Influence of Environmental Loading Factors on System Design

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ABSTRACT

A closed-loop, iterative FMEA/FMECA process is vital for a safe design, but the challenge is in performing these analyses in such a way that alternate scenarios can be rapidly considered, and changes implemented to improve the design. This paper identifies an explicit model-based method to optimise system design by linking the failure identification process to specific operating scenarios and environmental conditions (Environment Loading Factors (ELF)). Current methods exist to define operating scenarios for FMEA/FMECA, but are limited by the lack of connectivity and traceability between the two. Without connectivity a failure mode analysis is limited in scope, and emergent scenarios cannot be easily understood without repeating the entire analysis process. This paper outlines a model-based method to define operating scenarios, each with a user defined Operating Environment (OE). The OE is defined by a set of Environmental Factors (based on a taxonomy) and is then used to modify the expected criticality of associated physical failures of the system. By linking physical failures to an operating scenario, changes to the operating scenarios can be made to automatically update and advise failure mode changes to the design FMEA/FMECA. The linkage can be used to explore a wider variety of operating conditions and use-cases, including the ability to perform trade studies to compare different environments and examine their impact on the design. By comparing and assessing operating environments concurrently in the design process, a safer and more robust design can be realised.

1. INTRODUCTION

Model-based engineering analysis software offers a flexible, consistent, and traceable work tool in which complex engineering systems can be managed over the product's lifetime. As a single point of reference and entry for pertinent data, the system model can be updated as a design matures or the product extends into its operating life. This allows for a broad range of analyses to be partially or fully automated. As an alternative to more widespread authored spreadsheet style of analyses a model-based tool offers an increased focus on producing a sound representation of a system's functions and the manner in which failures develop, with analyses being produced from this model when requested.

A system model is created with certain assumptions that inform the design and operation of system. These assumptions also form the knowledge base and support of any analyses produced from the model and as a result, the data and information used to create that analysis is contextual to the assumptions made.

These assumptions include the role, the physical design and configuration, and external environmental context of the product under consideration. The assumed operating conditions have a direct impact upon failures observed in the system during operation and as such will influence associated analysis outputs. If these assumed conditions are changed the analyses must be updated to reflect this change or in the case of a model-based analytical tool, parameters in the interactive system model itself require updating.

Recognising that operating context impacts upon major inputs required for failure analysis, it follows that changes to the operating context assumptions will result in changes to these inputs and analyses outputs themselves. Using MADe, a model-based engineering tool, as its use case, this paper describes a formalized approach to standardizing and automating updates to physical failure data and criticality data, based upon changes in the assumed external operating environment. The authors, in their role at PHM Technology, developer of the MADe software, sought to build on the existing model-based FMEA capability by specifying a consistent framework with which to evaluate a system contextual to the influences of an external operating environment.

It is possible to identify a set of broad environmental influences/factors that are consistently encountered across any foreseen operating environments. By describing external operating environments in these terms, vastly different operating environments may be compared on a like-by-like basis with consistent analytical outcomes with replicable consequence for the resultant analyses.

The outlined procedure utilizes an Analytical Hierarchy Process (AHP) style of analysis (Saaty, 1980). Operating environments are defined using a set taxonomy of environmental factors. These factors are given ratings by the analyst or user in terms of the magnitude of severity of the factor of interest within that operating environment. The target system's sensitivity to external environmental factors is then defined based on the relative sensitivity to each factor. Once both the environment and system sensitivity are defined these weightings are multiplied together and the set of values are plotted as a chart. The area of an operating environment's characteristic chart acts as a quantitative measure of environmental severity in context of the operating environment's impact upon a system's failure characteristics. This process provides a logical framework with which to assess and compare operating environment impacts upon a specific system.

2. SPREADSHEET-BASED ENGINEERING ANALYSIS

The development of FMEA/FMECA (US Department Of Defense (USDOD), 1980) (or failure analysis more broadly) using an authored spreadsheet is common current practice in industry. Failure analysis is conducted through facilitated committee discussions whereby the failure causes, failure modes and end effect on the system are determined. In this manner the analysis is built, manually entering data into the requisite cells of the FMEA table or form sheet. Although the individuals involved are likely informed experts of the system under consideration it can be questioned as to whether the analysis is consistently repeatable over time, even if no variables impacting the analysis are changed there is still the high potential that human error or subjective judgement will result in differing analysis.

