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System Reliability Allocation based on FMEA Criticality

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ABSTRACT

A new system reliability allocation methodology was applied on a steering product. The methodology makes use of design failure modes and effects analysis (DFMEA) and allows the allocation percentages to reflect differences in the criticality levels of the subsystems or components. The methodology was applied in conjunction with system reliability target setting. The paper first explores existing reliability allocation methods. It then introduces the new methodology. Finally, a real-life case is presented to show how the methodology was adopted and how and why it was modified. The approach presented here is one more way to make full use of the analytical efforts that have gone into the DFMEA.

INTRODUCTION

Reliability apportionment takes the system-level reliability requirements and allocates them into key subsystems (O'Connor, 1991). It allows a bottom-up way of addressing reliability requirements so as to support the overall system-level objectives. In case some of the subsystems are developed by sub-suppliers, reliability apportionment provides a clear goal for each sub-developer to meet. In this day and age when system designs are becoming more complex, along with the processes that involve global supply chains, it becomes ever more important to keep the integrity of product development strategy. In this light, reliability apportionment tasks are expected to contribute to maintaining the consistency of reliability requirements.

RELIABILITY APPORTIONMENT

Several methods have been proposed for reliability apportionment and allocation. Srinath (1991), as well as Kapur and Lamberson (1977), present the equal apportionment reliability allocation method, which is probably the simplest. The ARINC (Aeronautical Radio Inc.) method allocates reliability for independent components configured in series based on the constant failure rate assumption (Kececioglu, 1991).

Cost as a criterion has also been used to allocate reliability requirements. Elegebede et al. (2003) and Blanks (1992) propose a reliability allocation and optimization method subject to cost minimization. Mettas (2000) extends this approach and allocates the reliability by formulating the cost function and using it in a nonlinear algorithm. Several reliability allocation problems have been formulated and studied extensively in the past using various optimization models (Tillman *et al*., 1968; Nakagawa and Nakashima, 1977; Blanks, 1992; Coit and Smith, 1996; Elegebede *et al*., 2003; Mettas, 2000). Kuo and Prasad (2000) provide an overview of the methods that have been developed since 1977 for solving various reliability optimization problems. Leung (1997) formulates an optimization model for software reliability allocation under uncertain operating profiles. These methods deal with redundancy allocation, cost minimization, and enhancement of component reliability by developing appropriate optimization models.

Few researchers have tried to combine different criteria for reliability allocation (Falcon *et al*., 2002; Wang *et al*., 2001). For example, Falcon *et al*. (2002) propose a new reliability allocation method known as integrated factors method (IFM). The IFM method uses a large number of factors such as the criticality index, complexity index, functionality index, and effectiveness index in order to facilitate its applicability to a wide variety of systems. Wang et al. (2001) consider seven factors for reliability allocation, which are both quantitative and qualitative in nature. Lyu *et al*. (2002) examine the interaction between system components and inter-component failure dependencies in reliability allocation problems.

Although these methods have been very effective in allocating reliability, they rarely use the knowledge and information generated through design failure modes and effects analysis (DFMEA) during the product development process (PDP). It is the authors’ opinion that a reliability allocation method that effectively communicates with other tools and techniques used in PDP is urgently needed. Such a methodology should enable sharing and exchanging of the critical knowledge and information developed during PDP. The proposed approach is an attempt in that direction.

PROPOSED METHODOLOGY

Sonnemans and Geudens (1999) address the issue of reliability management from a operations management standpoint, specifically in the context of product development. They argue that proper reliability management is an important factor for the PDP success. Two basic elements lie in their methodology: (1) system definition and (2) definition of quality levels. Key to the first is a top-down breakdown of the system description into the physical domain and the functional domain. This enables understanding of the "what" question, i.e., system functional requirements, which in turn points to the "how" question, i.e., physical solutions. The definition of quality levels, on the other hand, is better implemented bottom-up. This is because confidence about the system-level quality tends to be built up from lower components that have already gone through a verification process. This is very similar thinking to that applied in the three-dimensional system decomposition methodology of Yadav (2007), as well as of Goel and Itabashi-Campbell (2004).

Yadav (2007) states that "a thorough understanding of system composition, functional dependency, and degradation behavior is an essential task to facilitate objective reliability allocation to each component of the system." The methodology developed and applied to a steering product at TRW borrows much of this conceptual thinking from Yadav's methodology (Yadav, 2007). In fact, the approach used is virtually an adoption of Yadav's methodology with one modification. This is explained in detail below.

The proposed methodology is intended for series-configured systems and consists of two major steps: development of criticality indices and calculation of allocation weights.

STEP 1: CRITICALITY INDICES

Criticality indices are calculated based on design FMEA findings. Given,

S_{jk} = FMEA severity rating of the k^{th} line item from the DFMEA of the j^{th} subsystem

and

O_{jk} = FMEA occurrence rating of the k^{th} line item from the DFMEA of the j^{th} subsystem

where N_j = total number of line items for the j^{th} subsystem, so, $k = 1, 2, \ldots, N_j$

The criticality index of the j^{th} subsystem, C_j, then, is

$$C_j = \frac{1}{N_j}\sum_{k=1}^{N_j}\left(S_{jk} \times O_{jk}\right) \quad \ldots\ldots\ldots \text{ Equation [1]}$$

This is a straight adaptation of Yadav's methodology (2007) except for the $1/N$, i.e., averaging the product of severity and occurrence rankings. Averaging is done for two reasons:

1. A DFMEA project for a complex system often comprises of more than one DFMEA. It is not unusual for multiple teams to work on various subsystem DFMEAs. Even though they work to a single standard, some variability – especially in the length of each DFMEA document – is expected. Averaging accounts for such variability.

