} \tag{2}$$

where $\Delta \mathrm{NPV}_{\mathrm{Mfrs}}$ is the relative value of the over-design approach as compared to the redesign approach from a manufacturer's perspective, $\mathrm{NPV}_{\mathrm{Mfrs\ Over\text{-}design}}$ and $\mathrm{NPV}_{\mathrm{Mfrs\ Redesign}}$ are the net present values of the over-design and redesign approaches. A positive value of $\Delta \mathrm{NPV}_{\mathrm{Mfrs}}$ indicates that the over-design approach has a higher NPV, while a negative value indicates the redesign approach has a higher NPV.

Similarly from a customer's perspective a more precise version of Eq. (1), the difference of the NPV of the two approaches, is

$$\Delta \mathrm{NPV}_{\mathrm{Cust}} = \mathrm{NPV}_{\mathrm{Cust\,Over\text{-}design}} - \mathrm{NPV}_{\mathrm{Cust\,Redesign}} \tag{3}$$

where $\Delta \mathrm{NPV}_{\mathrm{Cust}}$ is the relative value of the over-design approach as compared to the redesign approach from a customer's perspective, $\mathrm{NPV}_{\mathrm{Cust\ Over\text{-}design}}$ and $\mathrm{NPV}_{\mathrm{Cust\ Redesign}}$ are the net present values of the over-design and redesign approaches. Once again, a positive value of $\Delta \mathrm{NPV}_{\mathrm{Mfrs}}$ corresponds to higher NPV for the over-design approach, while a negative value corresponds to a higher NPV for the redesign.

The NPV of each of the cash flows indicated in Fig. 1 can be calculated using well-known time value expressions. The present value of future cost or benefit (such as the price in Fig. 1(*b*)) is

$$\mathrm{PV} = A(1+v)^{-a} \tag{4}$$

where PV is the present value of the future cost or benefit (A), v is the discount rate per period, and a is the number of periods in the future that A occurs.

Equation (4) is the basis for creating an expression for the NPV of a cash flows (a series of costs or benefits, such as R&D cost). The NPV of a cash flow is expressed as

$$\mathrm{NPV} = \sum_{k=a_i}^{a_f} A_k (1+v)^{-k} \tag{5}$$

where NPV is the net present value of the cash flow, A_k are the periodic values of the cash flow, a_i and a_f are the initial and final periods of the cash flow.

Applying Eqs. (4) and (5) to each of the cash flows depicted in Fig. 1, Eqs. (2) and (3) can be expanded. In Secs. 3.2 and 3.3, expanded expressions are developed for the difference between the over-design and redesign approaches in terms of the values and timing of the cash flows.

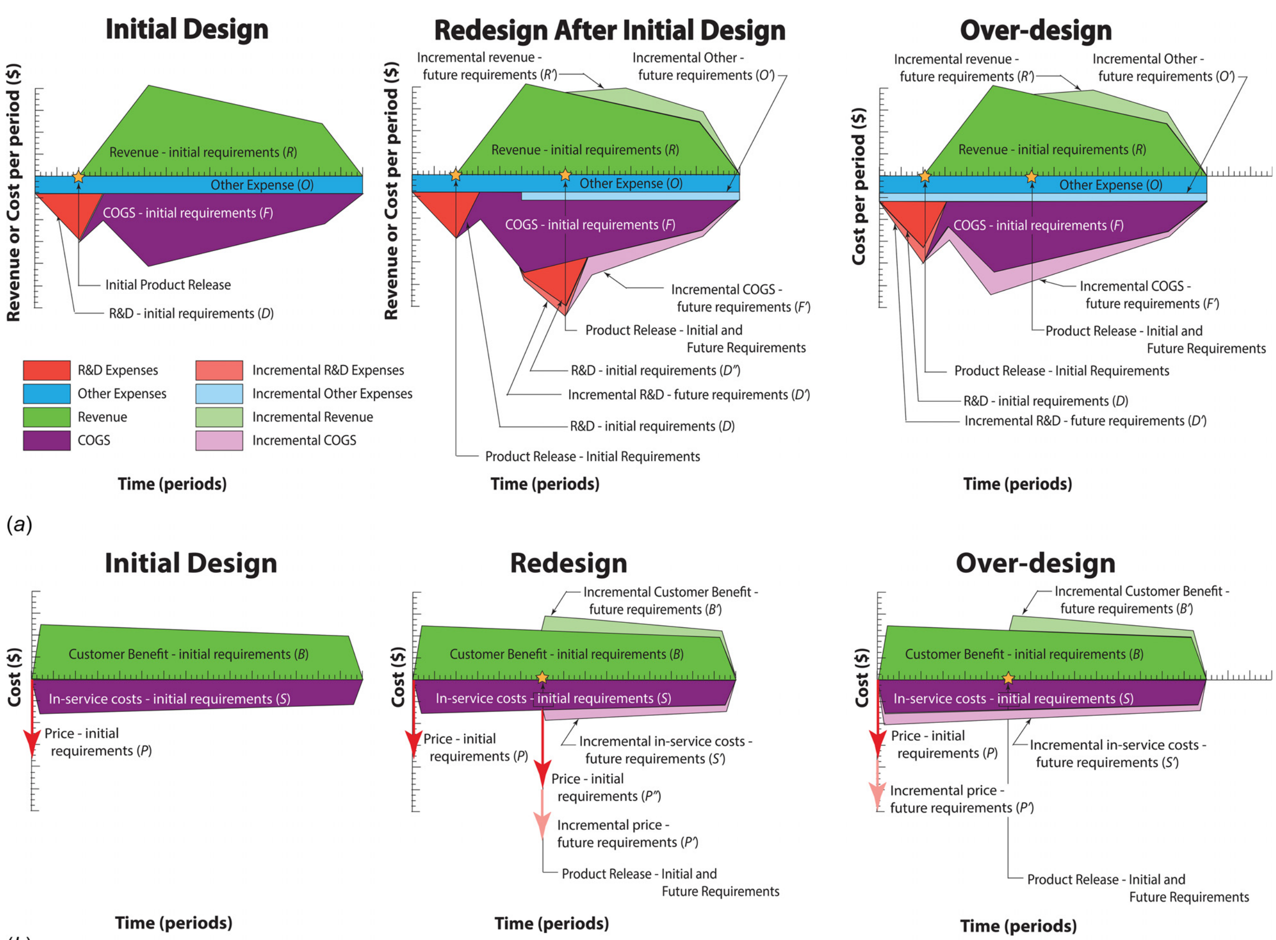

Fig. 1 Simplified cash flow comparisons of initial design, redesign after initial design and over-design approaches from manufacturer's and customer's perspective. Colored areas represent the revenue and cost flows, included in each cash flow, over time, as noted in the legend. Arrows represent one-time costs. When two arrows are stacked the upper arrow represents the price or cost of the product that meets the initial requirements. The lower arrow represents the additional price or cost associated with meeting the future requirements. Stars designate the timing of product availability for sale or purchase.

