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A generic approach for deriving reliability and maintenance requirements through consideration of in-context customer objectives

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ABSTRACT

Not all implementations of reliability are equally effective at providing customer and user benefit. Random system failure with no prior warning or failure accommodation will have an immediate, usually adverse impact on operation. Nevertheless, this approach to reliability, implicit in measurements such as ‘failure rate’ and ‘MTBF’, is widely assumed without consideration of potential benefits of pro-active maintenance. Similarly, it is easy to assume that improved maintainability is always a good thing. However, maintainability is only one option available to reduce cost of ownership and reduce the impact of failure. This paper discusses a process for deriving optimised reliability and maintenance requirements through consideration of in-context customer objectives rather than a product in isolation.

KEYWORDS:

Reliability and maintenance requirements ; customer requirements; technical metrics; customer objectives; failure avoidance; failure anticipation; failure accommodation; delaying maintenance.

Acronyms

ASPIRE: AeroSpace Project for the Insertion of Reliability—a collaborative project sponsored by the UK Department of Trade and Industry.

FFOP : Failure Free Operating Period

FEA: Finite Element Analysis

FMECA: Failure Modes, Effects and Criticality Analysis

MFOP: Maintenance Free Operating Period

MTBF ; Mean Time Between Failures

MTTR; Mean time to repair

QFD: Quality Function Deployment

URAM: Universal Reliability and Availability Model—a discrete event simulation

1. BENEFITS OF RELIABILITY & MAINTENANCE

Reliability is defined as "the probability that an item can perform a required function under given conditions for a given time interval" [1]. The definition contains 4 aspects, namely probability, function, time interval and conditions. Conditions include environment, user demand profile, user skill, maintenance and logistic support. It is a full definition of the scenario in which the system is required to exist and operate. Therefore, any numerical measure of reliability is scenario dependent. However, increased likelihood of product performance does not necessarily improve achievement of scenario objectives. Rather, it depends on the degree of linkage between it and those objectives, particularly where there are competing factors. For example, during design, increased reliability may compete against maximum performance or, in-service, increased maintenance may improve reliability but also increase cost. Generally, neither product reliability nor maintenance is an attribute required in its own right. Rather, they are desired because of the wider benefits they offer. This applies to all attributes related to reliability and maintenance (e.g. Durability & Dependability [1])). It could be argued, therefore, that reliability and maintenance should never be direct, specific customer requirements.

There are many benefits that can result from reliability and supporting maintenance. They could be summarised as improving such things as safety, operational effectiveness whole-life costs and customer satisfaction. However, not all benefits have equal priority or criticality and not all benefits are mutually supportive, for example, improved safety does not necessarily lead to improved operational effectiveness or reduced in-service cost. Change to reliability or maintenance characteristics may improve operational effectiveness in one scenario, but degrade it in another. It is only in the context of a full scenario that reliability and maintenance can be assessed, resolving conflicts and enhancing synergies.

2. The ASPIRE business model

Figure 1 shows the ASPIRE Business Model for Reliability as has been developed by Warwick University and agreed by the ASPIRE project partners. It identifies objectives, metrics, rules and constraints.

<<<FIGURE 1>>>

The model separates the technical and business aspects of a project into 3 viewpoints:

- *Technical design viewpoint*, which includes all the features and systems of a product – hardware, software, manufacturing, at all levels of the supply chain, and all measurements of its technical capability.
- *Customer/User viewpoint*, which includes operations, maintenance and all other business activities of the parties making use of the product after delivery, being focused on achieving whatever goals or objectives are appropriate.
- *Design/Manufacturing viewpoint*, which involves all companies involved with providing the *Design*, throughout all levels of the supply chain, being focused on achieving whatever goals or objectives are appropriate.

Each of these viewpoints measure reliability performance differently and have what are often conflicting objectives.