2. At the time reliability allocation must be done, not all DFMEAs may be complete. Averaging accounts for varying degrees of subsystem DFMEA completion.

Therefore, averaging helps to standardize the rankings and still capture relative differences in criticality.

STEP 2: ALLOCATION WEIGHTS

The criticality indices first need to be converted into base allocation weights. They are computed as follows:

$$\omega_j = \frac{C_j}{\sum_{j=1}^{m} C_j} \quad \ldots\ldots\ldots \text{ Equation [2]}$$

where ω_j = base allocation weight of the j^{th} subsystem, and there is a total of m subsystems in question

In other words,

$$\sum_{j=1}^{m} \omega_j = 1.0$$

Due to the series configuration of our system, the following relationship exists:

$$R_{sys}(t) = \prod_{j=1}^{m} R_j(t) \quad \ldots\ldots\ldots \text{ Equation [3]}$$

where $R_j(t)$ = reliability of the j^{th} subsystem

Equation [3] can be re-written as

$$R_j(t) = \left[R_{sys}(t)\right]^{W_j} \text{ . . . . Equation [4]}$$

where W_j = final allocation weight

At this point, a decision needs to be made. Reliability target allocation is directly tied to reliability demonstration. The higher the target, the greater amount of evidence will be required to demonstrate attainment of that target. The evidence is provided by testing, engineering analyses, or a combination of both. In this light, the following question needs to be asked: "Does the system developer desire to allocate targets in such manner so as to

- Mandate higher target demonstration on subsystems with higher criticality

or

- Reflect the fact that subsystems having higher criticality indices have not yet been proven out in the field (i.e., reflection of high DFMEA occurrence rankings)

If the former is the case, then

$$W_j = \frac{1 - W_j}{\sum_{j=1}^{m}(1 - W_j)} \text{ . . . . Equation [5]}$$

If the decision is the latter, then

$$W_j = \omega_j \text{ . . . . Equation [6]}$$

The next section presents an application example.

APPLICATION EXAMPLE

An example using an automotive steering system is presented here. The information is based on an actual product but is not a reflection or a statement of its reliability performance. Figures used are for demonstration purposes and are fictitious.

An electrically powered steering system was under development. The system was first decomposed into the following five key subsystems:

1. Mechanical subsystem 1
2. Mechanical subsystem 2
3. Steering torque sensor
4. Electronic control unit
5. Motor

Following the steps outlined in the previous section resulted in the figures shown below:

From Equation [1], the criticality indices were

- Mechanical subsystem 1 = 7
- Mechanical subsystem 2 = 25
- Steering torque sensor = 10
- Electronic control unit = 22
- Motor = 18

From Equation [2], the base allocation weights were calculated to be

- Mechanical subsystem 1 = 0.09
- Mechanical subsystem 2 = 0.30
- Steering torque sensor = 0.12
- Electronic control unit = 0.27
- Motor = 0.22

In this case, the decision was to require higher targets for higher criticality. Therefore, Equation [5] was applied. This resulted in

- Mechanical subsystem 1 = 0.23
- Mechanical subsystem 2 = 0.17
- Steering torque sensor = 0.22
- Electronic control unit = 0.18
- Motor = 0.20

Assume that the system-level reliability is set to be 95% at one vehicle life, for demonstration purposes. Using Equation [4] yields the following targets:

- Mechanical subsystem 1 = 98.83%
- Mechanical subsystem 2 = 99.11%
- Steering torque sensor = 98.88%
- Electronic control unit = 99.07%
- Motor = 99.00%

The table below summarizes these outcomes.

	$C_j = \frac{1}{N_j}\sum_{k=1}^{N_j}(S_{jk} \times O_{jk})$	$\omega_j = \frac{C_j}{\sum_{j=1}^{m} C_j}$	$W_j = \frac{1 - W_j}{\sum_{j=1}^{m}(1 - W_j)}$		$R_j(t) = \left[R_{sys}(t)\right]^{W_j}$
Mechanical subsystem 1	7	0.09	0.23		98.83%
Mechanical subsystem 2	25	0.30	0.17		99.11%
Steering torque sensor	10	0.12	0.22		98.88%
Electronic control unit	22	0.27	0.18		99.07%
Motor	18	0.22	0.20		99.00%
Sum:	**82**	**1.0**	**1.0**	Product:	**95.0%**

CONCLUSION

The proposed methodology logically maps the findings of the DFMEA to reliability demonstration strategy. This is one more way to utilize the power of DFMEAs and link them to design validation activities.

In this example, the decision in allocating reliability targets was based strictly on each part's criticality and how the team wishes this criticality to be reflected in the reliability assessment effort. A potential consideration for the future is to include the cost factor into the weighting calculation. This will be to handle cases in which reliability demonstration costs are a major issue.

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