**A bibliographic review of trends in the application of ‘criticality’ towards the management of engineered assets**

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**Abstract** - Increasing budgetary constraints have raised the hiatus for allocation of funding and prioritisation of investments to ensure that long established and new assets are in the condition to provide uninterrupted services towards progressive economic and social activities. Whereas a key challenge remains how to allocate resources to adequately maintain infrastructure and equipment, however, both traditional and conventional practices indicate that decisions to refurbish, replace, renovate, or upgrade infrastructure and/or equipment tend to be based on negativistic perceptions of criticality from the viewpoint of risk. For instance, failure modes, failure effects, and criticality analyses is well established and continues to be applied to resolve reliability and safety requirements for infrastructure and equipment. Based on a bibliographic review, this paper discusses trends in meaning, techniques and usage of the term ‘criticality’ in the management of engineered assets that constitute the built environment. In advocating the value doctrine for asset management, the paper proposes a positivistic application of criticality towards prioritisation of decisions to invest in the maintenance of infrastructure and equipment.

Keywords: Criticality trends; value doctrine; investment prioritisation; infrastructure and equipment maintenance

1. **Introduction**

In the context of this paper, we define criticality in terms of relative importance of an item to a decision maker. Something is critical if it is most important in a situation. It is in this context that the term has become colloquially adopted, especially since the 1940s as part of the design methodology referred to as failure modes, effects and criticality analysis (FMECA) (see MIL–P–1629, 1949). According to Bowles and Peláez (1995), reliability and safety requirements provided the impetus for the application of FMECA in the aerospace sector of the aviation industry. In 1966, NASA published a formal procedure for performing FMECA, and this was applied in several other NASA programs including Viking, Voyager, Magellan, and Galileo (NASA, 1967). The use of FMECA was primarily to ensure the safety and reliability of products in a wide range of industries, especially in the aerospace, automotive, biomedical and nuclear sectors (J. B. Bowles and Peláez, 1995; Sankar and Prabhu, 2001). This further spread to civil aviation and automotive sectors in the same period. Since then, the FMECA has become a common approach in reliability theory and practice (refer to IEC 60812; BS 5760–5; USM Standard, 1980). These standards describe techniques and approaches for criticality analysis as an essential function in the design and development of engineered components, equipment, and systems. Crespo Márquez *et al.* (2015) indicate that in addition to qualitative descriptors, FMECA has been extended to define parameters like risk priority number (RPN) to prioritize maintenance activities.

The term criticality appears extensively in literature on equipment maintenance. It is in this regard that we have focused this paper on the trends in use and application of ‘criticality’ towards the management of engineered assets.

The rest of the paper is organised as follows: Section 2 presents the results of an extensive review of literature published between 1950 to 2016 using ‘criticality’ as the search criterion. Empirical data derived from the literature review is presented in section 3, while section 4 includes some conclusions.

1. **Review of Literature**

The source used for our study was academic journal articles published between 1950 and 2016. The search initially focused on articles indexed in Scopus and Google Scholar but also extended to citation search (both forward and backward) on the primary sources. This indirect search pointed to articles related to “criticality analysis” in terms of definition, technique and usage of criticality. This implies that articles merely describing the criticality analysis process have not been included.

* 1. Trend in the Definition of Criticality

The meaning of criticality has changed over the years. Sometimes even within a single organisation, different individuals may have different interpretations of equipment criticality (Smith, 2015). There are many unanswered questions about what asset criticality means.

EN 13306 (2001), defines criticality as; “numeric index of the severity of failure or fault combined with the probability or frequency of its occurrence”. By this definition, mathematically $C=S×P$, where $S$ is the severity of failure consequences and $P$ is the probability or frequency of occurrence. Also, according to USM Standard (1980), criticality is a relative measure of the consequences of a failure mode and its frequency of occurrence. Going by this definition, criticality is defined in terms of risk of failure. Some authors agree with this view of criticality, (refer to Cooper, 1971; Wilson and Johnson, 1983; Elperin and Dubi, 1985; McKinney and Iverson, 1995; Kim et al., 1996;Bevilacqua and Braglia, 2000; Bishop et al 2003; Bertolini and Bevilacqua, 2006; Hameed and Khan, 2014; and Benjamin, Tan and Razon, 2015).