Two major purposes of failure analysis are to identify potential failures that may impact the system and to progressively inform the design as it matures. Making the assumption that all possible failures are identified, traditional failure analysis may still fail in its purpose as a design feedback tool. Correctly conducted iteratively through design, failure analysis allows the assessment of outstanding items, with critical failures mitigated through design. However, this becomes impractical if analysis is time-consuming and inflexible (does not allow variation and modification). The result is a failure analysis conducted to produce FMEA and FMECA in order to fulfill administrative requirements, rather than a useful design tool.

3. MODEL-BASED ENGINEERING ANALYSIS

The MADe software offers a suitable tool for model based engineering. System modelling in this context refers to representing the system and its constituent items in a software tool. Each item in the system is represented by a functional block, with each block defined by the functional inputs and outputs of the item the block is representing. The blocks are interconnected by functional flows from one item's output to another's input. The model has an indentured structure representing the functional hierarchy of the system. In this way the system's functions are linked to the functions of the sub-systems within, each sub-system's functions are linked to the components within and so on. The resultant functional map describes the operation of the system. Defining a failure mode as the failure of an item to achieve a certain function, the failure modes of the system are autonomously defined through the system model.

3.1. Generating Analyses from a System Model

The model acts as a singular collection of data facilitating the automated production of a multitude of analyses in the failure, reliability, availability, and maintenance domains. The model allows analyses to be produced when requested using partially or fully automated report generation. If the model accurately reflects the system it is targeted to portray, then each analysis consists of processing and organizing the input data based on analysis type required, then outputting the results in a familiar format.

The major inputs facilitating failure analyses (FMEA, FMECA, Fault Tree Analysis (FTA) (SAE International, 1996)) and associated analyses (RCM (Ministry of Defence (MOD), 2012), Maintenance Cost Estimates (MCE)) are the failure paths (tracing failures from initiating event to end-effect) of the system alongside criticality and reliability data applied to those failure paths. In this context, failure path is a causal chain of events describing an initial physical failure event resulting in an item failing to perform its intended function (i.e. the functional failure mode of the item) and propagating through to the nominated end-effect of the system. Taking the Risk Priority Number (RPN) style FMECA (Ford Motor Company (FMC), 2004) as an example, each unique failure path has occurrence, severity, and detectability metrics.

3.2. Objectivity Through Taxonomy

MADe distinguishes between the following types of failure concepts. Physical failure causes, mechanisms, and faults and functional failure modes. A taxonomy of failure concepts allows consistent descriptions of failure paths to assure a level of analytical objectivity. Each failure concept can be catalogued and compiled into a software library. Each item's failure characteristics can be described using the terms from the taxonomy.

During design the concepts applied to the model may be based on historical data or designer experience, these representing the best information at hand. As the system enters its life of operation the failure diagram (interactive list/profile describing the causational paths potentially leading to a failure mode) can be updated based on observed failures. This will correspond to an updated failure analysis.

By cataloging each concept in a software library, causational links can be made between certain environmental conditions/factors and failure concepts within the established taxonomy they have been shown to induce, accelerate, or otherwise impact.

4. OPERATING CONDITIONS

4.1. Assumed Usage Scenario

The modelling of a system for the purpose of failure and reliability analysis is created with underlying assumptions regarding the product under consideration; the system structure and properties as well as the conditions under which it is going to be operated under. Analysis derived from this model will, either explicitly or implicitly, be generated with these assumptions in place.

In accordance with the process out-lined within this paper, the individual or team tasked with producing the initial model is required to establish the design or baseline operating environment, ideally prior to modelling the system and certainly prior to the undertaking of any failure analysis. This forms a large portion of the context in which judgements impacting the model, and hence analyses, will be made.

4.2. Implications on Model Analysis

Inherent reliability of a system is often described as not being able to be changed (excluding re-design of the system). This may be true, however through manipulating the environment and role of a system it can be demonstrated that the operational/contextual reliability can indeed change (e.g. the frequency of failures increasing or decreasing dependent upon changes in operating conditions).

When reliability values are input into the MADe model (or applied to any system regardless of modelling approach) there are underlying assumptions as to what conditions these values are relevant and accurate for. These assumptions include the operating conditions of the system (e.g. the environment and role). This principle applies for the large majority of data applied to the model. The same assumptions that provide context for the reliability data also underpin the modelling of physical failures and the criticality of failure pathing. With the correct sets of data entered, under a set of assumed operating conditions, analysis such as maintenance costings and FMECA can be undertaken.

If the environment or role of the system is changed then the underlying assumptions on which any analysis has been generated no longer hold true and it is appropriate that these analyses are re-evaluated under the new conditions.

