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Evidencing the Need for Consistency in Long Term Investment to Secure the Safety of Road Bridges

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Abstract **-** Due to limited budgets, bridge managers need to be aware of the different factors affecting the maintenance of their bridge stock. Since traffic levels are intensifying along with the likelihood of extreme events (as a result of climate change), the safety and reliability of road networks are at risk. This places immediate emphasis on the need for strategic investment policies to maintain and improve the network. Organisations rely heavily on the data collected at the time of inspection in order to prioritise maintenance tasks, however a budget that can address all substandard bridges is no longer viable due to restricted investment and effects of the coronavirus pandemic. Therefore, a method or tool for making informed choices is needed to show the effects of particular decisions. This paper will review current literature on how maintenance is prioritised both within the research community and in practice. A focus will then be placed on a toolkit designed to assist with the management of structures, with a look at how different budgets affects both the short-term and long-term condition of the bridges and how inspector bias affects the prioritisation results.

Keywords**:** bridge management, maintenance prioritisation

1. Introduction

With budgets limited and decreasing yearly, it is crucial that funding allocated is spent in the most effective way and that there is an understanding how decisions made effect the future condition of bridges. Many countries across the world introduced methods to provide a ranked list of bridges requiring the most urgent attention. Each of the methods, both within the research field and in practice, all take into account different factors that they believe have the highest impact on the need for maintenance. While these approaches look at what bridges to maintain, it is important to consider how decisions made about what structures to maintain or replace impact on the future condition of the entire network. Therefore, this paper will begin with a literature review looking at the recent developments in the area of maintenance prioritisation. This review will be broken up into two sections, firstly advancements in research and then secondly methods currently used in practice across the world. As part of the review, the Structures, Asset, Valuation and Investment (SAVI) toolkit will be introduced, this toolkit will be the focus of the remainder of this paper. A case study which takes a sample of bridges from the Northern Ireland's (NI) Department for Infrastructure (DfI) bridge stock will then be introduced. The SAVI toolkit will applied on this sample of bridges to show three things; firstly, how different budgets affect the future condition of the bridges both in the short-term and in the long-term, secondly, how these budgets are allocated to different elements and finally, how slight changes in recorded element condition effects the maintenance plan. This paper will conclude with an overview of the findings and discuss possible areas of further work.

2. Literature Review

This section provides a brief review of maintenance priority literature. This section consists of two parts, Section 2.1 will focus on the advancement in the research over recent years and Section 2.2 will look at current methods being used across the world in practice.

2.1. Research

Much of the current literature pays particular attention to complex artificial intelligence and data mining methods in conjunction with deterioration models including Markov models. Most recently, Morato et al [1] proposed a joint frame-work of dynamic Bayesian networks (DBNs) with Partially Observed Markov Decision Processes (POMDPs) for inspection and maintenance planning. The author presented this as a method to overcome the shortcomings faced when using DBNs while keeping the practical advantages of integrating DBNs. However, using DBNs for real world applications results in a number of assumptions being imposed. Firstly, a discrete state space is required, however the higher the number of states used, the computational complexity increases. Secondly, the Markovian assumption, which states that the next condition state of the bridge will only depend on the current state and not its past, will apply.

Multiple researchers have established optimisation problems that consider a variety of criteria. For example, Gui et al [2] introduces a multi-parameter maintenance optimisation model using a combination of the Markov method and a radial basis function neural network for condition prediction and Principal Component Analysis for weight calculation. This study focused on three parameters, bridge condition, average daily traffic (AD) and sufficiency rating (SR) and presented a case study on bridge data from a single bridge in Texas. Additionally, Das and Nakano [3] introduced the technique for order of preference by similarity (TOPSIS) into a multi-criteria decision making framework in order to consolidate a variety of data and use them in the prioritisation of maintenance at the same time. An advantage of the proposed method is that it can be integrated into a BMS for decision support to assess multiple options and providing useful insights to decision makers.

