Towards Dynamic Criticality-Based Maintenance Strategy for Industrial Assets

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Abstract: An asset's risk is a useful indicator for determining optimal time of repair/replacement for assets in order to yield minimal operational cost of maintenance. For a successful asset management practice, asset-intensive organisations must understand the risk profile associated with their asset portfolio and how this will change over time. Unfortunately, in many risk-based asset management approaches, the only thing that is known to change in the risk profile of the asset is the likelihood (or probability) of failure. The criticality (or consequences of failure) of asset is assumed to be fixed and has considered as more or less a static quantity that is not updated with sufficient frequency as the operating environment changes. This paper proposes a dynamic criticality-based maintenance approach where asset criticality is modeled as a dynamic quantity and changes in asset's criticality is used to optimize maintenance plans (e.g. determining the optimal repair time/replacement age for an asset over it life cycle period) to have a better risk management and cost savings. An illustrative example is used to demonstrate the effect of implementing dynamic criticality in determining the optimal time of repair for a bridge infrastructure. It is shown that capturing changes in the criticality of the bridge over time and using this understanding in the risk analysis of the bridge provided the opportunity for better maintenance planning resulting to reduction of the total risk.

Keywords: Dynamic criticality; asset management; asset risk profile; replacement age; maintenance plan.

1. INTRODUCTION

Many European and North American countries undertook an enormous investment in construction of infrastructures such as highway networks in the second half of the 20th century, most of which are either completed or near completion. As a result, the need in funding changed from building new structures to repair, rehabilitation, and replacement of the existing ones (Neves & Frangopol 2005). Given that funds and maintenance resources are scarce and ever decreasing, there is need for appropriate techniques to maintain adequate level of safety and serviceability in infrastructure assets while minimising the total expected life-cycle cost. Decision makers are faced with the challenge to decide when and how to repair, rehabilitate, replace and/or shutdown the deteriorating facilities (Kong & Frangopol 2003).

Infrastructure assets will require effective cost evaluation methods to assess reasonable expenditures allocated for their life-cycle cost management. It is very important to optimise investment for management of any such infrastructure asset over its lifetime. In order to achieve this, it is crucial for the organisation to have good knowledge and understanding of the risk profile associated with their asset portfolio and how this changes over time. Unfortunately, traditional methods of modelling and simulating lifecycle performance for infrastructure management, including bridge management systems, commonly do not account for risk associated with potentially failure scenarios (Ayyub, B. and Popescu 2003).

There are two types of maintenance interventions for infrastructure assets; preventive maintenance and essential maintenance (rehabilitation) (Robertson & Weligamage 2003). While essential or rehabilitation is carried out to make infrastructure safer for users, preventive maintenance is conducted to avoid costly unplanned maintenance. For an optimum maintenance plan, an assessment of the asset's life-cycle cost is first carried out to justify both short and long-term strategy. Several methods based on probabilistic theories have been used for life cycle models which are mostly based on a deterministic approach. However, the condition of most infrastructures is mostly stochastic and the factors that determine their criticality are dynamic in nature. A comparison between static and dynamic methods for life cycle cost analysis in (Zayed et al. 2002) show conflicting results. There is need for dynamic models and tools to quantify risk, and benefit associated with infrastructure asset.

1.1 Objective

The methodology proposed in this paper considers a risk-informed decision approach to maintenance planning (e.g. timing of interventions in a capital program) for infrastructure assets such as bridges. The risk analysis takes into account the dynamic nature of an asset's criticality and uses the changes in criticality to optimise the timing of interventions for an asset. The methodology gives a true picture of the criticality of the bridge as it takes into account social, environmental, and political impacts. A systems

dynamic approach is used to model the criticality of the asset as a dynamic function which changes over time due to factors such as population growth, urban growth, and new developments (e.g. industries).

The objective of this study is to develop and demonstrate a methodology for assessing dynamic criticality of assets which changes over time and to use this understanding to optimise timing of intervention in order to achieve better risk management and better cost savings.