4.3. Operating Environment in the Context of a System Model

The operating environment of a system encompasses the immediate external settings that the system under consideration experiences at any point within its lifetime. All conditions, circumstances, influences, stresses, and combinations of these surrounding and affecting the system or equipment during major lifecycle phases including storage, handling, transportation, testing, installation, use in standby status and mission operation may be considered when defining a systems operating environments. This can include man-made or self-induced environments that affect the function, performance, reliability, or survival of an item.

When performing failure or reliability analyses the operating environment represents a demonstrable, major variable in the development of failures within a system. When considering the operating environment of a system there must be an emphasis on defining the operating environment in terms that are comprehensible and consistent. The operating environment's definition must be understood by a varied range of professionals involved in the design and operation of the product. Consistency of terminology and approach allows comparisons between operating environments on a like by like basis possible.

4.4. Developing an Environmental Taxonomy

The aim in implementing a taxonomy of environmental factors with which to describe operating environments was to identify environmental variables that fit two criteria. Firstly, each factor should have the potential to impact upon the failure performance of a system. Secondly, each factor should be consistently observed to some degree across a wide range of operating environments within the terrestrial, marine, and aerospace domains. Here failure performance can be defined as the reliability as well as the specific failure causes of a system. The second requirement is to maintain consistently comparable variables for each operating environment (or "environmental profile"). This ensures any two operating environments created can be fairly compared.

A taxonomy of environmental factors was created through a process of literature review and application of the above discussed criteria of selection. The primary sources for the Environmental Factors were military standards MIL-HDBK-338B (USDOD, 1998) and MIL-STD-810F (USDOD, 2000). Through review of existing literature, the following environmental factors were identified (see Table 1).

Table 1: Taxonomy of environmental factors and characteristics

Environmental Factor	*Environmental Characteristics*
Acceleration	Exposure to high accelerations, Exposure to zero gravity
Electromagnetic Radiation	Exposure to solar radiation
Gaseous Contamination	Corrosive environment, Exposure to ozone
Humidity	High humidity, Humidity differential, Low humidity
Liquid Contamination	Corrosive environment, Exposure to rain
Nuclear Radiation	Exposure to nuclear radiation
Pressure	Atmospheric pressure, Atmospheric pressure differential, Atmospheric pressure fluctuations/cycle, High air pressure, High atmospheric pressure, Low atmospheric pressure
Shock	Exposure to shock
Solid Contamination	Corrosive environment, Exposure to salt and dust
Temperature	Exposure to thermal shocks, High temperature, Low temperature, Temperature change, Temperature differential, Temperature fluctuations/cycle
Vibration	Exposure to vibrations

As defined above the external environmental factors are relatively broad. These external factors are used to describe the external, ambient operating conditions of a system. The associated environmental characteristics are descriptive elements to aid in clarifying a specific operating environments circumstance and do not quantitatively contribute to analysis. The identified taxonomy of environmental factors is used as a consistent set of variables with which to describe all operating environments.

5. IMPACT OF ENVIRONMENT

5.1. Which Model Characteristics are Impacted by External Environment?

Variation in Operating Environment has a demonstrable performance impact (DOD, 1998) across the failure characteristics and hence the reliability of products. This relationship between environmental severity and a system may manifest itself through several mechanisms. Environmental factors may trigger variance in the occurrence of certain failure causes, they may accelerate progression of failures, or they may result in previously unobserved failures to be initiated in operating scenarios where previously this would not occur.

5.2. Current Approaches to Taking Environmental Impact into Account

In developing a systematic procedure to evaluating environmental impact on system life the current industry practice and available literature on the subject indicates a largely inconsistent approach to analysis, if any suitable approaches do even exist.

The functionality required from a process can be distilled into the following question: how can variance in external operating environment express change on failure and reliability analysis in support of a design process?

The current state of the art in this area can be grouped into two generalized approaches:

- Qualitative description of an operating environment and its impact on a system. A typical application of a qualitative approach may be a set of potential operating environments being available with each operating environment having a broad description of the conditions that a system may be exposed to. These environmental descriptions are taken into account by the engineer when completing analyses based upon the analyst's judgement. One such approach is detailed in the System Reliability Center's operating environment definitions (System Reliability Center (SRC), 2001).

- Quantitative item level multiplying factors applied to part failure rates which require extensive operating data, classification of items, physical dimensions, and material properties. Based on the physical attributes of the item under consideration and environmental influences it is experiencing a baseline failure rate is adjusted up or down corresponding with observed trends in similar items This style of approach can be seen in MIL-HDBK 217F (USDOD, 1991) and NSWC-10 (US Naval Surface Warfare Center (USNSWC), 2010).