Some researchers have focused on group maintenance in an attempt to decrease maintenance cost and shared system inactivity. Liang et al [4] introduces a novel genetic algorithm with agglomerative mutation (GA-A) that is used for predictive group maintenance policy. Components' deterioration is modelled as a continuous-time multi-state stochastic process with the sojourn time of each state being exponentially distributed. As an extension to this paper, Hadjidemetriou et al [5] introduced a method to calculate a bridges criticality based on its closeness to essential services and other critical nodes.

Various studies such as Echaveguren et al [6], Dromey et al [7] and Contreras-Nieto et al [8] have developed priority indexes based on the factors that have been determined to have an impact on maintenance needs. The first of these focuses on short-term maintenance planning. In this case, the priority index considered bridge condition index, hydraulic vulnerability, seismic risk and strategic importance. This index was then used to calculate bridge maintenance cost hence a limitation of the proposed method is that it relies heavily on a unit price database for maintenance activities which is not readily available. Similarly, Contreras-Nieto et al [8] presented a prioritisation framework by using bridge ratings and average daily traffic. The weights were determined based on importance of bridge ratings when investigating four key criteria (safety, resilience, serviceability and comfort) by using the Analytic Hierarchy Process (AHP). A case study which compared water crossing and non-water crossing bridges was used to show the method was robust and reliable. In a slightly different approach, Dromey et al [9] focuses on a prioritisation calculation which separates the bridges into two categories, critical-condition and non-critical. Each of these two calculations consider different factors which the authors used to reflect the different motivations used when determining maintenance projects in practice. This study concluded with outlining that critical condition bridges most influential factor was the overall structure condition, on the other hand non-critical condition bridges ranked hydraulic vulnerability as most important. These studies clearly indicate that the importance of including multiple potential influential characteristics in a prioritisation calculation.

2.2 In Practice

Many countries have introduced a method to prioritise maintenance of bridges. In a recent study by Amini et al [10], the authors looked at different bridge management systems and gave a detailed overview of several countries maintenance strategies. For example, in Chile [11] strategic importance, hydraulic vulnerability, seismic risk and bridge condition index are used to calculate an integrated bridge index, the resulting value ranked each bridge, with the bridge scoring the lowest value identified as most critical.

In the United Kingdom, an application known as the Structures Asset Investment and Valuation toolkit (SAVI) was developed as a multi-functional, condition-based decision support tool and has been used in practice across England and Scotland. It was released in 2020 with the aim of helping asset owners with managing their structure stock. It has three main functions which are valuation, short-term planning and long-term planning. Firstly, valuation which determines the replacement cost of the structure stock, secondly the short-term planning that develops a programme of works including maintenance and replacement based on a particular budget set by the user over a five-year time span. Finally, the long-term planning which follows a similar process to the short-term but the user can define annual budgets for each year of the analysis up to 120 years and intervention thresholds. In order for SAVI to run the various types of analysis, each structure's information needs to be input. This includes details of 17 structural attributes including length of structure, number of spans and traffic levels of the route supported by the bridges. For each structure at least one element condition needs to be entered.

3 Case Study: Bridges in Northern Ireland

This section will provide an overview of the bridges that were selected for inclusion in this case study. These bridges are taken from the Southern Division of the Northern Ireland Department for Infrastructure's (DfI) bridge stock. There are approximately 7000 bridges in NI which are spilt over 4 divisions: North, South, East and West based on their geographic location as shown in Figure 1.

