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Use of Margin to Absorb Variation in Design Specifications: An Analysis Using the Margin Value Method

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Abstract

Predicting the impact of changes in a design can be challenging, especially for complex designs. Margins are often built into the designs which can absorb the knock-on effect of such changes, erroneously allocating which can however, lead to propagation. A method for localising and sizing margins in an incremental design context is the Margin Value Method. This paper adapts MVM in the context of uncertainty in input specifications. It discusses possible ways to allocate them in a design such that undesirable effects of margins are minimised while preventing change propagation.

Keywords: design margin, robust design, engineering change, design optimisation

1. Introduction

Design processes in industry often experience engineering changes (ECs) throughout the lifecycle of a product, some of which may have high-cost implications (Clarkson et al., 2004). The need for such changes arises from various avenues. Some changes are initiated due to the components not meeting specifications, while some others may be the result of incremental improvements in the design itself (Eckert *et al.*, 2004). Surveys and studies deem the effects of such changes to be as high as 30-50% of the total engineering capacity, costs and schedules (Fricke et al., 2000; Maier & Langer, 2011). Although changes are inevitable (Ahmad *et al.*, 2013; Eckert *et al.*, 2004), the undesirable effects can be mitigated by making designs more robust, i.e., making them less sensitive to the factors which cause variability (Park *et al.*, 2006).

A strategy to make designs more robust to variations is to have large tolerances in parameters and process variables while maintaining functionality (Suh, 2001). These tolerances, also known as margins (Eckert *et al.*, 2019), in effect are expected to act as shock absorbers, thereby preventing a change from propagating (Chua and Hossain, 2012). Margins may, however, also be generated (excess in the terminology of Eckert et al., 2004) when using off-the-shelf (non-custom, ready-made parts bought from original equipment manufacturers), platform, or parts inherited from previous generations and therefore, in certain cases, may not require to be incorporated additionally or to the extent otherwise necessary. It is therefore important, especially in an incremental design context, to first locate and size existing margins and then weigh them according to their relative desirable and undesirable impacts. Additional margins may then be allocated in designs at appropriate locations as per requirements, while other excesses causing a deterioration in performance may be reduced or eliminated. An approach developed to achieve this is the Margin Value Method (MVM). MVM is aimed at routine designs and proposes the use of a parametric network-based approach to locate margins and an analytical method to size them in a design, where parametric relations are already known (Brahma and Wynn, 2020a). The analytical method results in a visual depiction that guides the designer towards margins that should be maintained and those that should be eliminated in future iterations of a design. While margins allocated in existing designs are fixed, variation can occur in design specifications (requirements) arising from a range of uncertainties. Uncertainty in both specifications and the performance of off-the-shelf components may manifest as changes which may be triggered in the future or while in operation. This makes comparing the desirable and undesirable effects of margins for a trade-off during redesign a difficult task. This article addresses this by adapting the MVM approach (Brahma and Wynn, 2020a) to consider variations in the input specifications and in the specification of off-the-shelf components of a design when computing the desirability of margins. The adapted approach combines both the deterministic aspects of parametric design and the probabilistic nature of change, and aims to analyse designs that experience variation in input specifications which can potentially manifest as propagation in the design.

2. Role of Margins in Change and Uncertainty Propagation

Change propagation (CP) is a well-known problem in the industry and has attracted a wide variety of research in the recent past. Change Prediction Method (CPM), one of the more well-known approaches by Clarkson et al., 2004, addressed the problem of CP by considering the risk of changes which may propagate between components or subsystems in a design. Since its publication, much work has been done on developing the CPM further by various researchers. Hamraz et al., 2013, for example, proposed a variation on the CPM, in which they consider the interface between two subsystems and relate the propagation probabilities with them. Hamraz et al., 2013 explain this by considering a subsystem which accepts a wide range of voltages. How narrow or wide the range is, determines how robust the design is to a change, i.e., whether any change in voltage is propagated or gets absorbed. While the range of acceptable values specified by the interface, in this case, can be interpreted as margins, Hamraz et al., 2013, view this mainly as an approach to generate the input data required by the CPM, and do not elaborate on the implications for managing the margins themselves.