3.2 Manufacturer's Perspective: Net Present Value. From the manufacturer's perspective, an expression is developed for the difference in the NPV of an over-design versus a redesign approach, by first developing an expression for the NPV of the redesign approach ($\mathrm{NPV}_{\mathrm{Mfrs\ Redesign}}$)

$$\begin{aligned}\mathrm{NPV}_{\mathrm{Mfrs\,Redesign}} = &\sum_{k=r_i}^{r_f} R_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D_k(1+v)^{-k}\\ &-\sum_{k=f_i}^{f_f} F_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O_k(1+v)^{-k}\\ &+\sum_{k=r'_i}^{r'_f} R'_k(1+v)^{-k}\\ &-\left[\sum_{k=d'_i}^{d'_f} D''_k(1+v)^{-k} + \sum_{k=d'_i}^{d'_f} D'_k(1+v)^{-k}\right]\\ &-\sum_{k=f'_i}^{f'_f} F'_k(1+v)^{-k} - \sum_{k=d'_i}^{r'_f} O'_k(1+v)^{-k}\end{aligned} \tag{6}$$

where R_k and R'_k are the revenue due to the initial and incremental requirements in the kth period. Similarly, D_k, D'_k, F_k, F'_k, O_k, and O'_k are the R&D costs, COGS, and other costs associated with the initial and incremental requirements in the kth period. D'' is the portion of the redesign R&D cost associated with the initial requirements in the kth period. The index limits r, d, and f are the summation limits for each cash flow; and the subscripts i and f indicate the initial and final periods of the summation. In general the prime (′) refers to the incremental cash flows.

Second, an expression for the NPV of the over-design approach ($\mathrm{NPV}_{\mathrm{Mfrs\ Over\text{-}design}}$) is developed

$$\begin{aligned}\mathrm{NPV}_{\mathrm{Mfrs\,Over\text{-}design}} = &\sum_{k=r_i}^{r_f} R_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D_k(1+v)^{-k}\\ &-\sum_{k=f_i}^{f_f} F_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O_k(1+v)^{-k}\\ &+\sum_{k=r'_i}^{r'_f} R'_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D'_k(1+v)^{-k}\\ &-\sum_{k=f_i}^{f_f} F'_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O'_k(1+v)^{-k}\end{aligned} \tag{7}$$

Finally, applying Eqs. (6) and (7) to Eq. (2) results in an expression for the relative value of an over-design approach versus a redesign approach ($\Delta\mathrm{NPV}_{\mathrm{Mfrs}}$)

$$\begin{aligned}\Delta\mathrm{NPV}_{\mathrm{Mfrs}} = &\left\{\sum_{k=r_i}^{r_f} R_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D_k(1+v)^{-k}\right.\\ &-\sum_{k=f_i}^{f_f} F_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O_k(1+v)^{-k}\\ &+\sum_{k=r'_i}^{r'_f} R'_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D'_k(1+v)^{-k}\\ &\left.-\sum_{k=f_i}^{f_f} F'_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O'_k(1+v)^{-k}\right\}\\ &-\left\{\sum_{k=r_i}^{r_f} R_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D_k(1+v)^{-k}\right.\\ &-\sum_{k=f_i}^{f_f} F_k(1+v)^{-k} - \sum_{k=d_i}^{r'_f} O_k(1+v)^{-k}\\ &+\sum_{k=r'_i}^{r'_f} R'_k(1+v)^{-k}\\ &-\left[\sum_{k=d'_i}^{d'_f} D''_k(1+v)^{-k} + \sum_{k=d'_i}^{d'_f} D'_k(1+v)^{-k}\right]\\ &\left.-\sum_{k=f'_i}^{f'_f} F'_k(1+v)^{-k} - \sum_{k=d'_i}^{r'_f} O'_k(1+v)^{-k}\right\}\end{aligned} \tag{8}$$

This equation can be simplified by recognizing that the R&D costs (R_k), COGS (D_k), and other costs (O_k) associated with the initial requirements are the same for both approaches. If the revenue is independent of the design approach (revenue only depends on the availability of required capabilities), then the revenue of the two approaches is also canceled out. The simplified equation is

$$\begin{aligned}\Delta\mathrm{NPV}_{\mathrm{Mfrs}} = &\sum_{k=d'_i}^{d'_f} D''_k(1+v)^{-k}\\ &+\sum_{k=d'_i}^{d'_f} D'_k(1+v)^{-k} - \sum_{k=d_i}^{d_f} D'_k(1+v)^{-k}\\ &+\sum_{k=f'_i}^{f'_f} F'_k(1+v)^{-k} - \sum_{k=f_i}^{f_f} F'_k(1+v)^{-k}\\ &-\sum_{k=d_i}^{d'_i} O'_k(1+v)^{-k}\end{aligned} \tag{9}$$

where $\Delta\mathrm{NPV}_{\mathrm{Mfrs}}$ is the relative value of the over-design approach as compared to the redesign approach from a manufacturer's perspective.