Other methods for computing criticality focuses on the consequences of an event alone (Theoharidou et al., 2009), that is from a cost perspective, simply as the severity of the consequences of failure. BS 3811(1984) and Norsok (2001) define criticality analysis as a quantitative analysis of events and faults and the ranking of these in order of the seriousness of their consequences. Pschierer-barnfather etal (2011) see asset criticality as a comparative measure of consequences. Other authors who defined criticality from a cost based perspective include Gajpal, Ganesh and Rajendran (1994), Ahmadi et al., (2010), Gilchrist, (1993), Pappas and Pendleton, (1983), Kendrick and Jr. (1966), Spencer (1962), Alvi and Labib (2001), Baruah and Vestal (2008), Canto-Perello, Curiel-Esparza and Calvo (2013), Walski, Weiler and Culver (2006), Al-Najjar and Alsyouf, (2003). This school of thought sees criticality analysis as a first step to risk analysis.

From the above views, the question arises as to whether asset criticality is the same as asset failure risk, or is it something different? Can asset criticality be view from a value-based perspective? In attempting to answer this question, we developed a classification of criticality in terms of risk-based, cost-based or value-based. Table 1 shows the classification of definitions with the corresponding literature sources grouped into different time periods.

Table 1: **Classification of definitions of criticality**

|  |  |  |
| --- | --- | --- |
| Criticality defined in terms of | Period | References |
| Risk(e.g. Consequence X Probability) | 1950 – 1970 | Moskowitz (1970), Greene (1970), Staat, Dallaire and Roukas (1970), Military (1949) |
| 1971 – 1985 | USM Standard (1980), Cooper, (1971), Romans (1971), Elperin and Dubi (1985), Wilson and Johnson, (1983), (Granziera, 1978), Mill and Sari, (1975) |
| 1986 – 2000 | McKinney and Iverson (1995), Bevilacqua and Braglia, (2000), Bromley and Bottomley, (1994), Borgovini, Pemberton and Rossi, (1993), Kim *et al.*, (1996), Matsumoto, (1998), Estes, (1997), Becker and Flick, (1996), Mariani *et al.*, (1996) |
| 2001 – 2017 | Benjamin, Tan and Razon (2015), Bishop *et al.* (2003), Braglia, Frosolini and Montanari (2003), Ye and Kelly (2004), Theoharidou, Kotzanikolaou and Gritzalis (2009), Shin *et al.* (2015), Molenaers *et al.* (2012), Stoll *et al.* (2015), Tsakatikas, Diplaris and Sfantsikopoulos (2008), Arunraj and Maiti, (2010), Bertolini and Bevilacqua, (2006), Flores-Colen and de Brito, (2010), Goossens, Basten and Dongen, (2014), Hameed and Khan, (2014),  |
| Cost or Impact(e.g. Consequences) | 1950 – 1970 | Kendrick and Jr. (1966), Spencer (1962) |
| 1971 – 1985 | BS3811 (1984), Pappas and Pendleton, (1983) |
| 1986 – 2000 | Gajpal, Ganesh and Rajendran (1994), AHMADI *et al.*, (2010), Gilchrist, (1993) |
| 2001 – 2017 | Norsok (2001), Alvi and Labib (2001), Baruah and Vestal (2008), Canto-Perello, Curiel-Esparza and Calvo (2013), Walski, Weiler and Culver (2006), Al-Najjar and Alsyouf, (2003), MECHEFSKE and WANG, (2003), Dong, Gu and Dong, (2008), Marriott *et al.*, (2013), (Moore and Starr, (2006), Nyström and Söderholm, (2010) |
| Value | 1950 – 1970 |  |
| 1971 – 1985 |  |
| 1986 – 2000 | Abdul-Nour *et al.*, (1998) |
| 2001 – 2017 | Yang, Frangopol and Neves, (2006), Participants, Ceo and Crc, (2004), Barnfather, Hughes and Wells, (2014)  |

* 1. Trend in Techniques for Computing Criticality

To understand the trend in the different techniques for calculating criticality, we used framework proposed in used in Liu et al (2013) for classifying the methods that have been identified in the literature. In this review, we divide the methods used in the literature into five main categories which are multi-criteria decision making (MCDM), artificial intelligence (AI), simulation (S), integrated approaches (IA), other approaches (OA). The five categories, each with their own related techniques and references, are reported in Table 2.