Other concepts that are used to manage uncertainty in design include flexibility, adaptability and robustness. While flexibility and adaptability are often used interchangeably, defined as the ability to respond to requirement changes (Lebjioui, 2018), authors widely regard the concepts to be effective in managing uncertainty in design (McManus *et al.*, 2004; Saleh *et al.*, 2009). However, researchers also point out the lack of scholarly maturity of the concepts both in terms of definitions and usage (Saleh *et al.*, 2009). Robust design, first developed by Taguchi & Clausing, 1990, on the other hand, has a solid track record of application in uncertainty management and is clearly defined in terms of a fixed behaviour for an uncertain range of external influences (Banerjee and de Weck, 2004). Initially proposed to make designs insensitive to noises from manufacturing processes (Park *et al.*, 2006), the concept of robust design has since been extended to other uncertainties, both in design and process domains (Chen *et al.*, 1996; Floricel and Miller, 2001). For instance, Chang et al., 1994 present a method based on Taguchi & Clausing, 1990's parameter design concepts to make designs more robust to changes. Specifically, they focus on changes potentially arising due to the collaborative nature of design in a concurrent engineering setting. Chang et al., 1994, argue that variations may arise from decisions being taken simultaneously by separate teams working on various parts of the design. Chang et al., 1994 treat possible variations as "conceptual noise" which they use in conjunction with optimisation techniques to robustify a design. While Chang et al., 1994's method, like the MVM, also accounts for performance loss, its application is focused on conceptual stages of design in contrast to the MVM, which was developed in the incremental design context.

Unlike the original method developed by Taguchi, which was based on experiments (Phadke, 1989), researchers have developed approaches which use computational simulation for achieving robust designs, recently also using digital experiments. Another relevant topic in this field, which has received significant attention in the research literature is Global Sensitivity Analysis (GSA). Multiple GSA techniques can be found based on approaches such as Monte Carlo Simulation (Sobol, 2001), Gaussian Quadrature (DeVuyst and Preckel, 1997) and so on. GSA techniques have been critiqued for being difficult to implement in an engineering design context due to their computational complexity (Chen *et al.*, 2006). Another closely related topic in robust design is Uncertainty Propagation (UP), in which metrics related to the mean and variance of design performance is studied against input uncertainty in a simulation setting. Multiple methods of UP have been proposed over the years. Comparative analyses of

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which can be found in Lee & Chen, 2009. Methods involving GSA and UP are usually applied in the design phase of a product and therefore are not suitable for the incremental design context, where the relationships among parameters are already well known. Furthermore, while UP approaches provide extensive ways to identify potential failure due to uncertainty propagation, they do not account for localised margins. UP methods also do not account for redesign choices, especially where off-the-shelf components are involved. In such situations, excesses in the system may change discretely depending on the redesign choices made, thereby altering the sensitivities of the system.

The review reveals that while there is a significant amount of literature on robust design, most are not aimed at the incremental design context. Similarly, in the field of change propagation, much work has been done in the past couple of decades, however, methods which accurately localise margins and utilise them to create designs robust against propagation have not been studied rigorously (Eckert *et al.*, 2019). This paper, therefore, aims to fill this gap by adapting an existing method called the MVM (Brahma and Wynn, 2020a) by utilising its margin sizing and localising capability to suggest designs which are more likely to absorb variations in input specifications without deteriorating performance. A summary of the key principles of MVM is presented in the following section before discussing the expanded approach.

3. Margin Value Method (MVM)

MVM (Brahma and Wynn, 2020a) is an analytical method that uses parametric dependencies in a design to first analyse it, then to localise the excess margin and finally quantify them considering the change absorption potential and the deteriorating effect margins have on the performance of the system. The method is based on the idea that excess margins are created when decisions are made in a design process (Brahma and Wynn, 2020a), for example, selection of an off-the-shelf component (Cansler et al., 2016). The method therefore provides guidance towards identifying those decisions, leading to the identification of all the margins in a design. The method was specifically developed for an incremental design context, where a design already exists, the parameters are known, and improvements are supposed to be made by making minor adjustments to the design. The method also focuses extensively on off-the-shelf components, the use of which is a common practice in routine design situations. The method requires the construction of a Margin Analysis Network according to the systematic method specified in Brahma and Wynn, 2020a, followed by the application of the Margin Value Analysis. The margin value analysis consists of calculating three metrics:

- ***Local excess margin:*** The first metric quantifies the local excess at each margin node in the margin analysis network. In other words, it quantifies by how much a decided value exceeds the required value at each margin node (The term excess is borrowed from Eckert et al., 2004).
- ***Impact:*** The second metric is calculated based on the performance parameters - considering the actual design versus the performance parameters - if it is assumed that the margin is eliminated at each node. This metric indicates the deteriorating effect of each margin node has on the performance parameters.
- ***Absorption:*** The third metric is calculated by first calculating the variance in the specification possible which do not lead to any changes in the design and then quantifying the effect of that on the margin node. In other words, how much of the margin at each margin node can actually be absorbed without causing a propagation of changes.

For details regarding these metrics, the reader is referred to (Brahma & Wynn, 2020a).

Finally, the method suggests that the metrics calculated for undesirable impact and change absorption potential be aggregated based on the relative importance of the performance parameters and the prioritisation of change in the specification. The two metrics can then be used to show the relative importance of each of the margin nodes in terms of their absorption potential and the undesirable impact on the performance of the system. Previous developments of MVM focused on its theoretical development and application to a machine design case (Brahma and Wynn, 2020a) and its use in a CAE-driven design context (Brahma and Wynn, 2020b). However, as discussed in the introduction section, while MVM addresses the requirements of identifying, localising and quantifying excess

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margin in a design, it does not explicitly address the issue of robustness, especially against varying specifications. It can, however, be adapted to address this problem, as explained in the next section.

4. Adapting MVM for Variation in Specifications

MVM being analytical uses precise numerical values for its specification parameters. For example, in the conveyor case presented in Brahma & Wynn, 2020a, five specification inputs of interest were highlighted; desired conveyor capacity C in T/h, velocity of the belt V in m/s, bulk density of the material conveyed ρ in T/m^3, coefficient of friction between belt and pulley μ and the nominal carcass weight of the belt B_{CT} in kg/m^2. For all five of these parameters, fixed values were used in the design. In reality, these parameters may experience variations in them depending on various external factors, especially during operation. For instance, the quality of material being conveyed may vary significantly, causing a change in the bulk density (ρ) of the material. Similarly, there may be an increase or decrease in the conveying capacity due to the feed coming in from another system, of which the designed conveyor forms a part. By accounting for such potential variations, it should be possible to achieve a more robust design than if they are considered to be discrete. Moreover, this enables an appreciation of the trade-off between robustness and performance considering the undesirable effects of excesses. An approach to handle this is presented in this paper.

4.1. Conceptual Approach

To adapt the MVM to this problem, instead of using a single data point for each specification parameter, a range of possible values is considered. Ideally, it is expected that historical data is collected, and a suitable probability density function is fitted. Using a probability distribution function (PDF) to model each specification parameter in the MVM leads to the generation of two sets of data. The first set is the data corresponding to the impact metrics, and the second is the data corresponding to the absorption metrics (see Section 3). The number of datasets in each metric corresponds to the number of margin nodes in the margin analysis network (MAN), i.e., if there are n margin nodes in the MAN, there would be n datasets of absorption and n datasets of impact; each corresponding to an individual margin node. If these datasets are plotted as probability distributions, they can be compared with each other showing the increase and decrease in the absorption potential of a margin node and the adverse impact they have on performance. Conceptually, because the specification parameters may vary, the value that eventuates determines the amount of margin remaining available for absorption. For instance, if the specification parameter were at the lower (or least challenging to meet) end of the range captured in the PDF, this would result in more excess margin in the design. In this case, the design would be more overspecified relative to the minimum required, meaning a loss of performance (weight, cost etc.). In summary, therefore, variation in the specification parameters creates variation in the impact metric of the MVM.