3.3 Customer's Perspective: Net Present Value. Following a similar process, an expression can be developed for the relative value of the two approaches from a customer's perspective. From a customer's perspective, the redesign equation corresponding to Eq. (6) is

$$\begin{aligned}\mathrm{NPV}_{\mathrm{Cust\,Redesign}} = &\sum_{k=s_i}^{s_f} B_k(1+v)^{-k} - P(1+v)^{-p_1}\\ &-\sum_{k=s_i}^{s_f} S_k(1+v)^{-k}\\ &+\sum_{k=s'_i}^{s'_f} B'_k(1+v)^{-k}\\ &-\left[P''(1+v)^{-p_2} + P'(1+v)^{-p_2}\right]\\ &-\sum_{k=s'_i}^{s'_f} S'_k(1+v)^{-k}\end{aligned} \tag{10}$$

where B_k is the customer benefit function in the kth period, P is the price of the initial product associated with the initial requirements, P' is the incremental price of the redesigned product associated with the future requirements, P'' is the price of the redesigned product associated with the initial requirements, S_k and S'_k are the in-service costs and incremental in-service costs in the kth period.

Equation (7) is analogous to the following over-design equation from a customer's perspective:

$$\begin{aligned} \mathrm{NPV}_{\text{Cust Over-design}} &= \sum_{k=s_i}^{s_f} B_k(1+v)^{-k} - P(1+v)^{-p_1} \\ &\quad - \sum_{k=s_i}^{s_f} S_k(1+v)^{-k} \\ &\quad + \sum_{k=s'_i}^{s'_f} B'_k(1+v)^{-k} - P'(1+v)^{-p_1} \\ &\quad - \sum_{k=s_i}^{s'_f} S'_k(1+v)^{-k} \end{aligned} \tag{11}$$

By applying Eqs. (10) and (11) to Eq. (3), an equation is developed for the difference between the over-design and redesign approaches

$$\begin{aligned} \Delta\mathrm{NPV}_{\text{Cust}} = &\left\{ \sum_{k=s_i}^{s_f} B_k(1+v)^{-k} - P(1+v)^{-p_1} \right. \\ &- \sum_{k=s_i}^{s_f} S_k(1+v)^{-k} \\ &+ \sum_{k=s'_i}^{s'_f} B'_k(1+v)^{-k} - P'(1+v)^{-p_1} \\ &\left. - \sum_{k=s_i}^{s'_f} S'_k(1+v)^{-k} \right\} \\ &- \left\{ \sum_{k=s_i}^{s_f} B_k(1+v)^{-k} - P(1+v)^{-p_1} \right. \\ &- \sum_{k=s_i}^{s_f} S_k(1+v)^{-k} \\ &+ \sum_{k=s'_i}^{s'_f} B'_k(1+v)^{-k} \\ &- \left[P''(1+v)^{-p_2} + P'(1+v)^{-p_2} \right] \\ &\left. - \sum_{k=s'_i}^{s'_f} S'_k(1+v)^{-k} \right\} \end{aligned} \tag{12}$$

where $\Delta\mathrm{NPV}_{\text{Cust Redesign}}$ is the difference between the NPV of the over-design and redesign approaches from the customer's perspective.

Simplifying this equation results in an equation analogous to Eq. (9)

$$\begin{aligned} \Delta\mathrm{NPV}_{\text{Cust}} = &P''(1+v)^{-p_2} + P'(1+v)^{-p_2} - P(1+v)^{-p_1} \\ &- \sum_{k=s_i}^{s'_i} S'_k(1+v)^{-k} \end{aligned} \tag{13}$$

Section 4 further addresses the question posed at the beginning of Sec. 3; under what conditions is it more advantageous to produce or purchase an over-designed product with potentially higher initial costs than a pair of products that more closely match the immediate needs? Equations (9) and (13) are used to evaluate the relative value of the over-design and redesign approaches using four real world applications.

4 Analysis of Over-Design and Redesign Based on Four Diverse Applications

The equations presented in Sec. 3 can be applied to any manufacturing operation or customer purchase application. Equation (9) indicates that when evaluating the difference in NPV between the over-design and redesign approaches, from a manufacturer's perspective, the most significant cash flows are the incremental R&D costs, incremental COGS, incremental other costs, and the redesign R&D costs. From a customer's perspective, Eq. (13) indicates that the most significant cash flows are incremental purchase price, incremental in-service costs, the price of the redesigned product. Manufacturing and customer purchase applications can be compared based on these significant cash flows.

A sampling of all possible applications includes products from defense contractors, automobile, pharmaceutical, and microprocessor manufacturers. Products from each of these manufacturers could be considered for redesign or over-design. For example, an automobile manufacturer may include (1) features for a future entertainment system (e.g., power, interconnects), (2) battery system, (3) lights (LED), or (4) features to enable qualification of upcoming government regulations. While these are not current requirements they may become future requirements and can be address by either over-design or redesign.

Also, a sampling of customer purchase applications is presented (i.e., vehicle, television, cell phone, washing machine, and building). Once again, each of these can be a candidate for redesign or over-design. For example, the purchase of a building, such as a home, has immediate and potential future requirements. Initially, perhaps, only two bedrooms or a two-car garage or a simple entertainment system (excluding wiring) is required. However, expanding to three bedrooms or a three-car garage, or a more comprehensive entertainment system may be needed in the future. These future needs may be addressed by either purchasing an over-designed product (temporarily unneeded space) or by redesigning (remodeling or rebuilding).

These ten applications, including five manufacturers (with production operations further detailed in Table 2), and five customer purchase opportunities, are represented in Fig. 2. The horizontal axis of the graphs represents the investment that is required: R&D cost (normalized by revenue) for the manufacturers and price for the customers. The vertical axis represents the ongoing cost (COGS or in-service cost) normalized by either the R&D cost for the manufacturers or the price for the customers.

To obtain an understanding of the relative value of an over-design approach versus a redesign approach as a method to address emergent future requirements, this section reviews four of these applications. The first two applications are taken from a manufacturing perspective. As can be seen in Fig. 1(*a*), the relative size of the R&D cost and COGS cash flows are significant factors. Two realistic applications (based on actual data from Table 2) have been selected as extreme examples of the COGS to R&D cost ratio. Applications 1 and 2 are

(1) High COGS to R&D cost ratio (0.81/0.025 = 32.4). Example: Defense contractors (refer to Table 2)
(2) Low COGS to R&D cost ratio (0.533/0.21 = 2.5). Example: Microprocessor suppliers (refer to Table 2)

The next two applications are taken from a customer perspective (refer to Fig. 1(*b*)). As with the manufacturing applications, extreme ratios of the significant cash flows (in-service cost to price ratio) are considered. Applications 3 and 4 are

(3) High in-service cost to price ratio (0.25). Example: vehicle purchase.
(4) Low in-service cost to price ratio (0.02). Example: building purchase.