2.1 The Technical Viewpoint

“Design” indicates those physical features that are directly discernible and visible from the design process. They include material, layout, dimensions and components. “External Constraints to Design” will include technology and manufacturing limitations, as well as interface requirements and international standards. Where the product needs to match existing systems, these too would impose “External Constraints to Design” “Design” is the physical nature of the product. However, product performance attributes require a context. In the case of reliability, they require at least an environment. In addition, they may only be measurable indirectly through an analysis process and may be expressed in several alternate ways. The translation process, taking into account context and any analysis process, is indicated by what can be termed “Mapping”. This “mapping” converts the “Design” elements into the “Technical Metrics” which are the chosen means of performance expression and the associated quantitative values. For reliability, “Technical Metrics” would include, for example, failure rate, MTBF, life, and probability of individual mission success. This way of thinking can equally be applied to maintenance and maintainability where the technical maintainability metrics could be MTTR, maximum repair time and % fault isolation.

Reliability is particularly badly served with analyses to predict reliability during the design process. There is poor correlation between individual analysis tools, resources expended, and reliability achieved for many products.[2] Testing of prototypes is often necessary and may offer somewhat better correlation, provided the testing reflects future operation and environment — in other words, reliability performance of a design cannot be divorced from customer usage. The metrics used to quantify reliability performance have usually used some variation of the international definition of reliability, namely “the ability of an item to perform a given function in a stated environment for a defined period of time." This is a technical description of reliability and as such, when quantified against such a measure, is a Technical Metric.

2.2 The Customer Viewpoint

"Customer Metrics" are not synonymous with "Technical Metrics" the customer's perception of reliability is influenced by factors that he considers important. In other words, not all product failures are equal. Some will cost the Customer considerably more than others, in reputation as well as financially. For example, random failures that would disrupt missions or machine operation will likely be more critical than those preventable by scheduled or prognostic anticipation. Small differences in reliability, in "Technical Metric" value or character, can be the catalyst for major changes in the customer's operating scenario and achievement of "Customer Metrics". Thus, a technical definition of reliability is inadequate to measure value, which can be considered as the totality of a product's contribution to the customer and his objectives, relative to the cost of that contribution "Customer Metrics", on the other hand, are tailored to directly assess that value. For example customer metrics could be such things as operating delays, operating efficiency, deployment efficiency, and maintenance resource requirements. Customer Metrics will also include financial measures such as profit and cash flow. What is of value to the customer is influenced by the "Customer Objectives" and the "Mapping" from "Technical Metrics" to "Customer Metrics" therefore requires a detailed operating and logistic scenario and alternate scenarios will result in differing "Customer Metric" values from identical "Technical Metrics". This mapping may be as simple as an arithmetic calculation but where there is strong scenario dependency, more complex analysis will be required, for example using a discrete event simulation. "Customer Objectives" are an important feature in any business model. They identify the customer motivation for purchasing the product in question. There will usually be several objectives, with associated priorities or ranking. The objectives will usually include words such as maximise and minimise. They should not include specific values or words such as optimise. This is because optimise is part of a process to identify the "Design" that provides the balance of maximise and minimise of several objectives that, according to priorities or ranking, gives the best overall result. They may also be qualitative, such as being better than the competition. However, in such cases, specific features would need to be identified to be used as metrics. Example Customer Objectives might be "Maximise number of race-car wins during a season", "Maximise effective maritime aircraft patrol coverage", "Maximise return on investment", "Minimise financial risk"

"Customer Business Rules" are a set of operational and financial guidelines that the customer follows. They include such things as; "maximum development timescale, beyond which the business opportunity would be lost", "maximum purchase cost as limited by cash-flow or credit", "current organisation within which the new product must fit: skills, existing resources, etc." and risk exposure limits. These business rules affect potential opportunities as well as the mapping process. One of the goals of the ASPIRE Business Model is to promote opportunities for synergy between "Customer Objectives" and "Design". Therefore, existing Business Rules should not be taken necessarily to be unalterable. Rather, the role of the ASPIRE Business Model is firstly, to identify factors influencing the achievement of objectives and, secondly, to challenge them, to create new opportunities.