To further illustrate, consider Figure 1, which is conceptual in nature. On the vertical axis the absorption potential of a margin node m, considering all specification parameters, is shown. For a particular margin node, point $Amin_m$ represents a point where the absorption is at the minimum possible value. As a specification parameter value varies in the negative direction (the specification becoming easier to meet), there is an increase in the absorption potential of margin node m. A_m^{opt} represents the point where the specification parameter is at its nominal value, i.e., the nominal design point. If the specification value were to change in the 'more difficult' direction, this would cause the margin to be partially consumed to absorb this change depicted as the absorption zone in Figure 1. The underutilisation and the absorption zone is where changes do not propagate and is shown in blue. When all the margin is consumed, for the design to meet its specification a new (larger) component needs to be selected, which will regenerate available margin, this is shown in red. This can be viewed as change propagation, since a change in the specification has propagated to require a change to the design itself, with possible knock-on effects.

Similarly, the horizontal axis of Figure 1 shows the conceptual curve showing how as a change in specification is progressively absorbed, the adverse impact of the excess margin on the system performance reduces (since the design is less overspecified relative to the minimum required to meet the specification value). As the margins get consumed, the adverse impact reduces until the margin is

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entirely consumed (shown in blue), at which point a new component must be selected if the design is to satisfy the specification. As with absorption, a new component brings new margin and hence an increase in adverse impact, this is depicted in red.

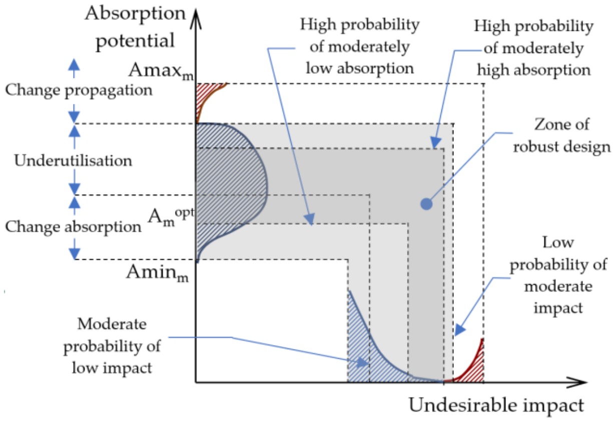

Figure 1. The trade-off between change absorption potential of a margin node vs undesirable impact the margin causes on the performance parameter for varying input specifications

Therefore, the ideal sizing of a particular margin, from the viewpoint of the undesirable adverse impact of the margin on design performance, would be in the range where there is a moderately high probability of low impact, up to where there is a very low probability of moderately high impact. The key point is that for a particular design, this range can be understood from the probability distribution of the specification parameter by transforming it through the MVM calculations to generate the corresponding distribution for each margin node's adverse impact metric. Similarly, when considering the absorption potential, the ideal design situation would be where there is high absorption potential, specifically preferable if the absorption potential is restricted to one component, i.e., no local minima in the plot. Figure 1 combines these inferences and shows a conceptual analysis of absorption vs impact for a design. An intersection of the ideal design zones based on both undesirable impact and absorption potential is therefore suggested to find a suitable value for the margin and hence, to size the related component.

4.2. Application to a Belt Conveyor Design

In the paper by Brahma and Wynn, 2020a, where the MVM was first introduced, a case study of a conveyor belt for bulk material handling was presented. The margin analysis network is reproduced in Figure 2. The case has five input specifications of interest which were expected to be affected in a change propagation scenario, namely; a) C - the desired conveyor capacity in T/h b) Velocity of the belt V in m/s, c) bulk density of the material conveyed ρ in T/m^3 d) coefficient of friction between belt and pulley μ and e) the nominal carcass weight of the belt B_{CT} in kg/m^2. All these specification parameters are marked in Orange in Figure 2. The conveyor case has nine decision nodes relating to the selection of the motor, gearbox, brake, three shafts and pulleys. These nodes are shown as large diamonds in the MAN. This produces nine margin nodes marked E1-E9, shown in hexagons. Further, the design has four performance parameters; a) TC_S - total cost of shafts, pulleys, motor, gearbox, and brake; b) TW_S - total weight of shafts, pulleys, motor, gearbox, and brake; c) I_S - combined moment of inertia or GD^2 values of motor and gearbox, and d) η_m - full load output efficiency of the motor.
As mentioned earlier, the paper aims to adapt the MVM for varying input specifications. In practical terms, all the five input specifications may be expected to be varying in reality. For example, it is common practice to measure the bulk density of coal at definite intervals, mainly for quality assurance purposes in various plants (Kleizen and van Brakel, 1984). Data from which can be collated and used to generate a distribution for such a parameter. For this paper, it is assumed that the specification parameters can be modelled as a normal distribution curve.
A Matlab simulation was set up, running the computations of the MVM for different combinations of specification parameter values picked from distributions. A Latin hypercube-based sampling method