Gajpal et al (1994) describe a three-level analytic hierarchy process (AHP) for evaluating the criticality of spares. AHP has since been used for maintenance strategy selection (e.g., Zaim et al, 2012; Bevilacqua and Braglia, 2000; and Alvi and Labib, 2001).

In attempting to compute criticality more efficiently Ilangkumaran and Kumanan, (2009) integrated two methods by introducing the use of analytic hierarchy process (AHP) under fuzzy environment and technique for order preference by similarity to ideal solution (TOPSIS) to select an optimum maintenance strategy for a textile industry. This methodology was designed such that the weight of each criterion is calculated to overcome the criticism of

Table 2: **Classification of evaluation methods for criticality analysis**

|  |  |  |
| --- | --- | --- |
| Categories | Techniques | References |
| MCDM | AHP/ANPHazopRBCRPNDecision Tree | Alvi and Labib (2001), Gajpal, Ganesh and Rajendran (1994), Molenaers *et al.* (2012), Stoll *et al.* (2015), Bevilacqua and Braglia, (2000), Goossens, Basten and Dongen, (2014), Nyström and Söderholm, (2010)Bishop *et al.* (2003)Theoharidou, Kotzanikolaou and Gritzalis (2009)Shin *et al.* (2015)Dong, Gu and Dong, (2008) |
| Integrated Approaches | Delphi-Color Coded-AHPFTA-SHAAHP-TOPSIS-VIKORFuzzy-MCDMAHP-GPFuzzy-AHP-TOPSISPAM-FMEA | Canto-Perello, Curiel-Esparza and Calvo (2013)Ye and Kelly (2004),AHMADI *et al.*, (2010), (Al-Najjar and Alsyouf, 2003)Arunraj and Maiti, (2010), Bertolini and Bevilacqua, (2006)langkumaran and Kumanan, (2009)Marriott *et al.*, (2013) |
| Artificial Intelligence | Fuzzy Logic | Braglia, Frosolini and Montanari (2003), MECHEFSKE and WANG, (2003), Feng and Chung, (2013), Pelaez and Bowles, (1994), J. Bowles and Peláez, (1995), Xu, Zhu and Luo, (2000) |
| Simulation | EPSMonte CarloMCNP | Walski, Weiler and Culver (2006)Romans (1971), Liu and Frangopol, (2004), Neves and Frangopol, (2005), Borgovini, Pemberton and Rossi, (1993), Banaei-Kashani and Shahabi, (2003)McKinney and Iverson (1995) |
| Other Approaches | Input – Output ModelFMEAEUACCBC | Benjamin, Tan and Razon (2015)Cooper (1971), Romans (1971), Tsakatikas, Diplaris and Sfantsikopoulos (2008), Abdul-Nour *et al.*, (1998)Flores-Colen and de Brito, (2010)Moore and Starr, (2006) |

unbalanced scale of judgments, uncertainty, and imprecision in the pair-wise comparison process. AHP was integrated with goal programming in Arunraj and Maiti, (2010), Bertolini and Bevilacqua, (2006), while Ye and Kelly (2004) formulated the AHP-TOPSIS-VIKOR integrated approach.

Artificial intelligence approaches have also been used to handle ambiguous, qualitative or imprecise information in a consistent manner and can fully incorporate engineers’ knowledge and expertise in the computation of criticality (Liu, Liu and Liu, 2013). The most used AI technique for criticality is fuzzy logic as seen in Braglia, Frosolini and Montanari, (2003); Mechefske and Wang, (2003); Feng and Chung, (2013); Pelaez and Bowles, (1994); Bowles and Peláez, (1995); and Xu, Zhu and Luo, (2000).