2.3 Design/manufacturing company viewpoint

Business Metrics are performance measures important to the design/manufacturing company. Cash-flow, profit and liquidity are lifeblood to a company. These must be predicted and controlled, by forecasting and budgeting. The "Design" process will consume resources, both current and future. In return, committed and potential sales will provide income, as would leasing but with different cash-flow. The business relationship between the design/manufacturing company and the customer/user will significantly influence the Mapping link between Technical Metrics and Business Metrics. Sales with in-service support costed separately would, in the short term, result in improved reliability reducing in-service support and hence potentially profit. Any sale or lease which included in-service support at the manufacturer's expense, the opposite would be true. It may be argued that sale of any product with poor reliability, offering a worse package than that offered by competitors would not provide long-term profit. Sales and reputation would be lost. However, in monopoly situations, customers do not have choice except not to purchase at all. Contract incentives and penalties have been used frequently as a means to control reliability achievement. However, these provide motivation to improve product reliability only whilst the incentive/penalty is greater than the cost of further development. The greater the cost of development, the less would be any improvement, notwithstanding the effectiveness of any change on "Customer Objectives." "Business Rules" are particularly important within the ASPIRE Business Model. They will significantly alter the synergy between maximisation of "Customer Objectives" and "Business Objectives." In addition to financial objectives such as maximising profit, "Business Objectives" should include strategic development and benchmarks such as being best-in-sector. The business objectives will identify those factors that look beyond short-term profit. If short-term profit is indeed an objective, the business objective should give the reason why. Any company that seeks short-term profit at the expense of maximisation of "Customer Objectives" is not likely to seek improved reliability. Therefore, such companies are also unlikely to use the ASPIRE Business Model.

External Constraints to business rules include government policy, legislation, competition rules, etc. They are limitations on the potential Business Rules.

3. SCENARIO OBJECTIVES

According to the ASPIRE business model safety, operational effectiveness and whole-life costs and customer satisfaction would be instances of "objectives". Particular customer or business scenarios will give priority between individual objectives. However, the manner in which the objectives are measured will either link optimisation more closely to the technical design or more closely to the customer/business scenario. The ASPIRE business model also notes that the designing company also has objectives (Business Objectives). These may be minimisation of warranty costs, maximisation of profit, customer retention, etc. There may be synergy between manufacturer (business) and customer (user) objectives, depending on the commercial relationship and liabilities. Vintr in [3] considers the influence of reliability and maintenance on the optimisation of warranty costs.

A technical design and its attributes indicate a particular solution intended to contribute to objectives achievement. The design attributes may be measured with greater or lesser focus on the product, and with greater or lesser focus on its contribution to objectives. These measures would use technical (design) metrics or customer/business (in-context) metrics accordingly. For example, a technical metric would be, say, system on-board diagnostic detection and isolation capability given particular assumptions of failure likelihood, while a customer metric would be, say, technical dispatch rate within a specific scenario of operation and maintenance support, or cost per hour of operation, again for a specific scenario. An operational effectiveness "objective" might be a strategic military objective such as delivering a mobile army group to a deployed theatre, ready to operate in minimum time. A cargo aircraft with its reliability & maintenance attributes is only part of that scenario. Such deployed theatres may easily be without maintenance facilities and, therefore, avoidance of down-route maintenance might be considered to have much greater impact on the overall objective than the average amount or cost of maintenance. Equipment that is to be operated away from any base support is worthless if it were to fail. Also, an ability to forecast and prevent failure before deployment might have significant impact. Equipment with a constant failure rate gives no stochastic prediction of when failure will occur and, therefore, reliability improvement focused on 'MTBF' would not improve opportunity to prevent failure before deployment. In a civilian context, the objective of a racing car team is to win races. It might easily be argued that car reliability takes second place to absolute performance. Consider 2 alternatives, namely a car with a 50% likelihood of winning if it finishes and a more reliable car that has a lower performance that would never win races, even if it finishes. The optimal solution would be the one with the overall higher number of probable wins. Thus, reliability requirements cannot be defined for a racing car in terms of minimum failure rates, except when balanced against the performance achieved. Objectives may also be more subtle, such as presenting an "as new" condition after several years of product usage, as part of a "customer satisfaction" objective. When applied to a car steering wheel, this would require wear, staining & discolouration to be unnoticeable after, say, 7 years. However, this is not the same as to say that wear should be minimised. Depth of texture and allowable wear would be related and thus would be subject to later analysis. They are not individually definable requirements at the early stages of analysis.

