

## FAILURE MODE ANALYSIS AS AN IMPLEMENTATION OF AXIOM 2 IN THE AXIOMATIC DESIGN FUNCTIONAL DECOMPOSITION PROCESS

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### ABSTRACT

Of the two central axioms of Axiomatic Design Theory, Axiom 2, the Information Axiom, is the more powerful concept in directly addressing the performance issue that most plagues design efforts: product failures. Prior work has described a complementary relationship between Axiomatic Design and Failure Modes and Effects Analysis (FMEA). This paper proposes that failure mode analysis is more than just a complementary tool to Axiomatic Design. Failure mode analysis processes are an embodiment of the second axiom and a practical method of applying the second axiom during the decomposition process.

**Keywords:** Axiom 2, Failure Modes and Effects Analysis (FMEA), P-Diagrams, information content, Axiomatic Design.

### 1 INTRODUCTION

Effective design and development processes in industry are an exercise in risk management. Management balances three key risks of performance, delivery and costs. Tools and techniques that can provide insight into risks and risk management strategies are valuable.

Axiomatic Design is a process tool that operates in the design domain. It offers an alternative viewpoint to analyzing and developing solutions to design problems. In particular, the second axiom, the Information Axiom, of the Axiomatic Design process teaches that assessing and considering risk is an important factor of the design synthesis process.

However, for reasons discussed in this paper, Axiom 2 is very seldom applied in the decomposition process. This is a real weakness of current Axiomatic Design practice.

This paper discusses the issues around applying Axiom 2 to the decomposition process. Then this paper proposes that the functional requirement decomposition process of Axiomatic Design produces a useful framework for risk assessment and mitigation, a key process of design management, that the second axiom is a fundamental approach to robustness, that the application of Axiom 2 concepts can be achieved by the application of failure mode analysis and mitigation to the decomposition framework, and, finally, that this approach results in a broader and more useful interpretation of Axiom 2 that is valuable for general development risk mitigation.

### 2 BACKGROUND

Axiomatic Design Theory proposes an analysis framework of top down hierarchical functional decomposition to develop potential solutions to a problem. An Axiomatic Design functional decomposition is a hierarchy of pairs of functions, called FRs, and solutions, called DPs. As an example, in a cell phone application, the FR is a requirement to notify the user of an incoming cell phone. The DP, in traditional cell phones, is a ring tone. A completed design is represented, often graphically, as an inverted tree with each branch having two or more FR-DP pairs. The balance of this text assumes a basic familiarity with Axiomatic Design processes, and references are suggested here for the reader seeking more information. [Suh, 1990; 2001]

Axiomatic Design proposes a rule, referred to as Axiom 2, or the Information Axiom, to evaluate the alternative goodness, of a set of proposed DPs, at a given decomposition level, at achieving the targeted FRs. A well-defined FR should have a target measure and a tolerance. This range of acceptable FR performance values is called the design range. Ideally, selected DPs will always deliver a solution within the acceptable FR design range. The range of (FR) solution values that the DP will (in actual practice) deliver is referred to as the system range.

Often selected DPs will not deliver system range results that are completely within the FR design range. For example, in a high ambient noise environment, buried in a pocket or purse, the cell phone DP of a ring tone may fail to notify the user of an incoming phone call.

Axiom 2 asks the designer to quantify the probability that selected DPs will deliver on the required Design Range. In the original definition of Axiom 2, a probability,  $p$ , was defined as the percentage DP system range falling completely within the FR design range. [Suh, 1990; 2001] In order to add up these probabilities across a set of  $n$  FRs and their DPs, the information content of Axiom 2 was defined as  $\sum_{p=1}^n \ln\left(\frac{1}{p}\right)$ .

As DP selections deliver increasing percentages system ranges within the FR design ranges, the information content approaches 0. As the system range within the FR design range falls to zero, the information content metric will approach infinity.

Classic Axiomatic Design proposes that when there are alternative solutions sets of DPs at a given decomposition level, the set that minimizes the information content is preferred as it is more likely, probabilistically, to deliver solutions within the desired FR design ranges.

Note that this application of the information content assumes an equal design value weighting of all the FRs. Also, this application focuses only on the fraction of the DP system range that falls outside of the FR design range, and is not a measure of the actual total error in achieving the targeted FR. And lastly, this assumes that the Axiom 1 does not provide a decision criterion.

To avoid confusion with other meanings of risk, this text defines the term Performance Risk as a measure of the likelihood that the proposed DP solutions will fail to deliver the required FR performance (as represented by the design range). The second axiom, the Information Axiom, per its definition is a metric of Performance Risk.