2. A BRIEF REVIEW OF LITERATURE

One of the main uses of criticality analysis for maintenance purpose is that it is used to provide input into the capital program so that "high criticality" equipment is given a higher priority for upgrade or replacement (Assetivity - Asset Management Consultants 2015). But also, the timing of intervention is very crucial to an optimal capital investment decision. Many risk-based approaches, in asset management, uses criticality as part of it risk analysis procedure for improving capital investment decisions. In (Pschierer-barnfather et al. 2011), the underlying methodology used in Condition-Based Risk Management (CBRM) to determine asset criticality was described. This methodology has been designed to be highly practical, enabling network operators to rapidly determine the criticality of many tens of thousands of assets, particularly when the available data is limited or incomplete. This methodology enables network owners and operators to target network investment towards the most beneficial parts of the network, providing a powerful tool for resource allocation and prioritisation. Condition-based risk management (CBRM) (Barnfather et al. 2014) was presented as a methodology that brings together asset information, engineering knowledge and practical experience of assets to define and quantify current and future asset condition, performance and risk. CBRM provides a means to express and communicate engineering information for large numbers of assets in a form that enables asset managers to define and justify future investment. The CBRM methodology was first created by EA Technology Limited (EATL) and Electricity North West Limited (ENWL) in 2002/3.

In (CHESTERTON et al. 2014)(IAN n.d.), Severn Trent Water (STW) strived to achieve a high degree of confidence in the serviceability of its reservoirs. The Portfolio Risk Assessment (PRA) is used to recommend programme for capital works schemes that further improved reservoir safety. Capital works were reviewed, ranked and initiated between the assessment periods. While the reservoir risk ranking was informative, the prioritisation of the works was more heavily led by works programming to effect construction cost efficiencies. As a result of the dynamic nature of the criticality of the reservoirs, the PRA also recommended that the assessment process be a live one and periodically revisited.

In the last decade, there have been fruitful research efforts worldwide on maintenance planning optimisation for deteriorating highway bridge structure systems in order to obtain a rational allocation of resources under financial constraints. Many of them focused on minimising cumulative life-cycle maintenance cost while enforcing permissible limits on relevant performance measures in order to keep bridges safe and serviceable (Liu & Frangopol 2004). However, the application of dynamic criticality (using system dynamic approach) is a new concept.

3. DYNAMIC CRITICALITY

One crucial question that must be answered by asset-intensive organisations is: "Do we understand the risk profile associated with our asset portfolio and how this will change over time?" a clear understanding of this is necessary to achieve strategy objectives and optimise maintenance investments for infrastructural assets.

3.1 Scenario description

In many risk-based asset management approaches, the only thing that is known to change in the risk profile of the asset is the likelihood (or probability) of failure. The criticality (or consequences of failure) of asset is assumed to be fixed and has considered as more or less a static quantity that is not updated with sufficient frequency as the operating environment changes (Adams et al. 2016). As seen in Figure 1(a), risk is defined as the combination of failure probability and the consequences of failure (criticality). The figures below describe what an asset risk profile (incorporating maintenance interventions) will look like when criticality is considered to be static versus when it is considered to be dynamic.
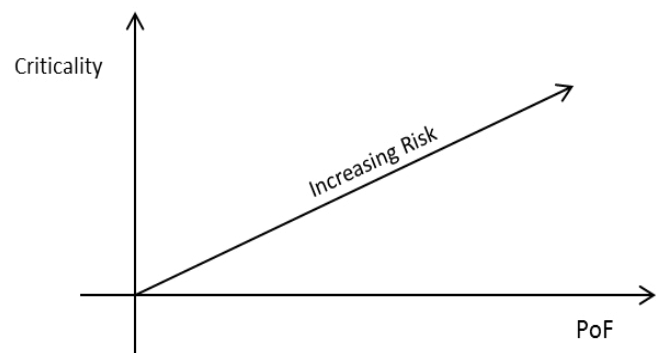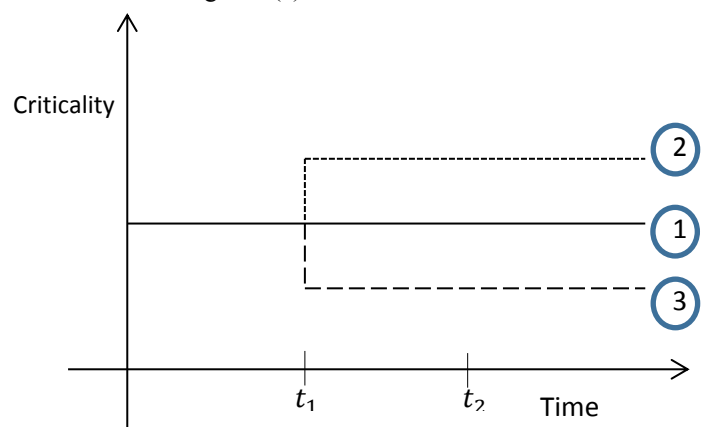