Neither approach is widely utilized and both have problems when applied in design. A qualitative approach suffers from many of the same drawbacks as spreadsheet based analysis in that it proves to be typically not repeatable as the process is not truly formalized and as such cannot be applied consistently. The quantitative item level factor style approach does not add value across the breadth of an iterative design process. Too much time and detail are required for effective generation of analyses. And for the majority of the design process the requisite detail required to obtain meaningful analysis is not feasible. For example, at the conceptual design stage the specific data required (e.g. dimensions, material properties) is not available.

5.3. Substantiating the Impact of Environment

In order to appropriately consider the impact of a change in operating environments on the system we will look to analytically qualify the relative severities of potential operating environments. To achieve this; operating environments must be defined in terms of their constituent environmental factors, then the system must have its own susceptibility to the external environment defined. At this stage the operating environments (with the context of the system's susceptibility) can be compared and ranked against one another. This general process is outlined in Figure 1.

The model of each unique system provides the information and context onto which the environment is applied, resulting in a change of failure performance (dependent on analysis type). As such the operating environments can be saved for later use with other systems, across a variety of analyses.

5.4. Environment Definition and Comparison Process Flow

In step 1 of the overall process operating environments are created in the operating environment library. Each operating environment is described using a set of environmental factors. Factors for each operating environment are selected from a set taxonomy and represent the environmental conditions that deviate from a nominal level and may impact on failure characteristics of a system

In step 2 selected factors are rated in terms of severity within that operating environment. These ratings are properties of the environment and are made independent of any system under consideration. Note that these parameters are unrelated to 'Severity' ratings of a failure path considered in the context of FMECA.

The operating environment is saved within the operating environment library in step 3.

Undertaking an Analytical Hierarchy Process (AHP) analysis in step 4, factors are compared against one another. This is used to define the sensitivity of the system's failure characteristics to factors the system may encounter.

In step 5 a Baseline Operating Environment (BOE) and Applied Operating Environment (AOE) are selected from a library of saved and pre-defined operating environments. BOE refers to an assumed environment at which the initial model has been created. The AOE is a prospective environment which is to compared in terms of overall severity to the BOE

In step 6 operating environments are compared and an Environmental Loading Factor (ELF) is calculated. This factor is a ratio comparing the two operating environments and expressed as (baseline environment / applied environment). This ratio represents the relative strength of the applied environment. Multiple applied operating environments can be selected each having a relative strength or figure of merit with which to compare.

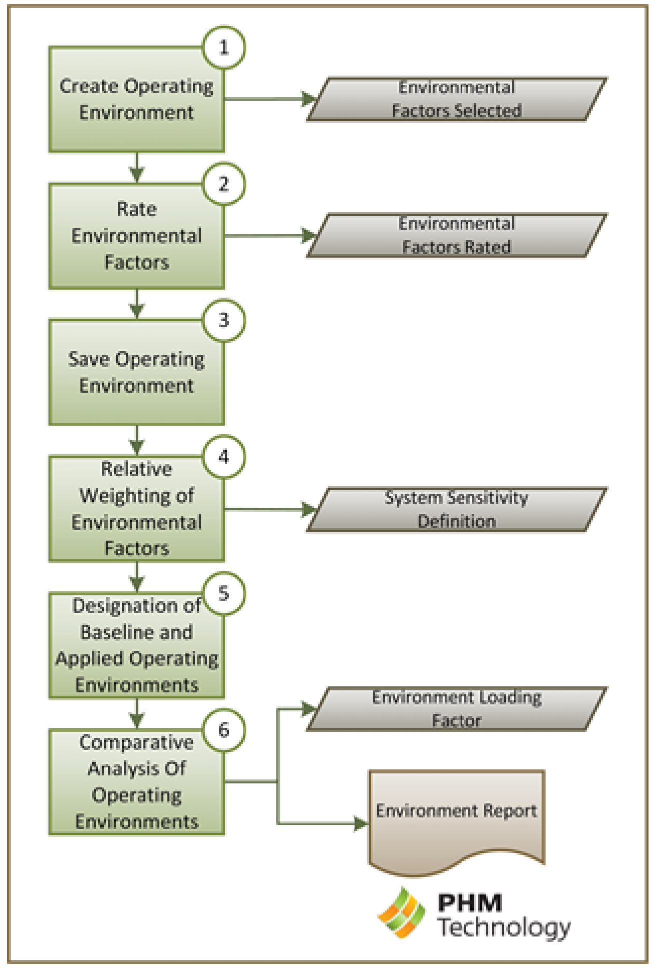

Figure 1: Operating environment definition process flow

5.5. Defining Operating Environments

Consistent with the above discussed selection process for the environmental factors it is assumed that each environmental factor is present within each operating environment, although it is recognized that some factors may be of negligible impact.