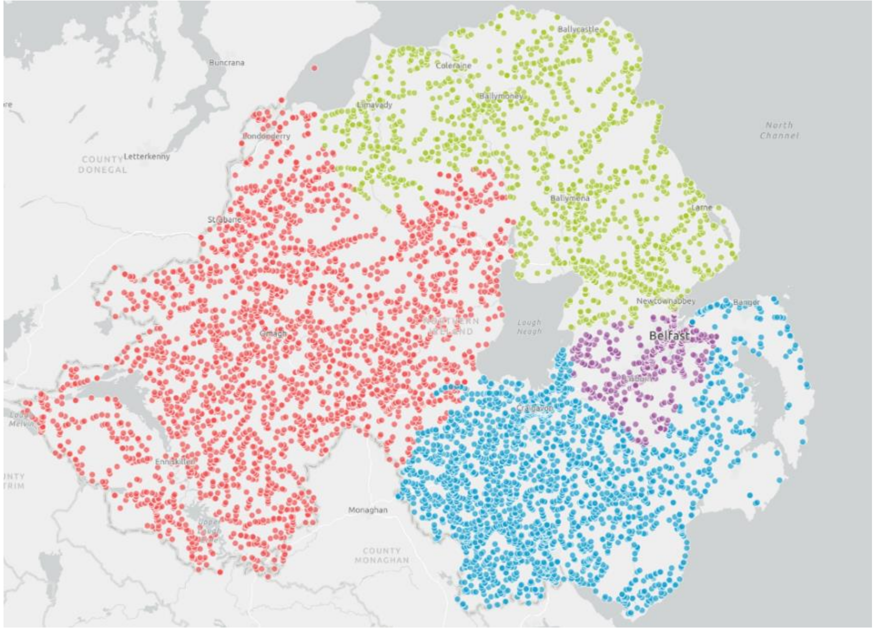
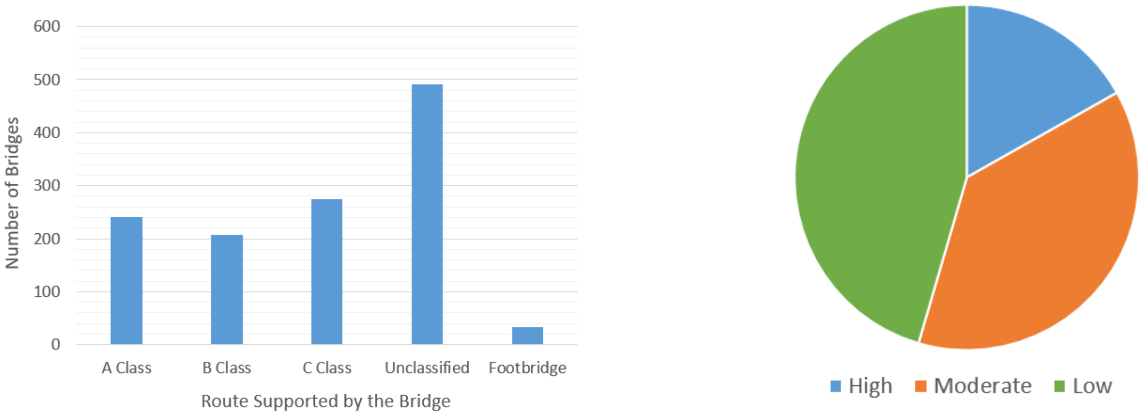


Figure 1: A map of Northern Ireland showing the location of the bridges. Each color represents a division – green is the Northern division, blue is the Southern division, purple is the Eastern division and red is the Western division.

For this case study, the Southern division was taken as a sample of which there are 1247 bridges covering a variety of bridge characteristics which are representative of the entire bridge stock. Although the majority of bridges in NI are single span, masonry arches with their primary function to carrying traffic over a river, it is important to consider structures from outside this grouping as they form some of the critical connections within the road network and hence must be considered in network wide maintenance planning. Using the most recent inspection from each of these bridges gives a wide range of bridge condition, the Bridge Condition Index (BCI) average ranged from 40 to 100. This was deemed to representative of the bridges within the NI network and has a similar distribution as the sample, with the majority of bridges falling in the range of between 80 and 93. When considering rehabilitation and replacement budgets, it is vital to consider how important the bridge is to the network. The bridges importance to the network can be deduced from a variety of characteristics such as the route supported by the bridge and the traffic levels. The distribution of these two characteristics within this sample is shown in Figure 2.