Figure 1(a): **Definition of Risk**

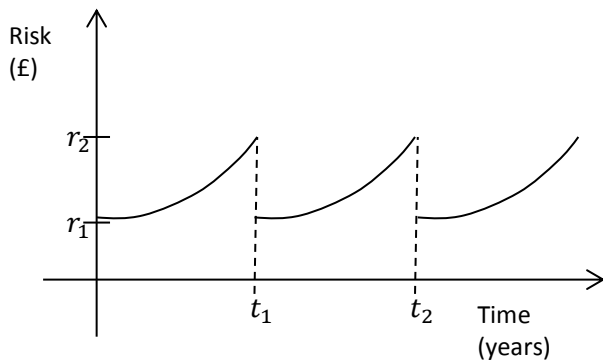Figure 1(b): **Scenarios showing changes in criticality**
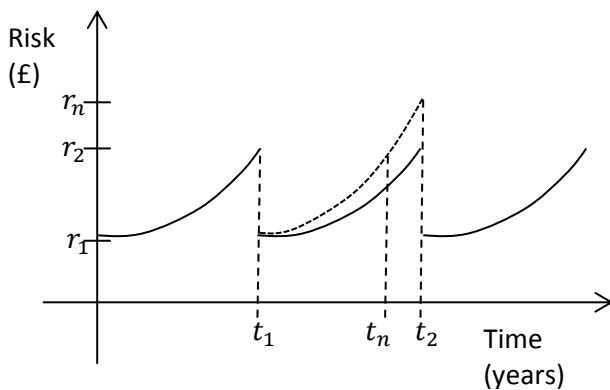
Figure 1(c): **Scenario 1 with a constant criticality**

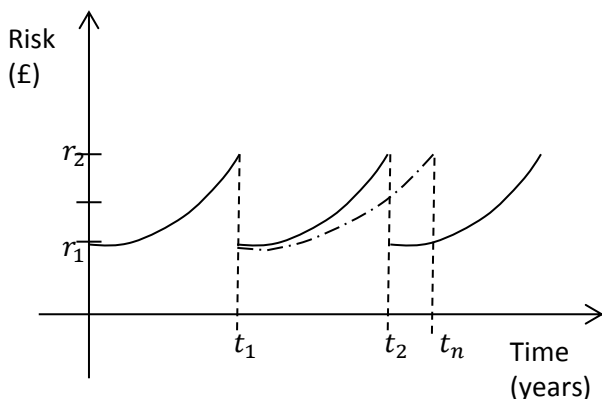Figure 1(d): **Scenario 2 with an increase in criticality**

Figure 1(e): **Scenario 3 with a decrease in criticality**

From Figure 1(b), three scenarios are shown where:

1. Criticality is constant
2. Criticality changed (increased) at time t_1
3. Criticality changed (decreased) time t_1

The effects or impact of dynamic criticality on the asset risk profile and optimal timing of intervention are shown in Figure 1-(c), (d), & (e) respectively. Figure 1(c) shows the timing of intervention proposed in the AMP when criticality is considered and risk changes only due to change in the probability of failure of the asset. It can be seen from Figure

1(d) (with increase in criticality) that in order to maintain a maximum risk of $r_2(£)$, a new intervention time t_n has to be adopted instead of the original time t_2 in the initial asset management plan. This will result in savings of $(r_n - r_2)£$ in the event that the asset fails before t_2.