Table 2 Financial summaries of manufacturers from 2015 annual reports. Noted as total dollars and as a percent of revenue.

	Revenue	COGS	R&D	Other	EBITDA
Defense contractors, typically companies with low R&D cost relative to COGS [51–55] (2015)					
Lockheed Martin Corp.	$46.13 B	$39.89 B	$0.84 B	$0.35 B	$5.05 B
		86.5%	1.8%	0.8%	10.9%
Northrop Grumman Corp.	$23.53 B	$17.88 B	$0.71 B	$2.00 B	$2.94 B
		76.0%	3.0%	8.5%	12.5%
Raytheon Co.	$23.25 B	$17.76 B	$0.71 B	$1.76 B	$3.02 B
		76.4%	3.1%	7.6%	13.0%
Boeing Co.	$96.11 B	$82.09 B	$3.33 B	$3.68 B	$7.01 B
		85.4%	3.5%	3.8%	7.3%
General Dynamics Corp.	$31.47 B	$25.34 B	$0.39 B	$1.56 B	$4.18 B
		80.5%	1.2%	5.0%	13.3%
Average		81.0%	2.5%	5.1%	11.4%
Microprocessor suppliers, typically companies with high R&D cost relative to COGS [56–60]					
Intel Corp.	$55.35 B	$20.67 B	$12.12 B	$8.33 B	$14.23
		37.3%	21.9%	15.0%	25.7%
Qualcomm, Inc.	$25.28 B	$10.10 B	$5.47 B	$4.10 B	$5.61
		40.0%	21.6%	16.2%	22.2%
Micron Technology, Inc.	$16.19 B	$10.98 B	$1.54 B	$0.73 B	$2.94
		67.8%	9.5%	4.5%	18.2%
Broadcom Corp.	$8.42 B	$4.10 B	$2.37 B	$1.27 B	$0.68
		48.7%	28.1%	15.1%	8.1%
Advanced Micro Devices, Inc.	$3.99 B	$2.91 B	$0.94 B	$0.47 B	$−0.33
		72.9%	23.6%	11.8%	−8.3%
Average		53.3%	21.0%	13.2%	12.5%

These four applications provide valuable insight, since many businesses and customer purchases fall near or between them (refer to Fig. 2).

For each application a set of baseline parameters is determined (refer to Table 3). These parameters are used to create a baseline cash flow model for each application, similar to Figs. 1(*a*) and 1(*b*). The models and results are normalized by the revenue or price. In practice, the incremental R&D cost, COGS, price, and in-service costs of the over-designed and redesigned products can range from a very small portion of the initial cost (e.g., 0.01 times) to almost as much as the initial cost (e.g., 0.90 times). A multiple of 0.15 is used as a reasonable incremental multiplier in this analysis (refer to Table 3).

Recall that three product designs are involved in each of these four applications. The redesign approach requires two product designs. The first is a product optimally designed for the initial requirements and available at the time of the initial requirements. The second is a product designed for both the initial and future requirements and available when the future requirements are demanded. The over-design approach only requires one product. It is an over-designed product in the sense that it meets the needs of both the initial and future requirements. It is available at the time the initial requirements are needed. Both the over-designed and redesigned products are optimally designed for the combination of initial and future requirements. Therefore, this analysis considers the over-designed and redesigned products to be identical but displaced in time.

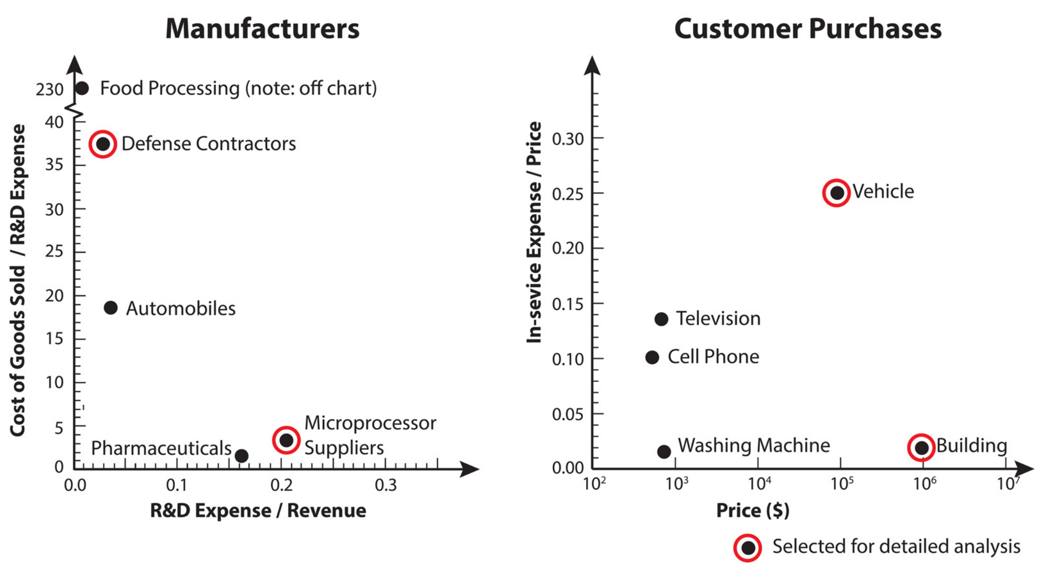

Fig. 2 Sampling of manufacturing and customer purchase applications. The horizontal axis is an indication of the investment (R&D cost or price). The vertical axis represents the ongoing cost, either COGS (for the manufacturer) or in-service cost (for the customer) normalized by the R&D cost or price, respectively. These normalized values are selected because of their significance in Eqs. (9) and (13). As indicated in the figure, defense contractors, microprocessor suppliers, vehicle and building purchases are chosen as diverse examples to be analyzed in detail. Data are from the following Refs. [47–70].