(a) (b)

Figure 2: (a) A bar chart showing the route supported by the bridges in the sample, (b) A pie chart showing the traffic levels

4 Results

Through the SAVI toolkit, there are two options for maintenance program, Short-term Asset Management Planning (SAMP) which is over a five-year span or Long-term Asset Management Planning (LAMP) which can be over up to 120 years. This section will look at how changes in budget and decision at the time of inspection impact the maintenance plan. Firstly, Section 4.1 will show how different levels of investment has on the projected condition of the bridges. Secondly, Section 4.2 will focus on how each of the budgets are spent with particular focus on which elements receive the most work as the budget increases and finally Section 4.3 will look at how inspector's decisions at the time of inspection effects the maintenance plan.

4.1 Effect of Budget

Due to constrained budgets, allocation of funding has become a crucial part of bridge management. For the set of bridges described in Section 3, this section will explore how different levels of investment effects the future condition of the bridges. Firstly, how these budgets effect the short term (5 years) bridge condition projection and then long-term (30 years). Figure 3 shows how four different budget levels affect the number of bridges that are in very good ($SCI_{Av} \geq 90$), good ($80 \leq SCI_{Av} < 90$), fair ($65 \leq SCI_{Av} < 80$), poor ($40 \leq SCI_{Av} < 65$) and very poor ($SCI_{Av} < 40$) condition respectively, where SCI_{Av} is the stock condition index average.