The use of simulation approaches such as Monte Carlo for criticality analysis was demonstrated in Walski, Weiler and Culver (2006); Romans (1971); Liu and Frangopol, (2004); Neves and Frangopol, (2005); Borgovini, Pemberton and Rossi, (1993); Banaei-Kashani and Shahabi, (2003); McKinney and Iverson (1995).

Other approaches include the input-output model by Benjamin, Tan and Razon (2015) and the cost-based criticality model by Moore and Starr (2006).

* 1. Trend in the Usage of Criticality to determine Maintenance intervention

Some of the potential uses for criticality analysis are (Assetivity - Asset Management Consultants, 2015):

* As an input to determine the overall priority for performing a maintenance task;
* To determine, at a high level, the type of risk mitigation strategy to be applied to an item of equipment;
* As an input into determining the optimum spare parts holdings required for an item of equipment;
* To assign priority for equipment upgrade or replacement
* To focus reliability improvement efforts on the most “critical” equipment
* To prioritize failure mode during the design phase in the life of an asset

To understand the trend in the different usage of criticality analysis, we classified the different uses of criticality based on the above potential uses of criticality, as identified in the literature. In this review, we divide the methods used in the literature into six main categories as shown in Table 3.

Table 3: Classification of the uses of criticality analysis

|  |  |
| --- | --- |
| **Uses of Criticality** | **References** |
| **Criticality analysis for prioritizing failure modes during design** | Bishop *et al.* (2003), Ye and Kelly (2004), (Cooper, 1971), Romans (1971), Greene, (1970), Dallaire, (1970), Staat, Dallaire and Roukas, (1970), McGinnis, (1969), Moskowitz, (1970), Moskowitz, (1971), Babb, (1974), Cooper (1971), Ahsen and von Ahsen, (2008) |
| **Criticality analysis for selection/planning of maintenance** | Alvi and Labib (2001), Benjamin, Tan and Razon (2015), Canto-Perello, Curiel-Esparza and Calvo (2013), Abdul-Nour *et al.*, (1998), AHMADI *et al.*, (2010), Al-Najjar and Alsyouf, (2003), Arunraj and Maiti, (2010), Bertolini and Bevilacqua, (2006), MECHEFSKE and WANG, (2003), Bevilacqua and Braglia, (2000), Dong, Gu and Dong, (2008), Flores-Colen and de Brito, (2010), Goossens, Basten and Dongen, (2014), Hameed and Khan, (2014), Ilangkumaran and Kumanan, (2009), Nyström and Söderholm, (2010),  |
| **Criticality analysis for spare parts management** | Gajpal, Ganesh and Rajendran (1994), Molenaers *et al.* (2012), Stoll *et al.* (2015), Tsakatikas, Diplaris and Sfantsikopoulos (2008), Botter and Fortuin, (2000), Braglia, Grassi and Montanari, (2004), Dekker, Kleijn and de Rooij, (1998), Gelders and Van Looy, (1978), Huiskonen, (2001), Partovi and Anarajan, (2002), Porras and Dekker, (2008), Ramanathan, (2006), Syntetos, Keyes and Babai, (2009), Teunter, Babai and Syntetos, (2010), Tsakatikas, Diplaris and Sfantsikopoulos, (2008), Zhou, P., Fan, (2007) |
| **Criticality analysis for prioritization of maintenance tasks** | Baruah and Vestal (2008), Marriott *et al.*, (2013), Moore and Starr, (2006), Nyström and Söderholm, (2010), Ming Tan, (2003), Elbehairy *et al.*, (2006), Cerrada *et al.*, (2007),  |
| **Criticality analysis for prioritizing decisions to acquire new equipment program** | Theoharidou, Kotzanikolaou and Gritzalis (2009), Marriott *et al.*, (2013), Pschierer-barnfather, Hughes and Holmes, (2011), Barnfather, Hughes and Wells, (2014), Alvi and Labib, (2001), Participants, Ceo and Crc, (2004), Andersen *et al.*, (2001) |
| **Criticality analysis for reliability improvement** | Braglia, Frosolini and Montanari (2003), Walski, Weiler and Culver (2006), Shin *et al.* (2015), McKinney and Iverson (1995), Ramirez-Marquez and Coit, (2007), Pappas and Pendleton, (1983), Xu *et al.*, (2002), Maucec, Ravnik and Glumac, (1998), Ćatić, Jeremić and Djordjević, (2011), Walski, Weiler and Culver, (2006) |

