A Bibliographic Review of Trends in the Application of 'Criticality' Towards the Management of Engineered Assets

Joel Adams, Ajith Parlikad and Joe Amadi-Echendu

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 definition · Criticality analysis · Criticality application

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J. Adams · A. Parlikad
Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, CB3 0FS Cambridge, UK
e-mail: ja579@cam.ac.uk

A. Parlikad
e-mail: aknp2@cam.ac.uk

J. Amadi-Echendu (✉)
Department of Engineering and Technology Management, Graduate School of Technology Management, University of Pretoria, Pretoria, South Africa
e-mail: joe.amadi-echendu@up.ac.za

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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). 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 [18, 57]. 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 [67]). These standards describe techniques and approaches for criticality analysis as an essential function in the design and development of engineered components, equipment, and systems.

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

2 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.

2.1 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 [59]. There are many unanswered questions about what asset criticality means.

EN 13306 [8] defines criticality as "numeric index of the severity of failure or fault combined with the probability or frequency of its occurrence". According to USM Standard [67], criticality is a relative measure of the consequences of a failure mode and its frequency of occurrence. Some authors agree with this view of criticality in terms of risk of failure, (e.g., Cooper [23]; Wilson and Johnson [69]; Elperin and

Dubi [26]; McKinney and Iverson [41]; Kim et al. [35]; Bishop et al. [15]; Bertolini and Bevilacqua [14]; Benjamin et al. [13]).

Other methods for computing criticality focus on the cost consequences of failure (e.g., Spencer [60], Kendrick [34], Pappas and Pendleton [50], Gilchrist [30], Gajpal et al. [28], Alvi and Labib [5], Al-Najjar and Alsyouf [4], Walski et al. [68], Baruah and Vestal [12], Theoharidou et al. [65], Ahmadi et al. [2], Canto-Perello et al. [21]). BS 3811 (1984) and Norsok [48] define criticality analysis as a quantitative evaluation of events and faults and the ranking of these in order of the seriousness of their consequences. Pschierer-Barnfather et al. [54] see asset criticality as a comparative measure of consequences.

Extant literature suggests that asset criticality implies failure risk. If so, can asset criticality also be viewed 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.

2.2 Trend in Techniques for Computing Criticality

To understand the trend in the different techniques for calculating criticality, we used framework proposed in Liu et al. [37] 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 some the related techniques and references, are reported in Table 1.

Table 1 Classification of evaluation methods for criticality analysis

Categories	Techniques	References
MCDM	AHP/ANP	Alvi and Labib [5], Gajpal et al. [28], Molenaers et al. [44], Stoll et al. [62], Goossens et al. [31], Nyström and Söderholm [49]
	Hazop	Bishop et al. [15]
	RBC	Theoharidou et al. [65]
	RPN	Shin et al. [58]
	Decision Tree	Dong et al. [25]
IA	Delphi-Color Coded-AHP	Canto-Perello et al. [21]
	FTA-SHA	Ye and Kelly [72]
	AHP-TOPSIS-VIKOR	Ahmadi et al. [2], Al-Najjar and Alsyouf [4]
	Fuzzy-MCDM	Arunraj and Maiti [7], Bertolini and Bevilacqua [14], Langkumaran and Kumanan [33]
	AHP-GP	Marriott et al. [38]
	Fuzzy-AHP-TOPSIS	
	PAM-FMEA	

(continued)

Table 1 (continued)

Categories	Techniques	References
AI	Fuzzy Logic	Braglia et al. [19], Mechefske and Wang [42], Feng and Chung [27], Pelaez and Bowles [52], Bowles and Peláez [18], Xu et al. [71]
S	EPS	Walski et al. [68]
	Monte Carlo	Liu and Frangopol [36], Neves and Frangopol [47], Borgovini et al. [16], Banaei-Kashani and Shahabi [10]
	MCNP	McKinney and Iverson [41]
OA	Input–Output Model	Benjamin et al. [13]
	FMEA	Cooper [23], Tsakatikas et al. [66], Abdul-Nour et al. [1]
	EUAC	Flores-Colen and de Brito (2010)
	CBC	Moore and Starr [45]

2.3 *Trend in the Usage of Criticality*

To understand the trend in the different usage of criticality analysis, we divide the methods found in the literature into six main categories as shown in Table 2.