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was used to assess the combined impact of all the input specifications on the MVM metrics (absorption potential and undesirable impact). The decisions, shown as large diamonds in Figure 2 representing component selections required to complete the design, are made by the Matlab code based on a defined selection criterion. Design options for off-the-shelf components are predefined as lookup tables extracted from manufacturer catalogues. The simulation selects an appropriate component based on the selection criteria such as power for the motor and failure mode for the shafts. This means that on each iteration of the Monte-Carlo simulation, the code automatically chooses the appropriate parts that are the minimum available to meet the particular specifications chosen for that simulation run. The simulation calculates nine sets of metrics relating to the absorption potential and the undesirable impact on performance, one for each of the nine margin nodes. The resulting data points relating to the absorption potential and undesirable impact metrics are plotted against the probability density, as presented in Figure 3 and Figure 4 respectively. Note that the vertical axis showing the probability density is clipped at 0.06 and 0.08 for clarity. Since a one-to-one comparison of the impact and absorption metrics are unnecessary, they have not been put on the same scale. For each margin node E1 - E9, separate absorption and impact plots are generated.

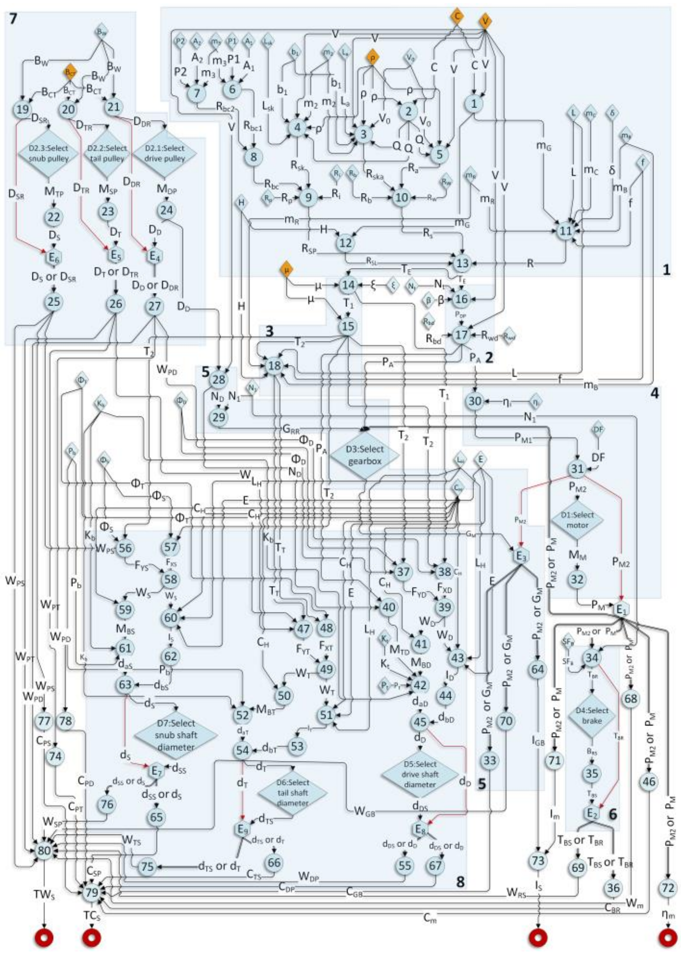

Figure 2. Margin Analysis Network of the conveyor case. For a full-size version, readers are referred to Brahma and Wynn, 2020a.