Table 3 Baseline values used in this analysis

(a) Manufacturer's perspective. These ratios are calculated based on the values in Table 2

	Initial requirements (% of initial revenue)				Future requirements (% of initial revenue)			
	Revenue	COGS	R&D	Other	Incremental revenue	Incremental COGS	Incremental R&D	Incremental other
High COGS to R&D ratio	1.000	0.810	0.025	0.051	0.150	0.121	0.004	0.008
Low COGS to R&D ratio	1.000	0.533	0.210	0.132	0.150	0.080	0.031	0.020

(b) Customer's perspective

	Initial requirements (% of initial revenue)			Future requirements (% of initial revenue)		
	Benefit	In-service	Price	Incremental benefit	Incremental price	Incremental in-service
High in-service to price ratio	1.000	0.2400	0.7100	0.150	0.0360	0.1065
Low in-service to price ratio	1.000	0.0020	0.9300	0.1500	0.0003	0.1395

(c) Product life cycle

Manufacturer		Customer
Time in development	Time in production	Time in service
48 months (4 yr)	192 months (16 yr)	192 months (16 years)

This analysis is performed in two steps. The first step analyzes the baseline (refer to Table 3) difference between the NPV of the over-design and redesign cash flows (ΔNPV). The ΔNPV is evaluated as a function of the timing of the emergence of the future requirements. That is, the ΔNPV is calculated assuming the future requirements emerge in a particular period, while the cash flows and discount rate (15%) are held constant. This process is repeated for all of the possible future requirement emergence periods. The second step is a sensitivity analysis of the baseline to changes in the discount rate and individual cash flows (i.e., R&D cost or price, incremental R&D cost or price, incremental COGS or in-service costs, and the R&D cost or price of the redesigned product).

4.1 Step 1: Baseline Analysis. In step 1, the ΔNPV is analyzed as a function of the period during which the future requirements emerge. The ΔNPV resulting from the baseline values is plotted for all possible future requirement emergence periods. This plot is referred to as the *emergence curve*. Figure 3 is the baseline emergence curve for each of the four applications. The horizontal axis represents the periods at which the future requirements are assumed to emerge for each ΔNPV evaluation. Despite how it might appear in Fig. 3, the ΔNPV is not a function of time and hence the horizontal axis is not time, but rather the period during which the future requirements are stipulated to emerge. Each point on the emergence curve represents a calculation of Eq. (9) or Eq. (13) and a future requirement emergence at that point. Therefore, the emergence curve is a collection of the ΔNPV for all possible future requirement emergence periods. The vertical axis is the normalized ΔNPV evaluated based on the future requirement emerging at corresponding period indicated by the horizontal axis. The fundamental variable used in this analysis is the timing of the emergence of the future requirements. Since the ΔNPV is over-design minus redesign, a positive ΔNPV indicates that the over-design approach has a higher NPV than the redesign approach. The point at which the ΔNPV equals zero is referred to as the crossover point (highlighted in Fig. 3 with a vertical line). It is the point at which the approach with the higher NPV changes from over-design to redesign.

There are several interesting points illustrated in Fig. 3:

– Over-design is always superior to redesign if the emergence of future requirement occurs near the release of the initial requirements.
– There is a crossover point for each application.
– The crossover point increases as the COGS to R&D cost ratio decreases (compare application 1 and 2) and as the in-service cost to price ratio decreases (compare application 3 and 4).
– Over-design may be more valuable to the customer than the manufacturer. Compare applications 1 and 3 (high COGS to R&D ratio or high price to in-service ratio) noting that the ΔNPV in the customer application (3) remains positive through period 170 while the ΔNPV in the manufacturer application (1) is positive only through period 80, similarly comparing applications 2 and 4 (low COGS to R&D ratio or low price to in-service ratio) the ΔNPV in the customer application (4) is positive through period 205 and only slightly negative thereafter, while the ΔNPV in the manufacturer application (2) is negative and sharply declining beyond period 170.

The last point is particularly interesting, since many manufacturers believe they are working in line with the best interests of the customer. Figure 3 reveals that in fact, under certain conditions, the manufacturers may not be providing the best long-term solution to their customers. Also it is interesting to note that for all applications, the over-design approach exhibits a higher ΔNPV than the redesign approach depending on the timing of the emergence of the future requirements.

It should be noted that this analysis is based on the NPV of each approach. As in all analyses, if significant benefits or costs, such as intangibles, are not quantified and included in the NPV analysis then the results may not represent the actual strengths/weakness of the approaches. These intangible include, for manufacturers: (1) available cash for investment, (2) longer term strategies, (3) legacy, or (4) historical influences and for customers: (1) available cash, (2) the desire to have a new product more frequently, or (3) other personal preferences.

4.2 Step 2: Sensitivity Analysis of the Baseline. Since the purpose of this paper is to examine the two approaches as a response to the emergence of future requirements, variations of the emergence curve are used for the remainder of this analysis. These variations are obtained by repeating the creation of the emergence curve while varying the value of a selected parameter. Specifically, each parameter is perturbed by a percentage of the baseline value (i.e., 50%, 75%, 100%, 125%, 150%). The effect