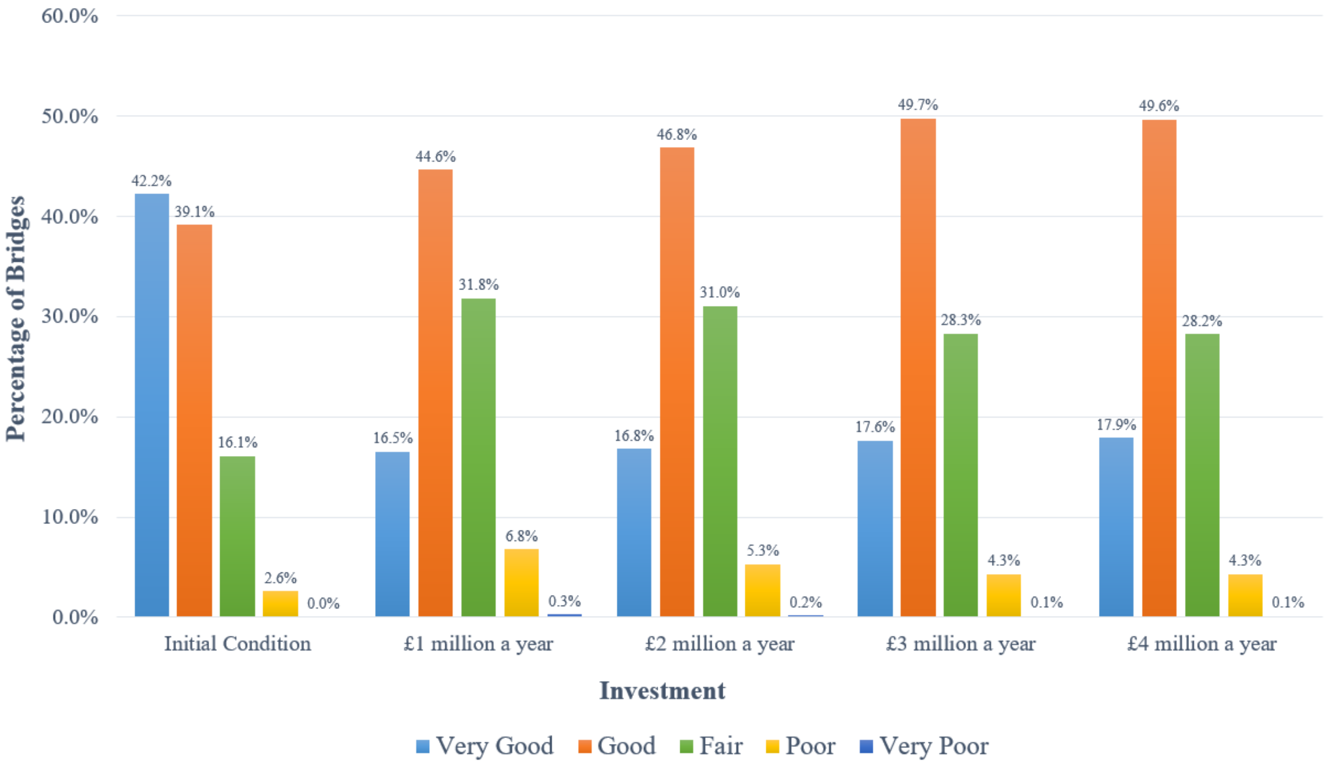


Figure 3: A bar chart showing how different investment levels effects the percentage of bridges in each condition rating group after a five year period.

Each bar represents a different investment with the first bar showing the initial condition of the bridges at the start of the five-year period, then each bar after that shows how £1 million, £2 million, £3 million or £4 million a year of investment over this time period affects the number of bridges in each category. Overall, the initial condition of the bridges shows that the majority of the bridges were in very good condition but after the five-year time period the majority of the bridges are in the good for every level of investment. However, looking at the good category we can see that as the investment increases so does the number of bridges in this group.

Throughout the different condition categories, we can see that there is a slight increase in the number of bridges in the very good and good categories with increased investment. However, when looking at the £3 and £4 million investments it is clear that the amount of bridges in the best condition categories is consistent. This shows that in the short term a larger investment doesn't necessarily equal a higher proportion of bridges in a better condition. But the next question that needs to be addressed is does this have the same impact in the long-term. Therefore, LAMP analysis over a 30-year period was used with 6 different investment amounts. The first four are £1 to £4 million as used previously. In addition to these, a figure of £3.5 million was used with a varying investment amount starting at £1 million where the amount invested increases every 5 years by £1 million i.e. year 1 to 5 had £1 million a year, years 6 to 10 had £2 million a year, up to years 26 to 30 having £5 million a year. Figure 4 shows the average condition of the bridges at the end of each year given the investment.