As can be observed from Figure 3 and Figure 4, the absorption potential and undesirable impact probability densities are distributed differently between various margin nodes. While some margin nodes such as E1, E2, E3 have absorption potential spread over a larger range of values and therefore low probability density, other margin nodes such as E9 have high probability density spread over a smaller range of low absorption potential values. Similar patterns can be observed in the impact plot as well. The interpretation and analysis of these curves is presented in the next section.

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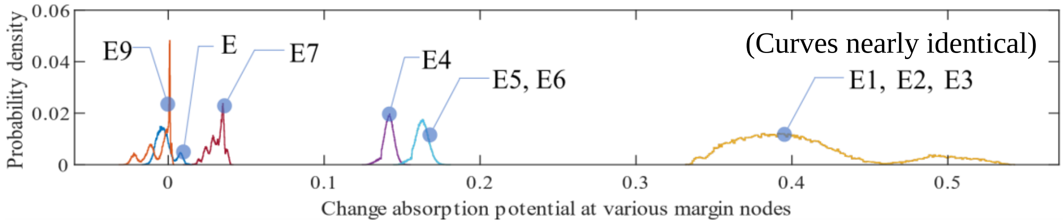

Figure 3. Probability density of absorption potential at each margin node

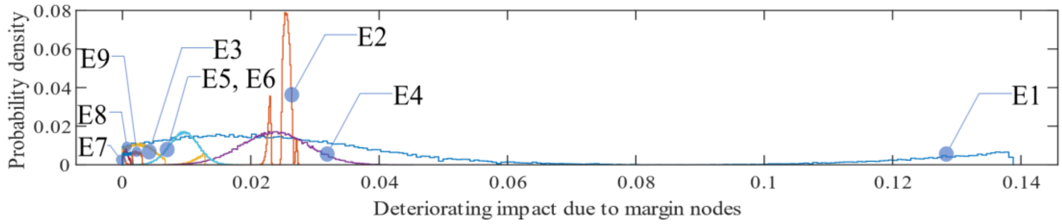

Figure 4. Probability density of undesirable impact due to excess at each margin node

4.3. Analysis and Optimisation of Design for Change Propagation

Consider margin node E1 and its absorption and impact plots in Figure 3 and Figure 4 respectively. The margin node E1 corresponds to the motor selection in the conveyor case. We will specifically consider variation in input specification corresponding to the conveying capacity C. As a reference point, the nominal value of C used in the conveyor case is 1270 T/h, which corresponds to an absorption potential value of 0.3922 in the plot. Plots specific to E1 is produced in Figure 5 in a different form, which also shows the covariation.

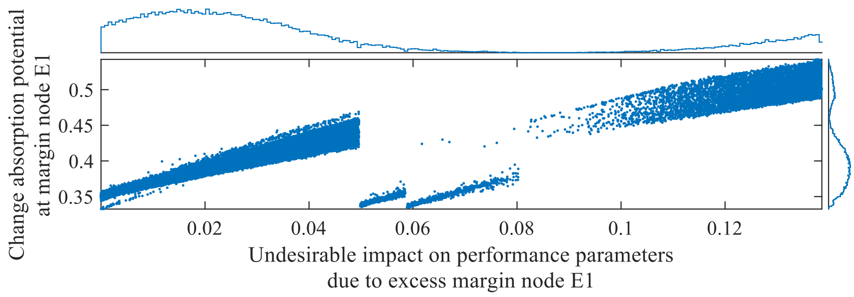

Figure 5. Scatter plot showing the relative distribution of data points related to the absorption potential and the undesirable impact metrics of margin node E1.

Figure 5, which is analogous to Figure 1 with an additional scatter plot, shows the relative absorption potential and the undesirable impact at margin node E1. The scatter plot shows four distinct population concentrations. These population concentrations show four component selection (propagated changes) points as the input specifications vary. Note that for the nominal value, the selected motor is 30 kW against a requirement of 28.60 kW. In Figure 3, which shows the absorption potential of the margin nodes, for E1, the peak (where the absorption potential value is approximately 0.4) shows the distribution around the nominal C of 1270 T/h. Above this point, in the increasing direction of absorption potential (until the point where the probability drops to almost 0) lies the underutilisation zone. In this zone, C is lesser than the nominal value, which results in an even lower motor power requirement (less than 28.60 kW), thereby increasing the margin and therefore the absorption potential, which remains underutilised. On the other hand, as C increases, the margin (difference between 30 kW and 28.60 kW) gets consumed, thereby absorbing the change. This is reflected by the dropping absorption potential probability and the simultaneously reducing absorption potential towards the bottom direction of the absorption potential histogram starting from the peak at 0.40. Another important point to consider is where the absorption potential value is approximately 0.456. At this point, all the margin is consumed, and there is hardly any absorption probable. If the input specification C is increased further, the