Reliability and maintenance, when considered at the business or strategic level often require lateral thinking, to go beyond usual technical descriptions in order to most clearly identify objectives. Specific reliability and maintenance requirements should never divert attention from those objectives. They should remain dynamic and be considered continually throughout design.

4. CUSTOMER MEASURES OF RELIABILITY AND MAINTENANCE

The definition of reliability is often assumed to relate only to a product function. This is not the case. A product is often part of a wider system and operated in a scenario context. Reliability may be viewed as a product parameter or as an in-context measure applicable to the scenario.

Technical measures of reliability, noted earlier to include failure rate and MTBF, also include system failure probability, equipment life, as well as various statistical models, availability when defined as $\frac{MTBF}{MTBF + MTTR}$ (or a related variation) and any measures of ability to detect, isolate, recover, prevent or correct failures. These may be integrated into concepts of avoiding failure, anticipating failure and accommodating faults. (Figure 2) Nevertheless, they remain technical measures because they are not measuring the direct benefit to a customer scenario.

<<<FIGURE 2>>>

Customer metrics are in-context measures that are closely correlated with achievement of customer objectives. They provide clear and visible links to objectives such as profit, consistency of service, strategic capability, whole-life costs, safety and sector placement for attributes such as end-customer satisfaction or quality of service. They allow identification and optimisation of solution. They often do not mention reliability or maintenance directly, but nevertheless are significantly affected by reliability and maintenance. Customer metrics allow comparison of alternate solutions because they are not product focused. They restrict alternatives only as demonstrably limited by the business or operational scenario. An example where a solution would be incorrectly restricted is a requirement that states that a system should have at least a specific minimum life. This assumes that a long life is automatically of merit. Rather, it could be argued that the requirement should be, say, of minimum whole-life cost over a particular operational life-time. If a lower whole-life cost could be achieved by cheaper, disposable items, saving on maintenance infrastructure but at the expense of individual product life, then this could be a better solution. Indeed, maintenance-free, disposable items may also utilise alternate manufacturing processes that themselves may improve reliability and also reduce initial costs. The merits of such an approach are of course product and scenario specific, but that is the point. A customer requirement should focus on achievement of the underlying objectives, and allow unrestricted design options to best meet those objectives. A product MTBF is much less likely to be a valid customer requirement.

5. REQUIREMENTS PROCESS MODEL

The importance of focusing reliability & maintenance requirements on customer objectives requires a greater consideration of alternatives than requirements based on product technical metrics. A structured process is required and a basic high level process is suggested here and shown in figure 3

<<<FIGURE 3>>>

5.1 Identify Customer Objectives

Customer objectives will often be unstated yet remain implicit. Customers may even explicitly state that "reliability and maintenance shall have equal priority with performance, cost and development timescale", yet such statements remain somewhat doubtful. Indeed, as has been argued above, it should not necessarily be the case that reliability or ease of maintenance have any direct priority, but rather that their benefits be identified and maximised. Alternate solutions may require radically different reliability and maintenance properties in order to achieve the same benefits. Customers may be unaware of the need to focus on benefits rather than individual reliability and maintenance. Telecommunication companies have requirements for the breaking strength of their overhead wires. These originated from the need to survive adverse weather and ice-accretion, and to break without secondary damage if fouled by, say, a truck. However, the manner in which the requirements are stated may preclude consideration of alternate strategies for cable design and erection.