1. **Observation and Findings**

This paper comprises a review of 94 articles published between 1950 to 2016, in order to understand trends in the meaning, technique of computation and usage of asset criticality. Table 1 reports the different views in the meaning of criticality, which are classified under risk-based, cost-based and value-based. The identified approaches, which are classified under 5 main categories including multi-criteria decision making, integrated approach, artificial intelligence, simulation and other approaches, have been summarized in Table 2. Table 3 summarizes the six main categories for the uses of criticality rating. Based on these journal articles, some observations are made in the following subsections.

Figure 1: **Trend in the Definition of Criticality**

* 1. The Prevalent Definitions

According to Figure 1, the most dominant view of criticality from 1950 to 1970 is the risk-based definition, with 67% of the total literature review. As seen, 33% of the literature consider criticality from cost perspective as a comparative consequence, while there was no report of value-based definition of criticality. Between 1971 and 1985, risk-based view of criticality was still prevalent with 70% count.

From 1998 onwards, we begin see a new perspective of criticality as impact of decision on values of an organization.

3.2 The Popular Techniques for Computing Criticality

As found in the previous sections, the category of method most frequently applied to criticality analysis was found to be MCDM with 34.0% of all the reviewed papers. Integrated approaches were the next most applied methods with 21.75%.

Figure 2: **Trend in the Technique for Computing Criticality**

According to Table 2, the most popular approach is AHP, followed by fuzzy logic, and then monte carlo. The wide applicability of AHP, and MCDM in general, is because it possesses certain unique advantages (Alvi and Labib (2001); Gajpal, Ganesh and Rajendran (1994); Molenaers et al. (2012); Stoll et al. (2015); Bevilacqua and Braglia, (2000).

* 1. Usage of Criticality Analysis

From Figure 3, the, following observations are made:

* In the 50’s, the most common use of criticality was for prioritizing failure modes. From that time to current period, there’s being a drop, from 56% to 7%, in the popularity of this use of criticality.
* Maintenance strategy selection is the second most popular use for criticality rating. The trend for this use has been relatively consistent over the periods considered.
* The third most popular use for criticality rating is reliability improvement programmes. This use also has remained relatively constant over time.
* The use of criticality for spare part management, work order prioritization and capital improvement has increasingly become popular over time. For example, the use of criticality rating for spare part management increase from 0% to 20% (of the literature reviewed) between the periods of 1950 and 2016.

Figure 3: **Trend in the Usage of Criticality**

1. **Conclusion and Recommendation for Future Work**

This paper is based on a literature review from 1950 to 2016 on the meaning, usage and techniques for computing criticality.

First, it was found that criticality analysis, which was first developed to meet obvious reliability and safety requirements (J. B. Bowles and Peláez, 1995), has been always been seen from a negativistic point of view. Also, the use of criticality for maintenance purpose is still at a nascent stage for most organisation (Adams et al., 2016).

Second, it was observed that several approaches were proposed for computing criticality. It can be observed from the reviewed literature that AHP is the most popular approach, followed by fuzzy logic, and then monte carlo.

Third, the most common use of criticality rating was for prioritizing failure modes, developing maintenance strategy and reliability improvement program. But trend from Figure 3 show that other uses of criticality for maintenance purposes, such as spare part management, work order prioritization and capital improvement, are increasingly becoming popular lately.

From this paper, the main suggestions for future work are as follows:

* There is need to adopt a positivistic view of criticality, in order to use it as a value-based maintenance management tool
* Criticality analysis methods should be able to incorporate multiple criteria, should be easily understood by managerial decision makers and should consider uncertainties and dynamicity issues.

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