Traditional Performance Risk assessment techniques rarely identify and analyze the relationship between FRs and their DPs. In part this is because most contemporary risk methods do not identify these parameters. But more significantly, in the author's experience, there is an implied assumption that the selected DP will, under a reasonable set of conditions, deliver the required FR performance. If such conditions did not readily exist, then the design would never get past the initial prototype stage.

Rather, designers interested in analyzing Performance Risk focus on events or conditions that might cause the DP to fail to satisfy the FR. These are often discontinuous and outside of the nominal FR-DP relationship. Examples include wear-out, product misuse, manufacturing mistakes, supply chain errors, and other factors affecting the nominal FR-DP relationship.

The Parameter Diagram or P-Diagram is a representation of the variables of process capability and a common tool in robust design analysis. [Guangbin, 2007] Translating this tool into the Axiomatic Design domain gives us the representation of Figure 1. Examining this figure we see a black box representation of a function where changing the input signal factor(s) varies the output response, subject to the influence of control factors and noise factors.

In the Axiomatic Design paradigm, DPs are signal factors, FRs are the response, and control factors are the designer specifiable child functions of the next lower decomposition level. In a process known as Parameter Design, designers typically select the control factors to either maximize the control of the FR by the DP, increasing the probability of FR success, or minimize the cost of implementing the functional relationship.

This P-diagram visualizes the requirement that a designer needs to address noise factors in order to assess the functional performance risk that the DP will achieve the required FR. Noise factors, often discontinuous, are typically environmental variables that have the potential to interrupt the 'Happy Path' relationship, between FRs and the DPs, that is desired and specified by the designer. These interruption events are called failure modes.

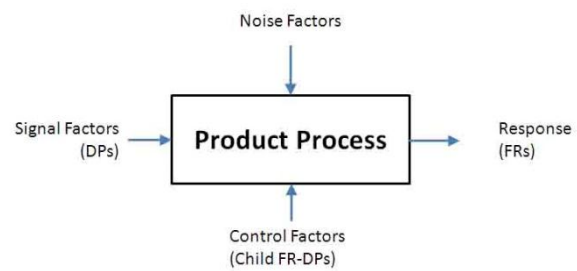


Figure 1. P-Diagram.

During the concept synthesis phase, while it is difficult to define the percentage of the DP design range within the FR range without significant additional information, the designer can reasonably identify and quantify the failure modes that might interrupt a nominal FR-DP relationship.

For example, at this writing, the Boeing Company is battling problems with its lithium battery system on the 787 airplane. [Pasztor *et al*, 2013]. Although the original nominal FR-DP design relationship was certainly extensively studied, tested and validated prior to deployment, a seemingly random and unanticipated failure mode is causing serious program disruptions. This underscores the importance of failure mode analysis and helps to establish its value to the design process and product functional performance.

The design industry has a process and a framework tool, Failure Modes and Effects Analysis (FMEA), used to capture and codify failure modes. For a given performance function, the FMEA process asks the designer to consider the noise factors and control factors, and list the potential failure modes. Three scoring assessments are made for each failure mode, normally on a ten point scale. These scores are for the probability of the failure mode, the severity of the failure mode, and the likelihood the failure mode would escape early detection and prevention and manifest itself in actual product use. These scores are multiplied together giving a product, called the Risk Priority Number (RPN), which can range from 1 to 1000 for a ten point scoring scale, with 1000 being the highest risk. For a more detailed description of an FMEA process see references. [Stamatis, 2003]

### 3 LITERATURE REVIEW

The application of Axiom 2 to decomposition is largely absent from case studies and literature. The author proposes that during the concept synthesis phase when the DPs are selected, at a given decomposition level, it is generally difficult to sufficiently quantify the traditional Axiom 2 information content definition for these reasons:

1. Such analysis requires details which are effectively the major work of the development effort and not available until near the end of the project.
2. The Performance Risk is highly dependent upon the external noise factors which are not (traditionally) included as part of the Axiomatic Design decomposition and analysis framework.
3. The Performance Risk is highly dependent upon the selection of potentially risk altering lower level child functions, which are not yet available to the designer when making DP tradeoff decisions.

On this third issue, it can be suggested that deriving a complete set of lower level child FR-DPs is included as part of the Axiom 2 information content analysis. However, executing this approach asks the designer to decompose all alternative DPs to their leaf levels. Given the number of DPs considered in typical design processes, this is hardly a realistic approach.