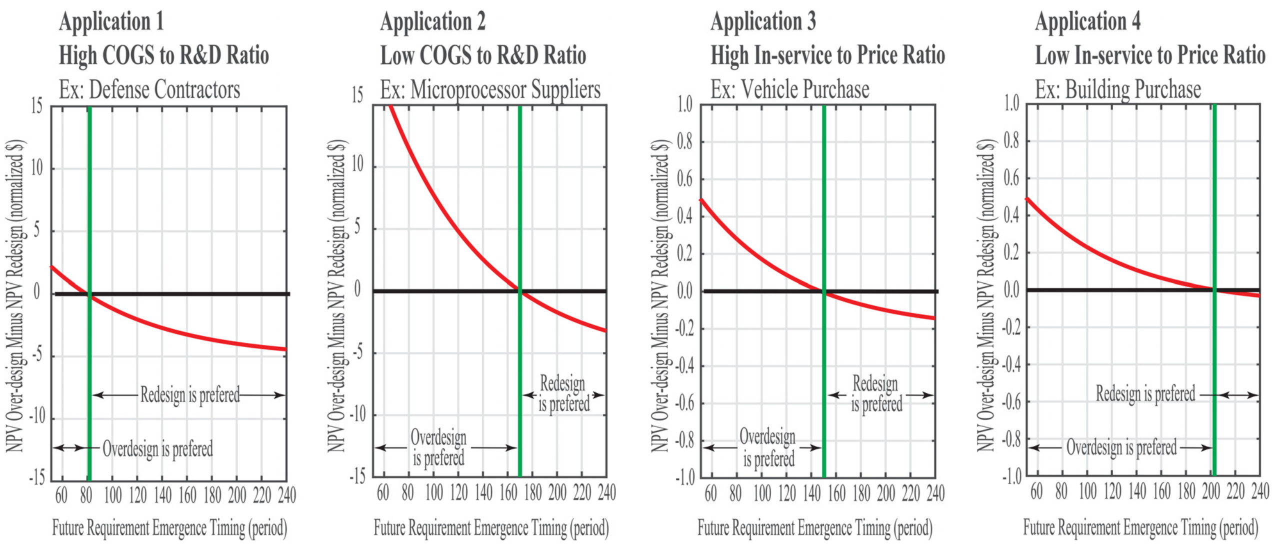

Fig. 3 The impact of the timing of emergence of future requirements on the NPV of the over-design and redesign approaches. Applications 1 and 2 (first and second graphs from the left) are from a manufacturer's perspective. Applications 3 and 4 (third and fourth graphs from the left) are from a customer's perspective.

of this perturbation is observed by the crossover point and shape of the emergence curve (as baselined in Fig. 3). Recall that the crossover point identifies the regions where each of the approaches provides the greater benefit (i.e., larger ΔNPV), and the shape suggests its sensitivity to the parameter under consideration as a function of the future requirement emergence timing. Variations in the following five parameters are considered in Secs. 4.2.1–4.2.5:

– discount rate;
– incremental R&D cost or price resulting from the future requirements;
– incremental COGS or in-service cost resulting from the future requirements;
– R&D cost or price resulting from the initial requirements;
– redesigned product R&D cost or price.

Emergence curves resulting from the sensitivity analysis are depicted in Fig. 4. The sensitivity to each of the five parameters are represented by the five subfigures (Figs. 4(*a*)–4(*e*)), create the rows of Fig. 4. The columns of Fig. 4 represent each of the four applications: (i) high COGS to R&D cost ratio (e.g., defense contractors), (ii) low COGS to R&D cost ratio (e.g., microprocessor suppliers), (iii) high in-service cost to price ratio (e.g., vehicle purchase), and (iv) low COGS to R&D cost ratio (e.g., building purchase). Rows of Fig. 4 illustrate the influence of changes of a particular parameter on each of the applications. Each row is a study of the impact of one of the five parameters on a particular application. The columns of Fig. 4 demonstrate how the variation of each parameter affects a particular application. Each column is a study of a particular application, and how is it affected by variations in its parameters.

4.2.1 Discount Rate. Figure 4(*a*) displays the effect of the discount rate on the over-design and redesign analyses. In each graph, the baseline application is the centerline. The other four lines are ±25% and ±50% of the baseline discount rate (15%). This variation of the baseline, ±25% and ±50%, is used in all subsequent sensitivity analyses in this section. Three observations can be made from Fig. 4(*a*). First, the discount rate often has a significant effect on the relative value of the over-design versus redesign approaches (ΔNPV). In general, reducing the discount rate moves the crossover point to the right, increasing the range in which the over-design approach has a higher NPV. Consider application 2, a 50% decrease in the discount rate increases the crossover point by 35.2%. An even larger impact is observed in application 4 (Building Purchase). Second, there is a point at which this relationship is reversed (note period 80 in application 1, Fig. 4(*a*)). After this reversal point, increasing the discount rate increases the over-design NPV relative to the redesign NPV. This behavior results as the emergence of the future requirements are pushed out in time, resulting in an increase in the duration of the incremental COGS (or in-service cost), while the impact of the R&D cost (or price) associated with the redesign becomes less significant (due to the discount rate). Therefore at a point, the total NPV is dominated by the incremental COGS (or in-service cost). As the discount rate increases, the incremental COGS (or in-service cost) is accentuated. This reversal point occurs early in application 1 (at period 80) and near the end of application 3 (at period 207). Third, if the future requirements occur immediately after the initial requirements, then the NPV *is dependent* on the discount rate. This difference *converges* toward the reversal point. Therefore, the influence of changes in the discount rate decrease as the emergence of the future requirements occurs later in time.

4.2.2 Research and Development Cost or Price Resulting From the Initial Requirements. The impact of the future requirements on the product design can be measured by the incremental R&D cost, price, COGS, and in-service costs required to achieve them (Fig. 4(*b*)). As previously noted, the baseline for each of these incremental costs is set relative to the initial revenue (or customer benefit) and cost at a 1.15 multiplier (refer to Table 3).

The R&D cost or price required to meet the initial requirements can effect the NPV of the two approaches. Three observations can be taken from Fig. 4(*b*). First, increasing the R&D cost or price required to meet the initial requirements increases the crossover point, thus increasing the NPV of the over-design approach. Second, there is a reversal point in each application. This reversal point is due to the increase in the incremental COGS (or in-service cost) as the emergence of the future requirements occur later in time. The R&D cost (or price) associated with the redesigned product occurs later in time, and hence its present value is decreased. The NPV becomes dominated by the incremental R&D cost (or price) of the over-designed product, the increasing of which decreases the NPV. Third, if the future requirements occur immediately after the initial requirements, then the NPV *is dependent* on the R&D cost (or price). This difference *converges* toward the reversal point.