We are seeking to define an operating environment in a consistent manner so that it may be applied to a variety of systems. Rather than re-evaluating an environment each time an analysis is required or for each individually modelled system or product, we are seeking to define an environment that will be applicable across multiple projects. In defining the operating environments, the user has described the ambient environment a system will be operating in, independent of the unique properties of the system itself.

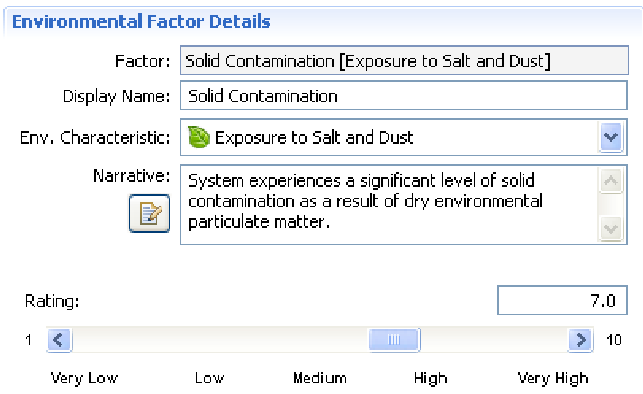

Figure 2: Rating environmental factor

The user rates each environmental factor within an operating environment. Each rating is made in terms of the magnitude of severity within that operating environment. This is done on a qualitative, sliding scale from Very Low to Very High (see figure 2). Quantitatively this represents a scale from 1.0 to 10.0. An operating environment is defined and can be saved into a library for later use when each environmental factor has been considered and rated.
Noting that many of the factors under consideration could be considered quantitative in nature in that they have measurable values (for example temperature or pressure). Whilst quantitative values can be used in a traditional AHP style analysis (Saaty, 1990) it can prove inappropriate to directly use these values in this context given a basic measure of magnitude may not be representative of the factor's severity and impact on system life, the characteristic that is being captured.

5.6. Define the Sensitivity of the System to Environmental Change

The operating environments are defined in terms that are independent of any system potentially under consideration. It can be recognized that one set of environmental factors may not necessarily have a uniform impact upon all systems or products, the amount of affect incurred will be dependent upon the magnitude of the environmental factor and the susceptibility of the system itself to that particular environmental factor. We have defined the magnitude of the condition as the level of potential impact within the generation of the operating environment; the susceptibility to each environmental factor now needs determining.

The specific system under consideration is rated in terms of its sensitivity to each environmental factor. Using the Analytical Hierarchy Process (AHP) (Saaty, 1980), environmental factors are weighted relative to one another based on their maximal potential impact to the system. These weightings will be applied at the system level and will be used to scale the environmental factors across all operating environments being applied to the system (i.e. when comparing a baseline operating environment to a prospective operating environment, both have their constituent factors weighted the same).

AHP is a flexible process designed to prioritise criteria, taking both objective, measured data as well as subjective and rough estimates of value and processing them in a consistent way to give a measure of objective value (Saaty, 1990). An AHP analysis is used to account for environmental factors with different magnitudes of impact upon the system. It will scale the magnitude of the axes that the environmental factors are plotted on as well as scaling the factors themselves.

In practice the modeler of the system (or user of the software) will be required to make a series of judgements as to how relatively sensitive the system is to one factor compared to another factor. Each factor is ranked against each other factor numerically, the higher the ranking the greater the general effect upon failure occurrence one factor has over another. These ratings are collected and sorted into a pairwise comparison table as seen below. AHP is specifically applied to systematize inconsistent and subjective input judgements.

Table 2: Pairwise comparison of factors

	Pressure	*Temperature*	*Humidity*	*Electro-magnetic Radiation*	*Liquid Conta*
Pressure	N/A	Equally As	Moderately Less	Equally As	Mode
Temperature	Equally As	N/A	Marginally More	Equally As	Marg
Humidity	Moderately More	Marginally Less	N/A	Equally As	Equall
Electro-magnetic Radiation	Equally As	Equally As	Equally As	N/A	Equally
Liquid Contamination	Moderately More	Marginally More	Equally As	Equally As	N/A
Solid Contamination	Severely More	Marginally More	Equally As	Severely More	Margin