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required value crosses the motor specification of 30 kW. The motor then must be replaced with a motor of a higher specification which in this case would be rated at 40 kW. On the other hand, as the margin increases, there is a slight increase in the undesirable impact, the probability of which dramatically reduces as the margins get consumed. The designer, therefore, has two options, as discussed in the next two subsections.

4.3.1. Restrict the Variation of the Input Specification

The first possible approach is to strictly restrict the input specification to the zone of robust design, as shown in Figure 1. For the example case, from the absorption perspective, the ideal design would be if C is restricted such that the probability density plot has only one local maximum. In the plot, this ranges from an absorption value corresponding to 0.347 to 0.456. The corresponding C can be recalculated to be 1170 T/h to 1339 T/h. If a 3σ variation is considered, the mean can be set at 1254.5 with a sigma of 28.16 T/h. The scatter plot presented in Figure 6 (left) shows the values from a rerun simulation with the values stated above. Clearly, there is a significant reduction in undesirable impact, while the probability of change absorption increases from 85% to 96%, as seen from the cumulative distribution function (CDF) on the right.

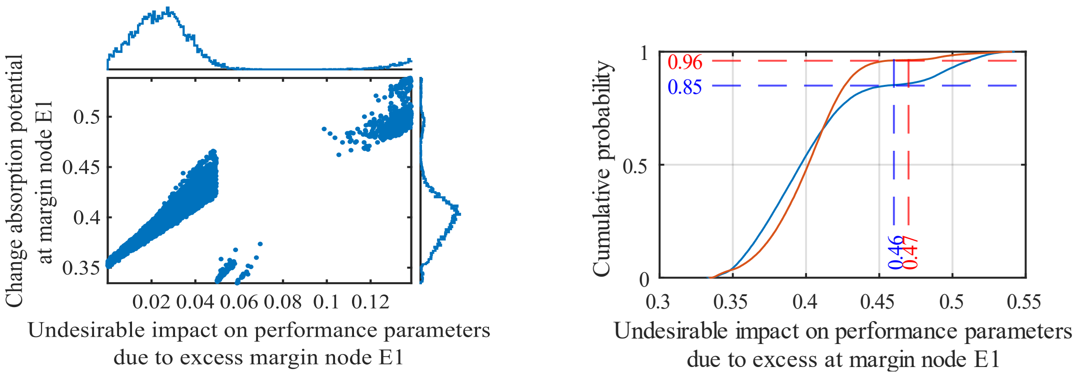

Figure 6. Simulation results of reduced variations in input specifications

4.3.2. Allocate a Larger Margin

The second possible approach could be to increase the allocated margin. However, due to the limiting effects of some margin nodes, it may not be possible to increase the absorption potential by increasing margins locally, for example by increasing the specification of the motor in isolation.