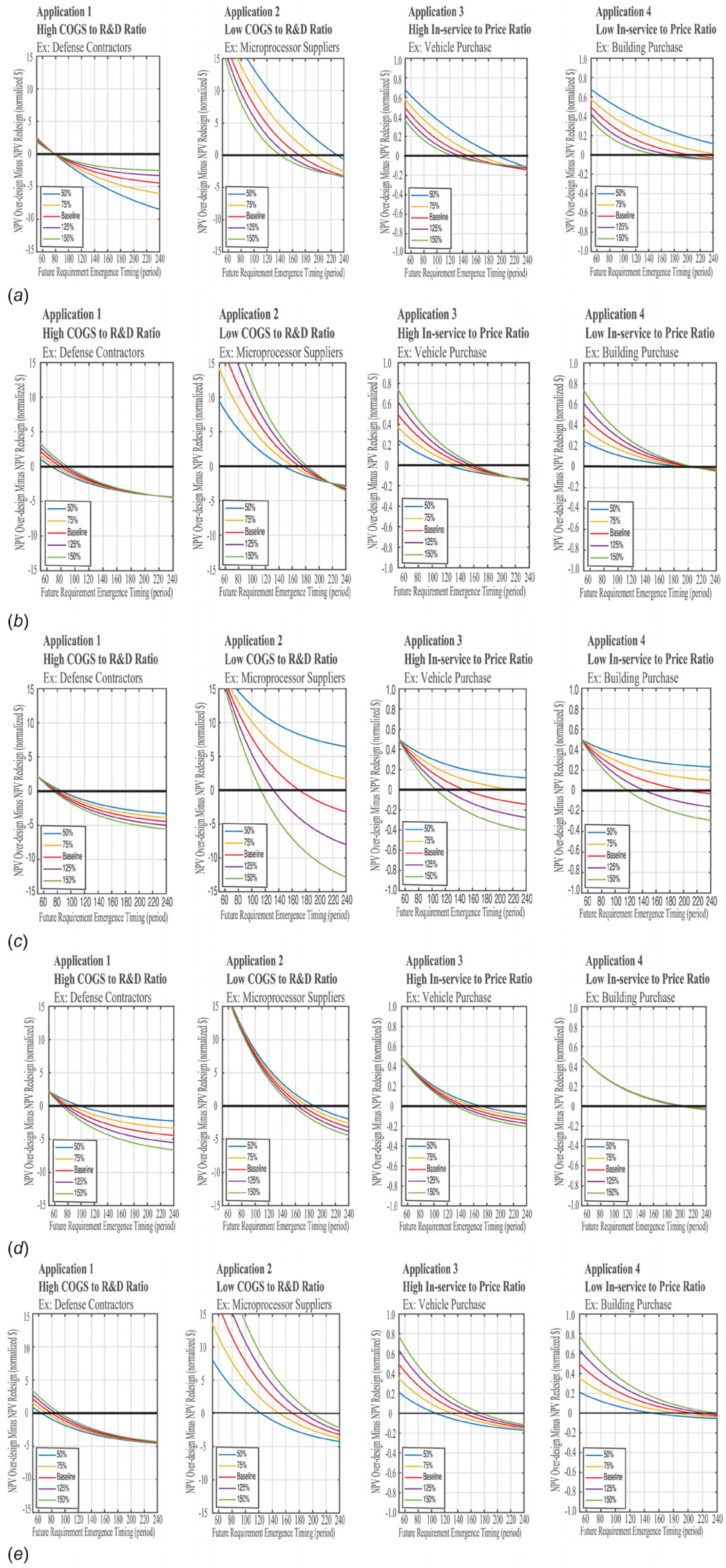

Fig. 4 Sensitivity analysis. The impact on the emergence curves (NPV of over-design minus NPV of redesign) of variations in discount rate, incremental R&D cost (or price), initial R&D cost (or price), incremental COGS (or in-service cost) and incremental R&D cost (or price) of only the redesigned product: (*a*) sensitivity of discount rate, (*b*) sensitivity of R&D cost or price due to initial requirements, (*c*) sensitivity of incremental R&D cost or price due to future requirements, (*d*) sensitivity of incremental COGS or in-service costs due to initial requirements, and (*e*) sensitivity of incremental R&D cost or price of the redesigned product.

4.2.3 Incremental Research and Development Cost or Price Resulting From the Future Requirements. Figure 4(*c*) presents the impact on the emergence curve of significant changes (±50%) in the incremental R&D cost and price associated with the future requirements. Four observations can be made from Fig. 4(*c*). First, the crossover point increases as the incremental R&D cost or price decreases. Second, products with a low COGS to R&D cost ratio are very dependent on this parameter, while products with high COGS to R&D cost ratios are almost independent of the incremental R&D cost. Third, low incremental R&D cost or price can result in crossover point outside the life of the product (refer to applications 2, 3, and 4 in Fig. 4(*c*)). In other words, the over-design approach is superior for all timing of future requirement emergence. Fourth, if the future requirements occur immediately after the initial requirements then the ΔNPV *is not dependent* on the incremental R&D cost or price. The NPV *diverges* as the future requirements emerge later in time.

4.2.4 Incremental Cost of Goods Sold or In-Service Costs Resulting From the Future Requirements . The observations for the impact of changes in the incremental COGS or in-service cost are essentially the same as those mentioned in the above analyses of incremental R&D cost and price (refer to Sec. 4.2.3; Fig. 4(*d*)). However, an interesting observation can be made. Application 4 in Fig. 4(*d*), illustrates that when the costs associated with the initial requirements are small, the ΔNPV is not sensitive to changes in the corresponding incremental costs.

4.2.5 Redesigned Product Research and Development Cost or Price. This last study reviews the impact of R&D cost or price of a redesigned product (Fig. 4(*e*)). The question may arise, what is the impact on the emergence curve if (i) the redesign can be completed with a minimal cost (due to development efficiencies) or (ii) the price of the redesign product can be offset by the sale of the initial product? Fig. 4(*e*) addresses this question. The first observation is that decreasing the R&D cost or price associated with the redesigned product increases the value of the redesign approach. For example, a 50% reduction in the R&D cost (or price) of a redesigned product results in a 30% decrease in the crossover point, thus making the over-design approach much less attractive. The second observation is that all of the emergence curves converge as the future requirements occur later in time and ΔNPV becomes dominated by the incremental R&D cost (or price) of the over-designed product. The last observation is that the earlier future requirements are demanded the greater sensitivity of the ΔNPV to the cost associated with the redesigned product.