Table 2 shows an example of a pairwise comparison between six environmental factors (far right of the table cropped out). The factors pressure, temperature, humidity, electromagnetic radiation, liquid contamination, and solid contamination, are being compared against one another to determine the relative sensitivity of the system to each factor. Each coloured cell represents one user input comparison of factors. The question to be answered by the user is "to what magnitude is the reliability of the system sensitive to the impact of environmental factor *y* relative to factor *x*?" From the bottom row of the example, solid contamination is being rated as having "severely more" impact on the system of interest than pressure and electro-magnetic radiation and "marginally more" impact than temperature and liquid contamination, as a result solid contamination will be weighted more heavily than the other factors (i.e. the system is more sensitive to solid contamination than the other five factors considered). In practice only the coloured cells of the table need to be filled out by the user as the cells above the diagonal can be inferred given the other entries. For example pressure is automatically assigned as "severely less" impactful than solid contamination as it has already been established that the inverse (solid contamination being "severely more" impactful than pressure) is true.

Factors consistently rated as more impactful than their counterparts are weighted more heavily relative to the other factors.

Following the AHP process:

- The user will fill out a pairwise comparison matrix where each cell answers the question; "to what magnitude is the reliability of the system sensitive to the impact of 'x' environmental factor relative to 'y' environmental factor?"

- The ratings are made on a qualitative scale from "severely less impactful" to "severely more impactful". This scale corresponds to a quantitative scale that can practically be decided by the user as long as it is consistently applied. For this paper, and within MADe, this scale will range from 0.25 to 4.0.

- The eigenvector of the comparison matrix is calculated.

- The numbers constituting the eigenvector are normalized against the mean value and these values represent the relative sensitivity of the system to each Environmental Factor.

5.7. Comparing Operating Environments

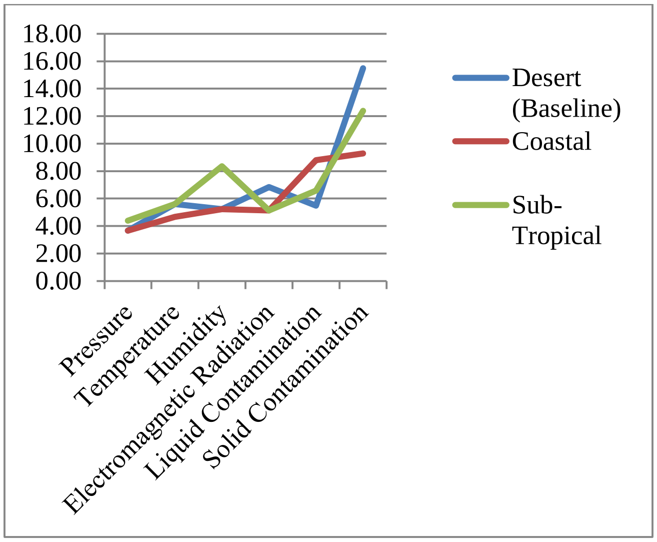

Figure 3: Characteristic charts of three operating environments displaying relative strengths of environmental factors

Environment is a set of factors that may have impacts upon failure properties. Each factor, for each operating environment is rated according to the potential strength of that impact. Each system will have a defined sensitivity to environmental factors. The combination of the two defines the severity of the environment on the system.

Once individual factors belonging to a defined operating environment have been rated by magnitude of severity and applied to the system of interest by scaling in accordance to the sensitivity weightings, a characteristic profile of the operating environment can be generated. This may be in the form of an area or spider chart (figure 3), with each factor either plotted along the x-axis or as an axis themselves (in the case of a spider chart).

Expressing each prospective operating environment of the system as an area chart allows comparisons to be made (with the sensitivity of the system providing context).

Table 3: Comparison of overall operating environments impacts

Operating Environment	*AHP Figure of Merit*	*Characteristic Area*	*Loading Factor (Area Ratio Normalized over Baseline)*
Desert – Baseline Operating Environment	67	109	1.00
Coastal	61	93	0.86
Sub-tropical	66	112	1.03

Table 3 displays an example of the analytical outputs of the entire process. The AHP figure of merit is the sum of all the pertinent factors within each operating environment; this is the primary output of any AHP analysis. The area of an operating environment's characteristic profile is dependent upon its constituent factors and as such is a quantitative expression of the environment's impact upon the system. Comparing each profile, the user can analytically rank operating environments severities. For the sake of simplification and application to the model each operating environment's area is normalized against the selected baseline operating environment and expressed as an Environmental Loading Factor (ELF). These values are indicative of an operating environments relative measure of impact upon a system's reliability compared to a baseline operating environment.