5.2 Identify all potential solutions & scenario

QFD is a structured process to translate requirements into solutions optimised against customer satisfaction and business advantage[5]. In the case of reliability and maintenance, it is a powerful tool to consider their effects on a wide range of business, operational and customer objectives. QFD helps identify and lists the potential impact of reliability and maintenance on business and customer objectives. It is an important tool leading to a final optimised solution however, it requires considerable skill and knowledge in ranking factors. Indeed, ranking of factors may not initially be possible with any degree of certainty and may itself be a product of the subsequent analysis process. The QFD process commences with identification and structuring of customer requirements into what is often called "the voice of the customer", often using brainstorming techniques.

Against each "voice", for which there will be an importance (priority), several alternative solutions can be compared, each of which will have a technical difficulty and synergy with competing voices. These alternatives may require refinement to lower-level detail before a single "best" technical solution can be identified. More likely, other analysis tools such as FMECA [7] will be required to conduct the comparative analysis in support of QFD. However, it is unreasonable to assume that an optimum solution can always be derived by QFD as a single discrete activity. Consideration and comparison of alternatives will often require an extended process of refinement.

5.2.1 Explore synergy

QFD requires all potential solutions to be assessed in detail for potential synergy where improvement in one feature would tend to improve achievement of another. This is particularly important when the goal would be to maximise or minimise parameters in order to maximise benefit. Introduction of maintenance free designs is often an example of this. Maintenance free products will not require access features, thus reducing parts and simplifying design. Access features are often points of contaminant ingress and seats of corrosion. If products do not require maintenance access, the manner of assembly might be altered, leading to cheapness and greater reliability. Elimination of in-service maintenance also affects support services, often reducing or eliminating them. Thus there is synergy between several aspects and, providing there is overall improvements in benefits to the customer, then maintenance free would provide a good opportunity.

5.2.2 Supporting analysis

Consideration of options and their benefits is not easy or necessarily mathematically certain. Indeed, traditional quantitative reliability analysis does not always apply to more complex situations and analytic models relating complex reliability and maintenance to combined business, operational and cost benefits cannot easily be derived. Analytic mathematical models are usually limited to particular sub-sets of reliability and maintenance measurements within constrained scenarios. For reliability and maintenance related requirements, discrete event simulation is often the only route to fully explore benefits and their sensitivities, to explore options and to identify detailed requirements that most effectively meet a customer business objective. In turn, discrete event simulation itself may require inputs from analysis such as Finite Element Analysis, historical data analysis, FMECA and other tools necessary to identify and predict appropriate technical characteristics.

5.2.3 Understand R&M Effect

Reliability and maintenance are expressed in many different ways, such as MTBF, life, MTTR, etc. However, when considering how reliability and maintenance best contributes to customer objectives, it is useful to aggregate their effect as being avoiding and anticipating failure, and of delaying maintenance by accommodating failure. Each failure will incur cost, but this cost will be modified by when the repair is undertaken and the degree of forward planning possible. This model (Figure 1) is a useful link between technical expressions of reliability and customer objectives. It highlights how strongly any particular feature will enable the objective in the scenario context. Prognostics, scheduled replacement, diagnostic capability, failure models, physics of failure usage models, durability and many other attributes link well into this concept of assessing ability to avoid failure, anticipate failure or delay maintenance.

5.3 *Refine & Eliminate Solutions*

A key factor in optimisation is retaining flexibility until such point in the design process that a clear decision is feasible. An early decision may inadvertently restrict options. Indeed, early decisions quite frequently affect reliability, perhaps unknowingly simply because knowledge is lacking of the potential effect. Rather, design decisions should not be finalised until all the evidence is known. [8] However, refinement will be possible within the level of knowledge available. This is the principle of set-based design. QFD and set based design link well together. QFD highlights links between detailed design features with objectives. Gaps or uncertainty in knowledge can be documented and managed using the QFD hierarchy.