4.3 Summary of Analysis. The studies presented in Secs. 4.1 and 4.2 are intended to address the question posed at the beginning of Sec. 3; under what conditions is it more advantageous to produce or purchase an over-designed product with potentially higher initial costs than a pair of products that more closely match the immediate needs? In summary some of the most significant findings include:

- Companies with low COGS to R&D cost ratios and customer purchases with low in-service cost to price ratios derive more benefit from over-design approaches (compare applications 1 and 2; and applications 3 and 4 in Figs. 3 and 4)
- Because of the relatively lower in-service cost to price ratio (as compared to the COGS to R&D cost ratio) customers can benefit from the over-design approach even when manufacturers do not benefit as much or at all (refer to Fig. 3)
- Over-design approach provides a higher NPV, and as a result can be of greater benefit when
  - future requirements emerge soon after initial requirements (refer to Figs. 3 and 4);
  - low discount rates are appropriate (refer to Fig. 4(*a*));
  - incremental R&D cost, price, COGS, or in-service costs to provide the future requirements are low (refer to Figs. 4(*c*) and 4(*d*));
  - initial R&D cost, or price to provide for the initial requirements is high (refer to Fig. 4(*b*));
  - incremental R&D cost or price of the redesigned product is high.

This analysis demonstrates, using diverse practical examples, that an over-design approach can provide manufacturers and customers with an advantage when faced with the potential need to satisfy future requirements.

5 Conclusions

It may be obvious that if a new or future requirement emerges shortly after the introduction of a new product then over-design to address this new requirement is advantageous. However, less obvious and possibly more interesting is that conditions exist where over-design can be advantageous even long after the initial product has been introduced. Some designers may have a blind spot with respect over-design. Their education has been centered on elimination of waste. Without analysis, over-design may be considered waste and summarily discounted or avoided. The relative value of an over-design approach and a redesign approach can be evaluated using NPV methods. By applying a specific application (R&D cost, COGS, price, and in-service costs) to the analysis method described in Sec. 3, a manufacturer or customer can make an informed decision regarding over-design and redesign.

The conditions under which an over-design approach excels have been documented using four diverse applications (manufacturers: defense contractors, and microprocessor supplies; and customer purchases: vehicle and building), refer to Sec. 4.3. An important point is that many manufacturing or customer purchasing applications can benefit from choosing an over-design approach. As seen in Fig. 3, products manufactured with low R&D cost to COGS ratios and products purchased with low in-service to price ratios are strong candidates for an over-design approach. Examples include manufacture of microprocessors and purchase of a building (refer to the discussion in Sec. 4 and Figs. 2 and 3).

Because of this insight, further work regarding the relative benefits of over-design relative and redesign approaches is warranted. Further research is needed to extend the analysis presented in this paper to include the probabilistic nature of future requirements and intangible factors influencing design decisions.

First, an obvious, but not trivial, extension is to modify the NPV equations (referred to in Sec. 3) to include a probability distribution of the emergence of the future requirements. Information from static probability distributions (that do not change as time advances) and dynamic distributions (the shape of which changes as time advances) should be included in the analysis. The focus should not be on creating the probability distributions but rather on utilizing them to improve decision-making.

Second, research is needed to expand the current analysis to include approaches that combine a partial over-design with a partial future redesign. The design options form a continuum ranging from no over-design and complete redesign to a complete over-design and no redesign. The ability to analyze partial over-design and partial redesign options greatly expands the options available to a design team.

Third, the previous three future studies enable expanding this work to take advantage of real options analysis. Real options analysis can be applied to the continuum of design options. This approach can be applied to circumstances when the engineer's understanding of the probabilities of emergence of future requirements is changing over time (dynamic probability distribution).

Fourth, it is clear that the timing of the emergence of new requirements is an important aspect of this analysis. While uncertainty, in general, is currently a major area of research in the literature [71–74], a more narrowly focused study on increasing the predictability of the emergence of new requirements would be very productive. This study may involve extensions of trend analysis methods [75], including trend for product releases, underlying technologies, and adjacent technologies or competitive analysis.

Finally, the analysis can be further strengthened by including less tangible value factors such as emotional, social, and/or political influences.

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Nomenclature

a = number of periods in a cash flow
A = future cash value
B = customer benefit cash flow resulting from meeting initial requirements
B' = incremental customer benefit cash flow resulting from meeting additional future requirements
D = research and development (R&D) cost cash flow required to meet initial requirements
D' = incremental research and development (R&D) cost cash flow required to meet future requirements
D'' = incremental research and development (R&D) cost cash flow required to meet initial requirements during the redesign
d_x = summation limits for the R&D costs associated with the initial requirements. The subscript refers to the initial period (i) or final period (f)
d'_x = summation limits for the R&D costs associated with the future requirements. The subscript refers to the initial period (i) or final period (f)
F = COGS cash flow required due to initial requirements
F' = incremental COGS cash flow required due to future requirements
f_x = summation limits for the COGS and other costs associated with the initial requirements. The subscript refers to the initial period (i) or final period (f)
f'_x = summation limits for the COGS and other costs associated with the future requirements. The subscript refers to the initial period (i) or final period (f)
NPV_x = net present value of a cash flow. The subscript designates the cash flow being designated, i.e., over-design, redesign, Mfrs over-design, Mfrs redesign, cust over-design, cust redesign
O = other cost cash flow required due to initial requirements
O' = incremental other cost cash flow required due to future requirements
P = price due to initial requirements
P' = incremental price due to future requirements
P'' = incremental price due to initial requirements included in redesigned product
PV = present value of a future cash flow
R = revenue cash flow resulting from meeting initial requirements
R' = incremental revenue cash flow resulting from meeting addition future requirements
r_x = summation limits for the revenue cash flow associated with the initial requirements. The subscript refers to the initial period (i) or final period (f)
r'_x = summation limits for the revenue cash flow associated with the future requirements. The subscript refers to the initial period (i) or final period (f)
S = in-service cost cash flow required due to initial requirements
S' = incremental in-service cost cash flow required due to future requirements
s_x = summation limits for the in-service costs associated with the initial requirements. The subscript refers to the initial period (i) or final period (f)
s'_x = summation limits for the in-service costs associated with the future requirements. The subscript refers to the initial period (i) or final period (f)
v = discount rate per period
$\Delta\mathrm{NPV}_x$ = total net present value of difference between a redesign and over-design approach. The subscript designates the perspective being considered, i.e., Cust, Mfrs

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