In the table 3 example, the results indicate that the coastal operating environment is less impactful upon the system than the initially assumed baseline desert operating environment. The sub-tropical operating environment outputs relatively similar results to the baseline indicating an overall similar level of impact incurred on the system. By enquiring further into the analysis at the factor level (seen in figure 3) it can be seen why the similarity in overall result. The system is most sensitive to solid commination hence these values being scaled higher (contributing more significantly to analysis). Solid contamination is strongest within the desert environment. More minor factors pressure, humidity, and liquid contamination are all stronger within the sub-tropical operating environment which collectively outweigh the solid contamination of the desert environment resulting in a similar measure of impact overall between the two operating environments, desert and sub-tropical.

6. ANALYTICAL APPLICATIONS OF EXTERNAL OPERATING ENVIRONMENT

The following process flow (figure 4) broadly describes the application of operating environments to a system model. In step 1 a system's operating environments are defined as is described in more detail in figure 1. The analyst then selects a baseline operating environment representing the initial assumed operating environment of the system. With this baseline as the environmental context, the failure concepts and criticality parameters are input into the model.

Applying a second operating environment to the model in order to represent a change in the system's assumed operating conditions allows the analyst to compare the two environments on a like-by-like basis and update the model parameters based on this comparison.

6.1. Physical Failure Modelling

A system level operating environment is defined with environmental factors being rated in magnitude of strength on a scale from very low to very high. As previously discussed, these ratings are made with consideration only afforded to the operating environment itself, independent of its immediate impact on any specific systems. As this is the external/ambient environment under consideration it should be recognized that items (subsystems/components/parts) within the system may be sheltered from certain external influences. This is dependent upon the level of physical protection afforded to the item from each environmental factor, as well as the susceptibility of that item to influence by that factor. To codify the impact of each environmental factor beyond the system into the items making up that system a process of review and exclusion is undertaken.

Each item below the system level (i.e. subsystem) will effectively inherit its operating environment from the system (i.e. an item is assigned the operating environment of its parent item). To account for the described sheltering, the modeler would have the option of excluding any environmental factors that are not observed at the lower level. In the same way that items may continue to be indentured further and further down so too can the user keep excluding factors until the lowest level of decomposition. Iteratively excluding factors down levels of indenture, down to the singular item level, results in an environmental profile being constructed for the product. It has now been specified which environmental factors are impacting on which items.