5.4 *Identify Opportunities for Improvement*

FMECA, referral to past experience, in-service data analysis of existing product, testing, design reviews and many other techniques allow identification of opportunity to improve reliability and maintenance. However, an opportunity should be implemented only where it provides an improvement to achievement of objectives. Reliability and maintenance improvements should be assessed initially in terms of reduced likelihood of failure, improved ability to anticipate and prevent failure, and in terms of advantages of delaying application of maintenance. Given the scenarios under consideration, these will be of greater or lesser advantage. The full advantage might not be able to be assessable without application of scenario simulation, using discrete event simulation. Discrete event simulation is a powerful technique able to identify sensitivity to change of reliability or maintenance properties and, in conjunction with priorities established using QFD, will be able to identify the merits of potential improvements and of the areas worthy of particular attention in order to achieve the most effect on objectives.

6. CONFIRMATION OF ACHIEVEMENT

Confidence limits are often applied to reliability and maintenance requirements. This is erroneous since a requirement is either quantitative, a balance between features, a maximum or a minimum, it should not be stated with confidence limits of any kind. Nevertheless, confidence limits are closely related to the achievement of reliability and maintenance requirements, they are necessary when confirmation of achievement is necessary through demonstration and testing since measurement of any stochastic property will inevitably produce varied results and confidence limits are simply a way of expressing the likely spread of these results. Demonstration and testing are expensive activities, therefore, they should be limited. The narrower the bounds within which the true stochastic parameter needs to lie, and the greater the confidence that must be achieved that the parameter does indeed lie inside the bounds, the greater the testing required. Consequently, the demand placed on the test should be according to assessed risk of non-achievement and the sensitivity of the relevant customer benefits to that parameter. The greater the level of aggregation being measured, the less will be test duration for a given ratio of upper to lower confidence bounds, because it will be being measured based on a greater number of events per unit of operation. Thus, it would appear sensible to measure benefit achievement directly rather than more detailed, solution-specific technical feature. Measuring benefit achievement closes the loop on the origin of reliability and maintenance requirements, namely customer benefits. However, direct testing and demonstration remain expensive activities and where risk or sensitivity is lacking, might usefully be avoided. Confidence limits are not in themselves part of a requirement.

7. SUMMARY

Technical reliability and maintenance metrics are not customer requirements, rather customer requirements should be expressed in terms of the benefits reliability and maintenance can deliver to the customers and as such are generally maximisation or minimisation of scenario objectives such as safety, operational success and whole-life costs. It is often the job of the reliability engineer to derive from these customer objectives the technical metrics that can be used to design the technical solution to the customer's problem. To do this a generic approach is best and this paper has suggested a structured, high level approach that can be used to make sure that the final technical metrics are derived properly, with no gaps or omssisons and that all necessary information is used to provide an optimised solution.

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Figure 1: The ASPIRE Business Model – (Aspire model.tif)

Figure 2: The three As of Reliability engineering – Avoidance, Accommodation and Anticipation of failure. (3As.tif)

Figure 3: The structured requirements process model. (generic process.tif)