Similarly in Figure 1(e), a decrease in asset criticality could be exploited to delay the timing of intervention until t_n instead of t_2. This obviously will mean exploiting more of the RUL of the asset before replacement/repair. The next section briefly discussed the benefits of understanding the dynamics of criticality.

3.2 Benefits: why is dynamic criticality important?

A true picture of the risk profile of an organisation's asset portfolio is required to enhance value, generated from the asset, to the organisation. As seen in the scenarios above, there are considerable cost savings to be made by making informed choices on the timing of repairs/replacements that strikes the right balance between value-versus-cost.

Another immediate benefit is better risk management, as the organisation now have a better picture of the risk and can determine a maximum tolerable risk they can cope with.

Section 4 uses an illustrative example to develop the dynamic criticality-based maintenance model.

4. THE DYNAMIC CRITICALITY-BASED MAINTENANCE MODEL

This section presents an approach to model maintenance decision (e.g. timing of intervention) using changes in asset criticality to determine an optimal decision. The example presented here considers a bridge asset in a network of road infrastructure of a county council. The council manages 800 bridges under it asset portfolio and uses a fixed maintenance policy developed under a 30 years asset management plan (AMP).

Under this policy, the intervention time to repair a bridge is every 5 years (with the assumption that bridge criticality is constant). There's a budgetary constraint of £10 million assigned for repair jobs for the 5 year period.

Model assumptions

- The average life of a bridge is assumed to be 60 years.

- Under the considered policy, the intervention time to repair a bridge is every 5 years (with the assumption that bridge criticality is constant).

- There's a budgetary constraint of £10 million assigned for repair jobs for the 5 year period.

Modelling the decision making process

- Determine the condition of the bridge and it probability of failure (PoF).

- Evaluate the criticality of the bridge "over a period of time".

- Determine the current total risk of the bridge based on current bridge condition and criticality.

- Determine the optimal repair time which minimises risk and save cost.

Determining probability of failure

For sake of simplicity, failure of bridge will mean a loss functionality whereby it becomes unusable by vehicle. The biggest threats to bridge structures are moisture for wooden structure and high salinity for steel and concrete structure.

Therefore PoF of bridge structure will depend on climatic conditions, population density of it location, volume of traffic/type of road (industrial roads).
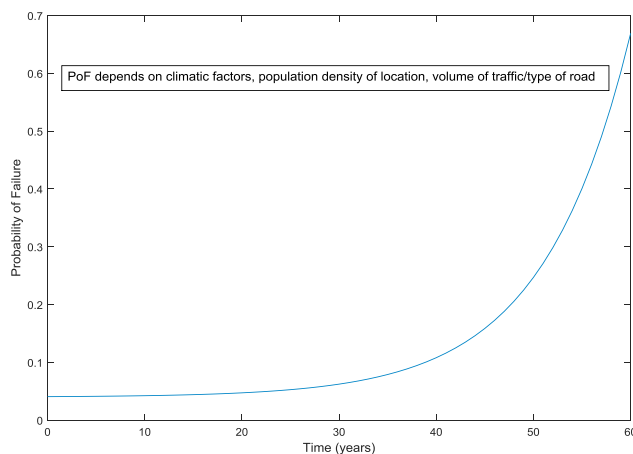

Figure 2: **Probability of bridge damage**

Determining criticality over time

Some of the factors that will affect the criticality of the bridge are: traffic volume; integrated transport; impact on network etc. the overall criticality of the bridge in this example is calculated considering only safety and service consequence categories.

The dynamic factors influencing change in criticality are: population dynamics, urban growth and new developments (e.g. industries). For instance, citing a new facility close to the bridge at time t1, as shown in Figure 3, might influence increase in traffic volume of the bridge users. This will result to increase in criticality of the bridge.
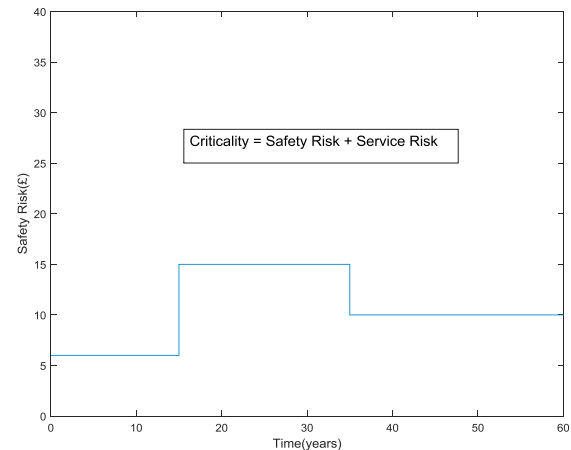