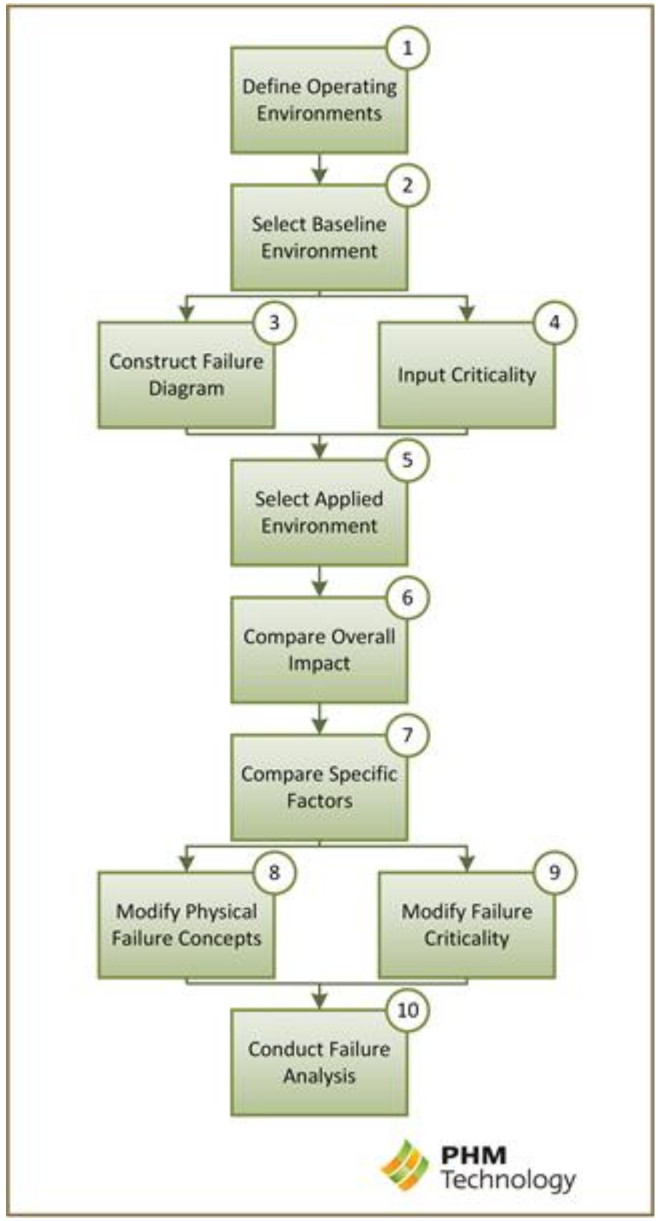

Figure 4: Applying operating environments to a system model

Failure causes can be associated with presence and strength of specific environmental factors. Applying this linkage to failure analysis and leveraging a system's environmental profile a system and its constituent items physical failure model can have failure causes filtered for ease of entry for the analyst. Depending on the operating environment created and applied to the model, sets of failure causes can be presented to the user as having high probability to be present. Once added to the physical failure model, these failure causes will be included within all resultant failure analyses produced from the mode such as FMEA, FMECA, and Fault Tree Analysis.

6.2. Modifying Criticality Due to Changes in Operating Environment

From the prior section a causal connection between environmental factor and failure concept has been made. If a specific environmental factor is present and severe in magnitude then one or more identified failure causes are more likely to occur (relative to an operating environment in which that environmental factor is not present, or not as severe).

With causality established, this relationship can be leveraged to automate changes and updates of model parameters (and hence analyses) based on changes to the assumed operating environment.

If the above outlined procedure has been completed, then within the MADe project there is a system model with a mission profile and a baseline operating environment associated with it. The baseline operating environment will have been detailed to the lowest level of indenture (e.g. part detail). If now another operating environment is applied, the difference between the two (in terms of environmental factor impact) can be expressed. These differences can be used to update related criticality model parameters.

Common FMECA styles RPN and 1629A analyses both use model parameters that may have causational links to environmental factors.

For a RPN FMECA, within the model, failure paths with failure causes associated with environmental factors that have changed significantly in measure of impact can have their occurrence criticality measure scaled depending upon the change observed in the associated environmental factor. In the case of a 1629A FMECA a failure mode's ratio may be moderated up or down depending on failure causes leading to the failure mode.

Figure 5 shows a simple failure diagram that describes a failure path leading to a component failing to provide force. Failure causes, high temperature and high mechanical load, when present together act through the mechanism of creep stress rupture resulting in the physical fault of a fracture. If the component's applied operating environment signaled an increase in temperature compared to the baseline environment this failure path within a model would have its occurrence scaled upwards to more accurately represent the new operating conditions experienced by the system.

7. CONCLUSIONS

A rigorous design process requires the consideration of the conditions in which a system may be operated within. Published processes and methodology for identifying and describing these conditions, in particular the system's operating environment, and reflecting this in failure and reliability analysis are not consistent in approach and are not applicable across the breadth of a design process.

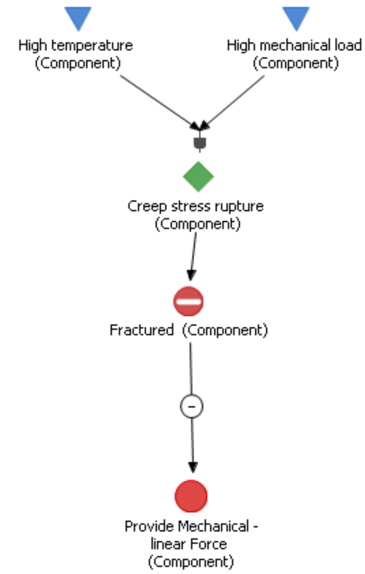

Figure 5: Example failure diagram

The use of an environmental factors taxonomy means operating environments can be described in consistent terms that make comparisons between operating environments practical. Defining an operating environment is completed by rating the environments constituent factors in terms of their magnitude within that environment. Applying an AHP style methodology to further define a system of interest's sensitivity to those same environmental factors allows a measure of an operating environments impact on the system's failure characteristics. Comparing multiple operating environments using this process may allow a user to rank operating environments by overall severity and account for impacting environmental factors throughout a design process.

Using a developed library of saved operating environments (within model-based engineering tool MADe) presents the opportunity for the automated updating of system model parameters in context of the assumed environments the system will experience over its lifetime of operation. Rapid generation of analyses via the software model allow impacts of environmental change to be reported to the design team for evaluation and consideration in their process.

Specific applications of this process are failure analysis, criticality analysis, and lifetime maintenance costings. Recognising causational links between the presence of certain environmental factors and the occurrence of related failure paths allows the moderation of criticality values (to be expressed with a FMECA) as well as the construction of a failure model for the system (outputting into FMEA and fault tree analysis).

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