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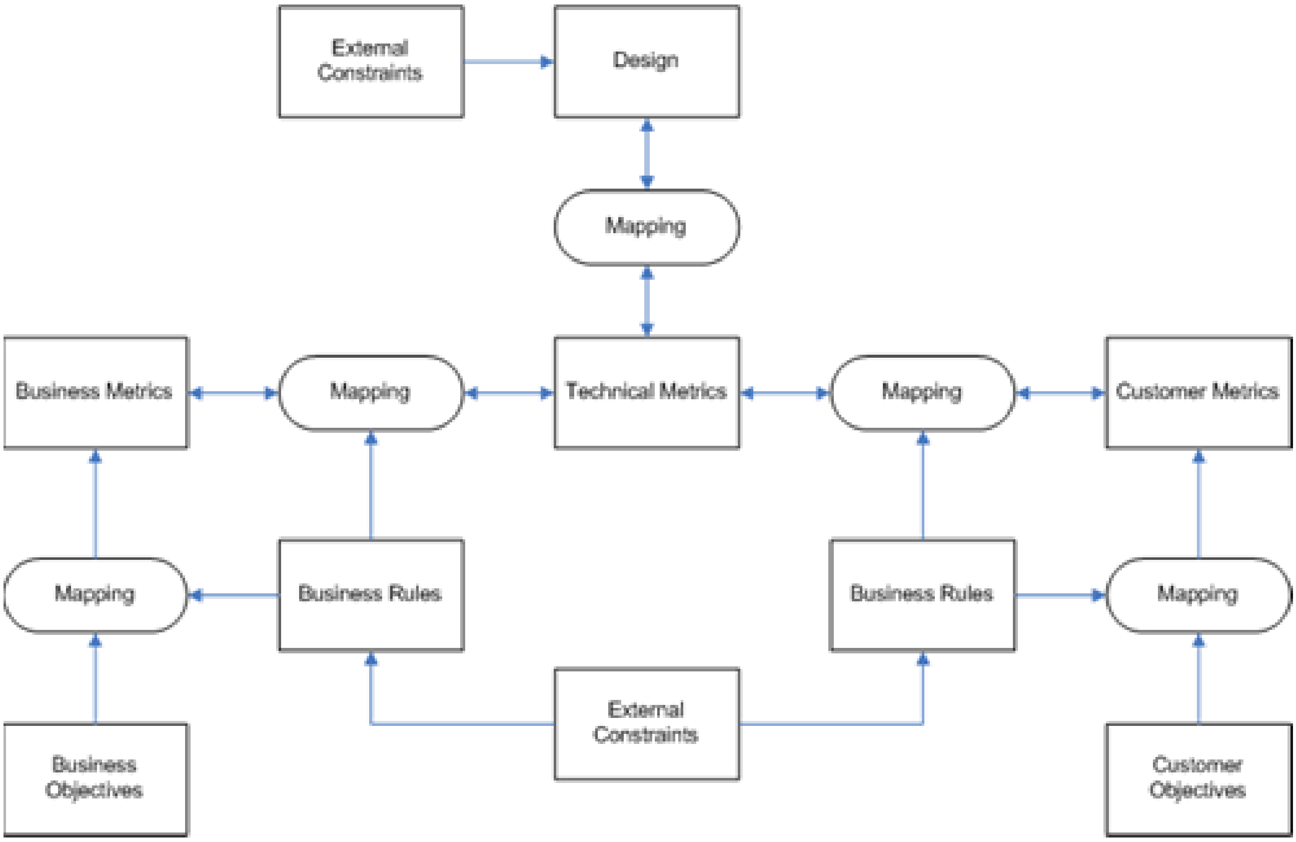

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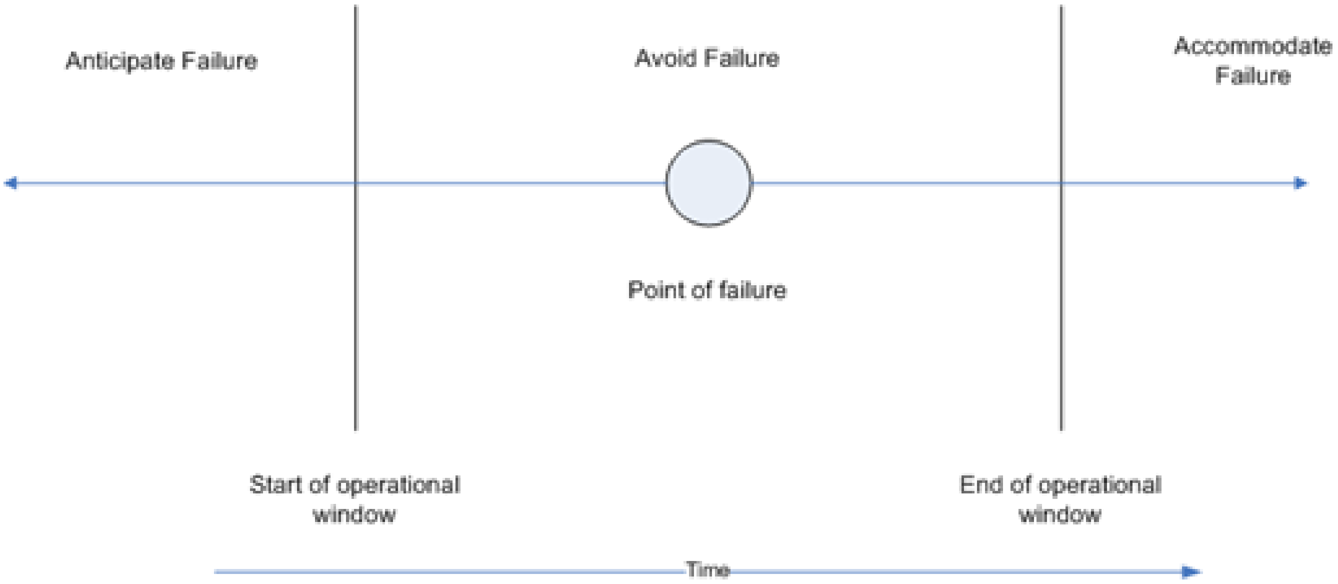