Figure 3: **Criticality changing over time**

Determining total risk using condition and criticality

Risk is a useful indicator for determining optimal time of replacement for assets in order to yield minimal or lowest cost per unit time. According to (Hastings 2005) the optimal replacement time for an asset can be deduced from calculating the minimum risk as shown in the following equation:

$$Risk\ (t) = Cnp \cdot (F(t)\ /\ t) + Cp \cdot (R(t)\ /\ t)$$

Where:

> **t** is the time to failure, **Cnp** is Corrective maintenance costs, **F(t)** is probability of failure, **Cp** is Preventive maintenance and **R(t)** = 1 − F(t): Reliability
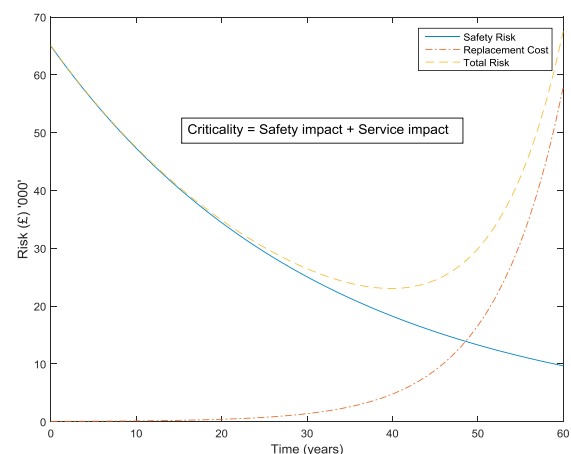

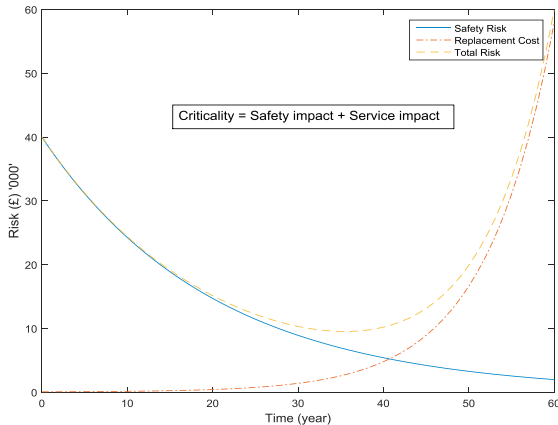Figure 4: Evaluating total risk using static criticality

Figure 5: Evaluating total risk considering dynamic criticality

	Considering dynamic criticality	Using static criticality
Optimal intervention time (year)	35	40
Risk (£) per year	12,010	24,000

Table 1: Optimal Intervention Time

5. CONCLUSION AND FUTURE WORK

5.1 Conclusions

This paper proposes a dynamic assessment of risk by considering the evolution of the impact of a feared event with time. The idea is to use this information to adapt consequently the maintenance planning. A case study is carried out within the field of bridge infrastructure. As seen from the results in Figure 4 and 5, a better understand of the changes in criticality of an asset will lead to better risk management and savings on operational expenditures over the life cycle of the asset. In order for maintenance manager to maintain a certain acceptable level of risk, say £12,000, a true picture of the asset portfolio risk profile must be known.

The example illustrated show the need for implementing dynamic asset criticality procedure to capture the benefits of better risk management and cost savings.

5.2 Future works

Dynamic criticality based maintenance methodology has been introduced as a method to monitor, review and update the asset criticality over time and use changes in criticality to review maintenance plan. Although this method is still at infancy stage, it promises to be a useful maintenance management tool.

Further work is required in enhancing the model to include various value metrics such as risk to users, risk to other assets (rail road, bridge etc), reputation and service disruptions.

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