Prior authors have linked the Axiomatic Design process to FMEA analysis. Mohsen and Cekecek [2000] identified integrating AD with other quality tools such as FMEA, P-diagram, FRS and testing and verifications to achieve better quality products with minimum development time and minimum cost. Arcidiacono *et al* [2004] discussed applying FMEA analysis to FR-DP trees and developed a metric, the Esteemed Risk Priority Number, to adjust RPN rankings for coupling affects. Heo *et al* [2007] described the direct and intimate relationship between Axiomatic Design and failure mode analysis as represented by Fault Tree Analysis. Trewn and Yang [1998] developed a model to characterize the relationship between functional reliability and component reliability considering failure dependence.

From both observation of Axiomatic Design practitioners, and a review of prior literature, it appears that the Axiomatic Design second axiom is represented as somehow separate from a traditional failure mode performance risk analysis tools. Yet, failure modes are clearly a variable of contemporary and historic design product Performance Risk. And potential failures are most commonly analyzed by considering the potential deviations from expected nominal design performance, whose drivers are called noise factors. And mitigating failure modes is a necessary step to improving Performance Risk. Therefore, if the reader accepts the concept that the information content is a measure of Performance Risk, then, by transitive logic, addressing noise factor and failure modes is a necessary and integral part of Axiom 2.

So the relationship between Axiomatic Design and the FMEA noted by the authors above is not just a convenient and complementary relationship between independent design processes. The FMEA is a direct technique to assessing and scoring Performance Risk, the same risk addressed by the Axiom 2 information content metric. Even more practical, FMEA analysis suggests actions to further minimize the Performance Risk. Whereas the Axiom 2 classical definition is a theoretical consideration of Performance Risk, the FMEA process is a practical and applicable tool to measure and mitigate Performance Risk during the concept synthesis phase.

**4 METHODS**

Given the limitations discussed above, how can a designer apply Axiom 2 concepts during the concept decomposition to evaluate and select DPs to minimize Performance Risk?

Failure mode analysis is a systematic approach to assessing and improving Performance Risk and, as such, is an implementation of the Axiom 2 value proposition. Therefore, this paper proposes that a systematic approach to implementing Axiom 2 during the concept synthesis phase, in order to measure and improve the Performance Risk, should

be to quantify and address the potential failures modes created by identified noise factors of the FR-DP relationship.

To implement such a process, at every level of decomposition, proposed DPs should be assessed for failure modes. Rather than try to calculate an information content metric on how well the DP delivers on the FR, ask the inverse question “What failure modes might cause the DP to fail to deliver on the FR?”

Applying an FMEA framework, each identified DP failure mode is analyzed, scored and the RPN calculated. The DP will then have a list of failure mode scores associated with it. If the DP is changed, the failure modes have to be re-evaluated. If alternative DPs are being considered, failure modes are independently assessed for each DP.

The DP decision process can be viewed as a tradeoff analysis between alternative DPs including, as part of the analysis, a consideration of the failure mode risks and RPN scores.

The RPN risk score (and thus logically the Axiom 2 information content metric) is not a static measure. As risks are identified, risk mitigation strategies can be developed and actively applied, reducing the Performance Risk associated with a DP. In the Axiomatic Design framework, failure mode mitigations are implemented as child functions of the FR-DP pair being de-risked.

For example, consider our cell phone FR to alert users to incoming calls. The classic DP is a cell phone ring tone.

- FR1: Alert user of incoming cell phone call
- DP1: Ring tone
- FR1 Target Measure: 100% notification rate

To assess the Performance Risk (Axiom 2) using failure mode analysis, consider Table 1 with a list of potential failure modes that would prevent the DP from achieving the desired FR. These failure modes are scored for probability, severity, and detectability per the FMEA process on a 1 to 10 scale (10 highest) giving an RPN risk score.

**Table 1. Failure mode analysis of ringtone DP.**

Failure mode	Probability	Severity	Detectability	RPN
Dead battery	8	5	10	400
Noisy environment	4	5	2	40
Cell phone sound damped in purse	4	5	10	200
Cell phone sound damped in pocket	4	5	10	200
Dirt blocked speaker path	2	5	3	30
Earphones in cell phone, but not in ears.	6	5	1	30

It is possible to score a weighted overall DP risk score, perhaps by summing the products of the probability and severity, when comparing alternative DPs. But this is too simplistic, and a review of the failure mode risks should be just one aspect of analyzing competing DPs. Note that only failures to notify were considered here which resulted in the constant severity score. It is not unusual to have multiple

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failure modes having varying severities. Also, these are qualitative assessments, appropriate for a concept phase analysis.

The dynamic nature of assessing Performance Risk can be demonstrated by evaluating each failure mode and determining potential mitigations. Table 2 summarizes proposed mitigations and post mitigation RPN risk scoring.