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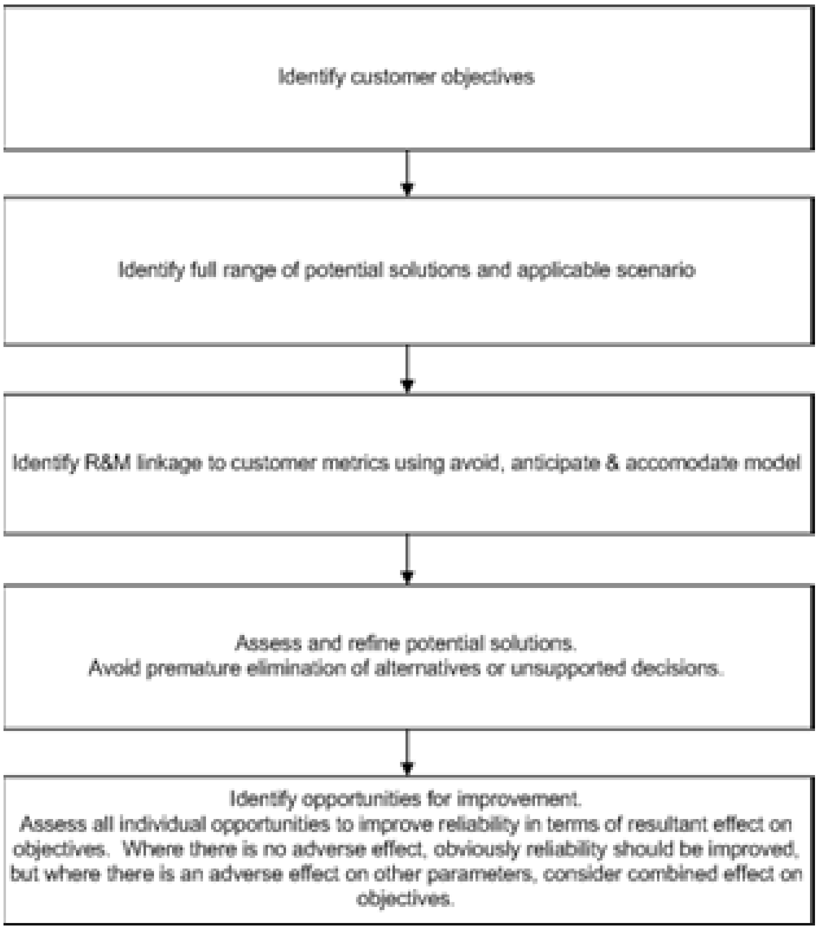

Identify customer objectives

Identify full range of potential solutions and applicable scenario

Identify R&M linkage to customer metrics using avoid, anticipate & accomodate model

Assess and refine potential solutions.
Avoid premature elimination of alternatives or unsupported decisions.

Identify opportunities for improvement.
Assess all individual opportunities to improve reliability in terms of resultant effect on objectives. Where there is no adverse effect, obviously reliability should be improved, but where there is an adverse effect on other parameters, consider combined effect on objectives.