Table 2 Classification of the uses of criticality analysis

Uses of criticality	References
Criticality analysis for prioritizing failure modes during design	Bishop et al. [15], Ye and Kelly [72], [23], Staat et al. [61], McGinnis [40], Moskowitz [46], Babb [9], Ahsen and von Ahsen [3]
Criticality analysis for selection/planning of maintenance	Alvi and Labib [5], Benjamin et al. [13], Canto-Perello et al. [21], Abdul-Nour et al. [1], Ahmadi et al. [2], Al-Najjar and Alsyouf [4], Arunraj and Maiti [7], Bertolini and Bevilacqua [14], Mechefske and Wang [42], Dong et al. [25], Ilangkumaran and Kumanan [33], Nyström and Söderholm [49]
Criticality analysis for spare parts management	Gajpal et al. [28], Molenaers et al. [44], Stoll et al. [62], Tsakatikas et al. [66], Botter and Fortuin [17], Braglia et al. [20], Dekker et al. [24], Gelders and Van Looy [29], Huiskonen [32], Partovi and Anarajan [51], Porras and Dekker [53], Ramanathan [55], Syntetos et al. [63], Teunter et al. [64], Tsakatikas et al. [66], Zhou and Fan [73]

(continued)

Table 2 (continued)

Uses of criticality	References
Criticality analysis for prioritization of maintenance tasks	Baruah and Vestal [12], Marriott et al. [38], Moore and Starr [45], Nyström and Söderholm [49], Ming Tan [43], Cerrada et al. [22]
Criticality analysis for prioritizing decisions to acquire new equipment	Theoharidou et al. [65], Marriott et al. [38], Pschierer-barnfather et al. [54], Barnfather et al. [11], Alvi and Labib [5], Andersen et al. [6]
Criticality analysis for reliability improvement	Braglia et al. [19], Walski et al. [68], Shin et al. [58], McKinney and Iverson [41], Ramirez-Marquez and Coit [56], Pappas and Pendleton [50], Xu et al. [70], Maucec et al. [39], Ćatić et al. [74]

3 Findings and Observations

From a review of 94 articles published between 1950 and 2016, we make the following findings and observations. The bar graph in Fig. 1a shows that, from 1950 to 1985, the dominant definition of criticality was risk-based followed by the cost perspective. However, from 1998 onwards, a new perspective emerges of criticality in terms of the impact of decisions on values of an organization. As illustrated in the bar graph of Fig. 1b, multi-criteria decision making techniques are most frequently applied to criticality analysis. Figure 1c also indicates that criticality is primarily applied to prioritize failure modes, formulate strategy for maintenance interventions and reliability improvements, and to improve the management of equipment spares.

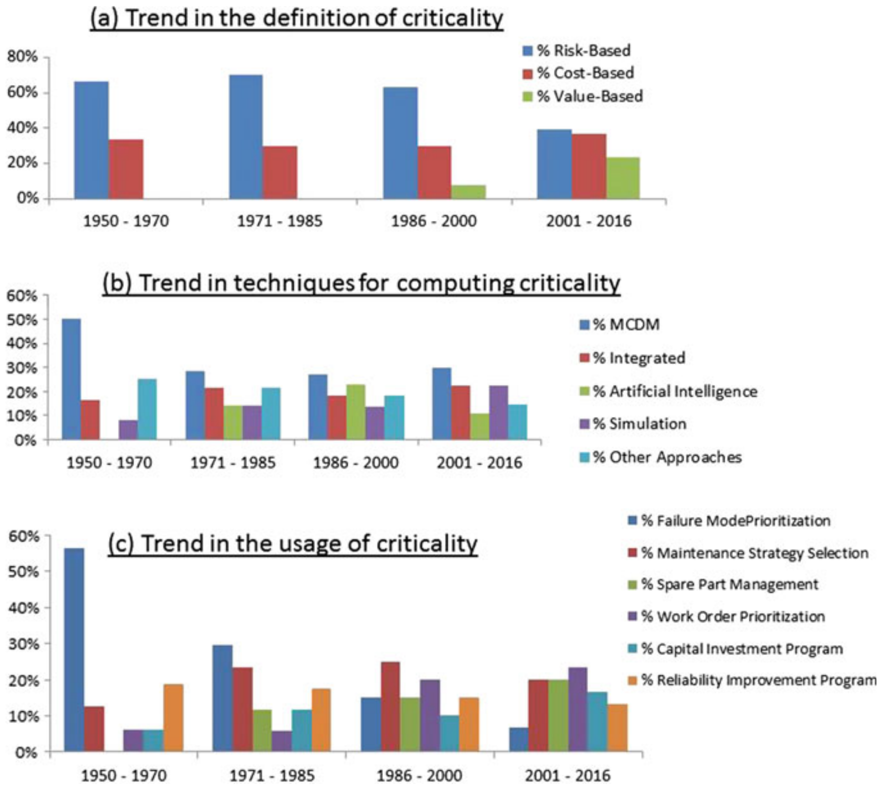

Fig. 1 Trends in the definition, computation and usage of criticality

4 Conclusions

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, has been always been seen from a negativistic point of view. Second, although several approaches are proposed for computing criticality, however, the reviewed literature suggests that multi-criteria decision methods predominate. Third, the most common use of criticality rating was for prioritizing failure modes, developing maintenance strategy and reliability improvement programs. Remarkably, in practice, the use of criticality for the maintenance purpose is still at a nascent stage in many organisations. Other increasingly becoming popular applications of criticality are for spare parts management, work order prioritization and capital investment decisions. This suggests a positivist view of criticality embodied in the value doctrine for effective management of engineered assets that constitute our built environment.

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