**Table 2. Ringtone DP performance risk mitigation.**

Failure mode	Mitigation strategy	Probability	Severity	Detectability	RPN
Dead battery	None (no Performance Risk change)	8	5	10	400
Noisy environment	Detect ambient noise and compensate ring volume	2	5	2	20
Cell phone sound damped in purse	After period of normal ring volume, increase volume	2	5	10	100
Cell phone sound damped in pocket	After period of normal ring volume, add vibration	2	5	10	100
Dirt blocked speaker path	Periodic power on sound test to analyze sound quality, detect problems/blockages, notify user.	1	5	3	15
Earphones in cell phone, but not in ears.	Detect earphones, after period of earphone ring, switch to speaker ring	1	5	1	5

Effective mitigations are incorporated as additional child functions of the DP, as noted below.

FR1: Notify user of important incoming cell phone call

DP1: Ring tone

FR1 Measure: 100% notification rate

FR1.1: Mitigate Noisy environment failure mode. DP1.1:

Detect ambient noise and compensate volume

FR1.2: Mitigate cell phone sound damped in purse failure

mode. DP1.2: After period of normal ring volume, increase volume

FR1.3: Mitigate cell phone sound damped in pocket

failure mode. DP1.3: After period of normal ring volume, add vibration

FR1.4: Mitigate dirt blocked speaker path failure mode.

DP1.4: Periodic power-on sound test to analyze sound quality, detect problems/blockages, notify user.

FR1.5: Mitigate earphones in cell phone, but not in ears

failure mode. DP1.5: Detect earphones, after period of normal ring volume, switch to speaker ring

Comparing Tables 1 and 2 demonstrate that failure mode mitigation has changed the RPN measures of the Performance Risk of the selected DP, and thus the design proposal. This demonstrates the dynamic nature of Performance Risk and points out the power of applying Axiom 2 considerations during the Axiomatic Design requirements decomposition process to improve Performance Risk by modifying the decomposition architecture.

In addition to being an active feedback mechanism to improving the FR-DP decomposition, the analysis can be easily extended into identifying the necessary manufacturing and field process steps, where applicable, to detect and catch the development of these failure modes before they impact the customer.

## 5 RESULTS AND OBSERVATIONS

The initial reaction a new practitioner might have is that failure modes would be more easily determined for lower level functions. It is the experience of the authors that upper level functions are also very easily analyzed for failure modes.

The authors considered the utility of developing a mathematical model to summarize RPN scores throughout the design hierarchy or across a decomposition level. Assuming that FRs are generally independent, assessing DP failure modes individually is valuable. Examining if aggregate scores bring additional value may be explored more in the future.

No attempt was made, nor did it seem useful, to categorize failure modes as design or process analysis, typical divisions of traditional FMEA processes. This means that detectability scores can vary in interpretation as a design or process measure. Also, the overall organization of this failure mode analysis is by the Axiomatic Design function (FR), whereas traditional FMEAs are usually organized by later phase artifacts such as part numbers. Also, failure modes can be introduced in all phases of the design process, so as the design progresses, it is very appropriate to repeat the FMEA in its more traditional forms. It is important to note that probability, severity, and detectability are all potential variables in risk mitigation as lower level design decisions (child functions) can affect all three measures. Also, implementing Performance Risk analysis at the DP selection point is preventative in timing, as opposed to design it in, then later analyze and fix problems created early in the design process.

Whereas traditional Axiomatic Design proposed applying Axiom 2 to comparing alternative DPs, the author's work has demonstrated that implementing failure mode analysis during decomposition is also an active risk mitigation process that can be applied after the DP selection to further improve Performance Risk. It can be inferred from this experience that applying Axiom 2 concepts to just comparing alternative DPs is a limited application and ignores the significant potential benefit of an expanded view of the concept.

And finally, if we examine the cell phone example above, we see the child FRs identified to mitigate the Performance Risk (as represented by failure modes) of a cell phone ringtone DP are all reasonable and easily implemented. Yet these mitigations are not found on contemporary cell phones. This demonstrates how experienced design teams of the cell phone industry are consistently failing to deliver on functional

design performance, a value proposition of Axiomatic Design.

## 6 CONCLUSIONS

The Axiomatic Design practitioner should consider using failure mode analysis as a practical technique to assess, compare and mitigate Performance Risk of selected DPs.

In the experience of the authors, when this technique is introduced to practitioners of Axiomatic Design, the resulting decompositions are substantively and dramatically improved resulting in reduced development risk. Prior to this technique, Axiomatic Design would be considered an interesting but narrow point tool that could be used to analyze and better visualize potential root causes of a functional design problem. With this technique, Axiomatic Design becomes a useful tool for Performance Risk management worthy of inclusion into a design and development toolkit and applied as a standard process over the entire design.

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