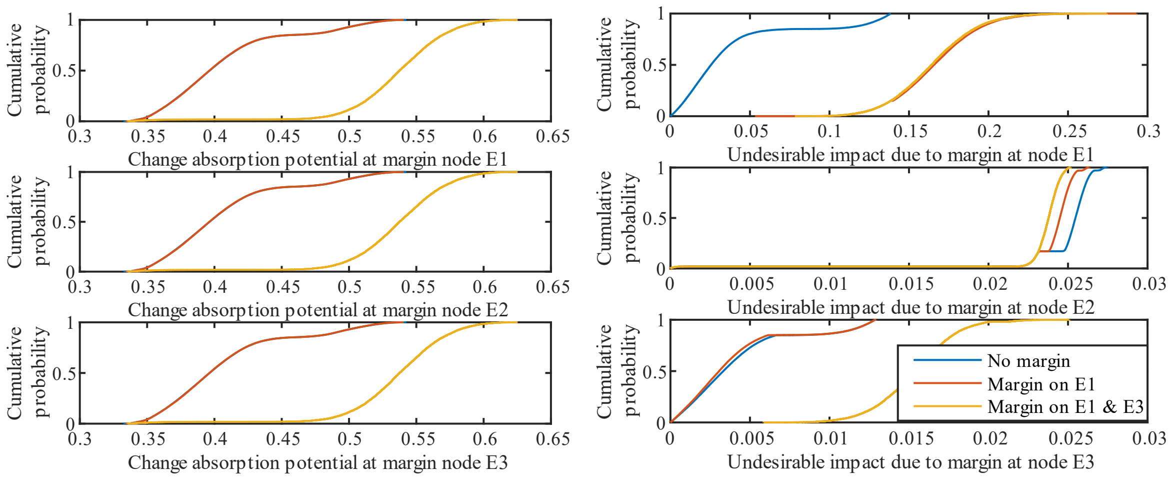

Figure 7. CDF of E1, E2 and E3 when extra margin is allocated compared to when no margin is allocated. Legend is common for all six plots

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Brahma and Wynn, 2020a, explained the concept of limiting and non-limiting margins where the absorption potential of certain margin nodes is restricted by the others. In other words, no matter how much margin is allocated in a component, it does not increase its absorption potential. In the case discussed in this paper, specifically in the context of varying specification parameters, the phenomenon is observed in the plots shown in Figure 7, where three situations are shown. First, when no extra margin is allocated, in this case, the absorption potential stands at 0.46 with an 85% probability. If an additional margin is allocated in E1 (in this example, by selecting the next higher specification component), no change in its absorption potential is observed. However, the undesirable impact increases from 0.08 with an 85% probability to 0.25 with a 100% probability. This reflects that the absorption potential is being limited by another component, which in this case was E3. In addition to the margin added to E1, a margin is also added to E3, resulting in a sharp increase in absorption potential to 0.61 (from 0.46), while the probability of change propagation reduces to 0%. The impact values and their corresponding probabilities remain the same as in the second case.

5. Discussion and Conclusion

The analysis approach discussed in this paper demonstrates that it is possible to apply the MVM to compute the probability that a change in input specification would propagate. Additionally, it is also possible to compare it with the undesirable impact a margin would have if used to absorb that change. Two strategies to handle this are presented in the previous section. On the one hand, the probability of propagation can be reduced by strictly restricting the input specification; on the other hand, additional margins can be used to have a similar effect. However, unlike the latter option, restricting variation of input specification does not cause any change in the undesirable impact on the performance parameters, which additional margins cause. Further, adding additional margins on one component may not be enough because of the limiting case, and multiple margin allocations may be necessary to extract any benefit out of the allocated margins. From the analyses of both the cases, it is demonstrated that if a ratio of absorption potential (i.e., probability of propagation) and undesirable impact is decided by a designer, it is, in theory, possible to design a product while maintaining the said ratio. This ratio would determine how much risk the designer is willing to take against the acceptable deterioration in the system due to the margins. In summary, it is important to know where and how much margin to allocate to effectively utilise them as change absorbers; otherwise, they may end up completely unutilised. The analysis approach also has certain limitations. Firstly, it does not account for variation in the specification of the off-the-shelf components, for example with time. As time progresses, the performance of components may decay due to wear and tear. Secondly, in this paper, the example compares only two margin nodes when allocating extra margins. There may be multiple limiting cases that need to be identified, and margins increased accordingly. Analysis of numerous margin nodes in such cases may be cumbersome and computationally intensive. Margins are also at times interdependent, the cumulative effect of which needs to be seen for a thorough analysis. In this paper, we have not discussed any such case. A limitation of MVM is also the complexity of constructing a typical MAN. A possible way of addressing this could be to adapt MVM to use pre-established methods such as Petri-Nets on readily available software platforms. In the future, we intend to continue this work and address all these limitations, including developing the analysis approach into a systematic method.

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