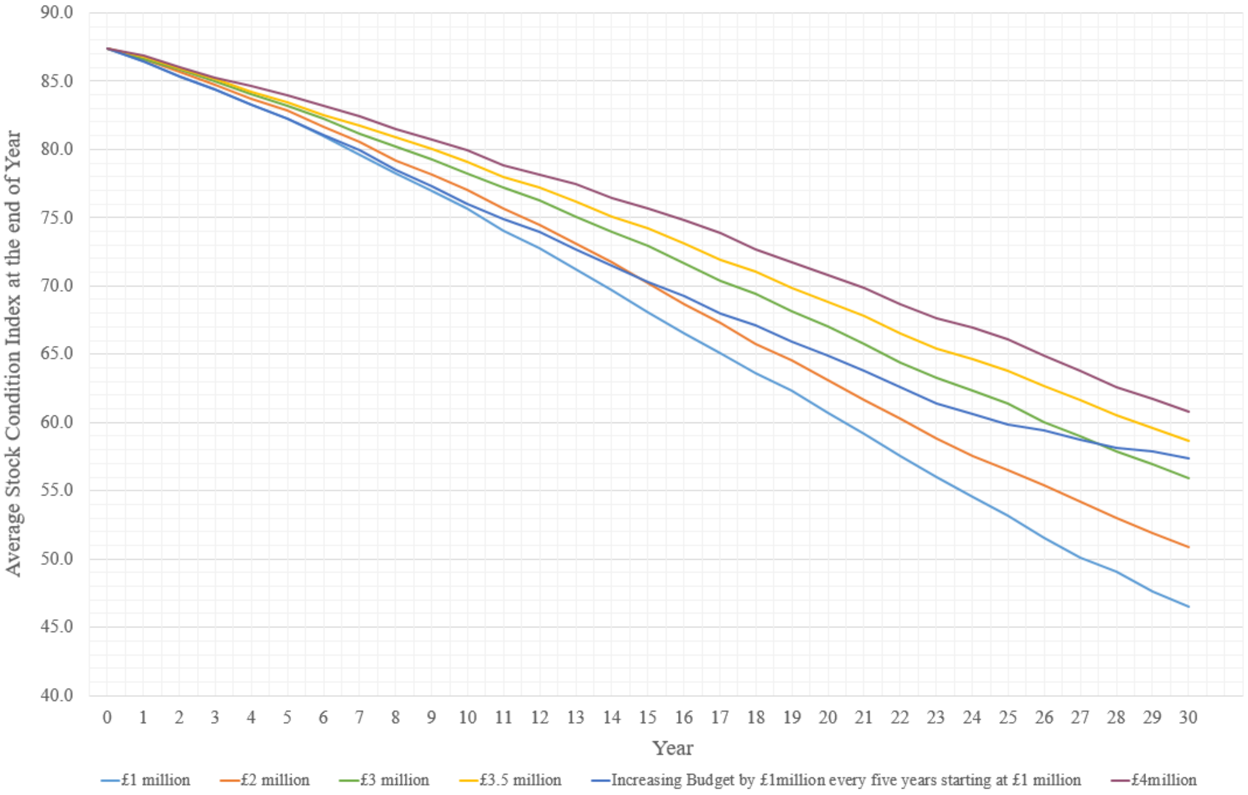


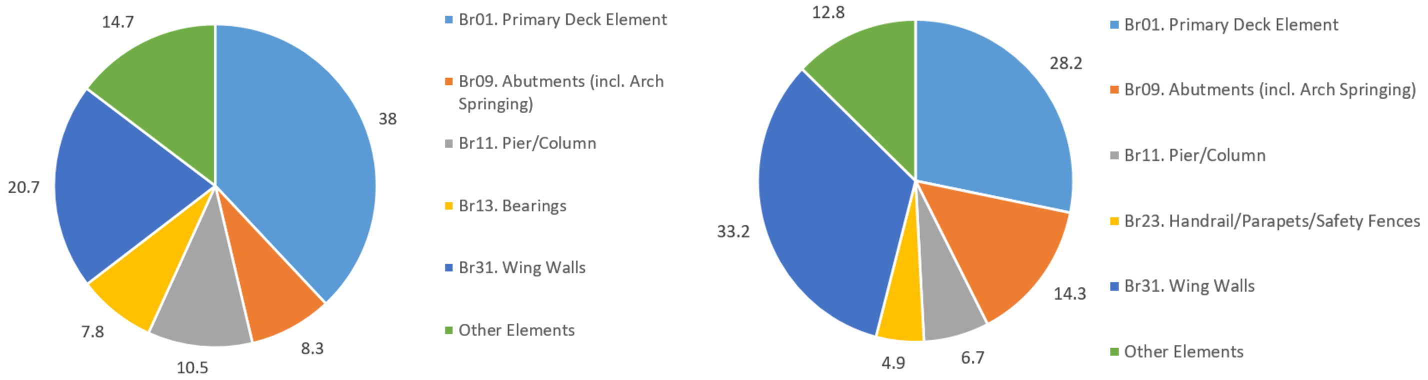
Figure 4: A line graph showing the results of the Long-term Asset Management Planning (LAMP) analysis where the average bridge stock condition at the end of the each year of maintenance work with varying maintenance budgets is displayed.

This graph shows that as the investment increases, the average bridge condition also increases in the long-term. Looking at the first 5 years, the lines are close together showing what we saw in the SAMP analysis in Figure 3. Looking at the £3.5 million a year investment and the increasing investment example, it is interesting to note that over the 30 years the same amount is invested (£130 million) however when this money is invested plays a key role in the future condition of the bridge stock. These lines show that even with the same amount of investment in the long-term, a consistent investment has a better effect on overall asset condition.

4.2 How the budget was spent – by element

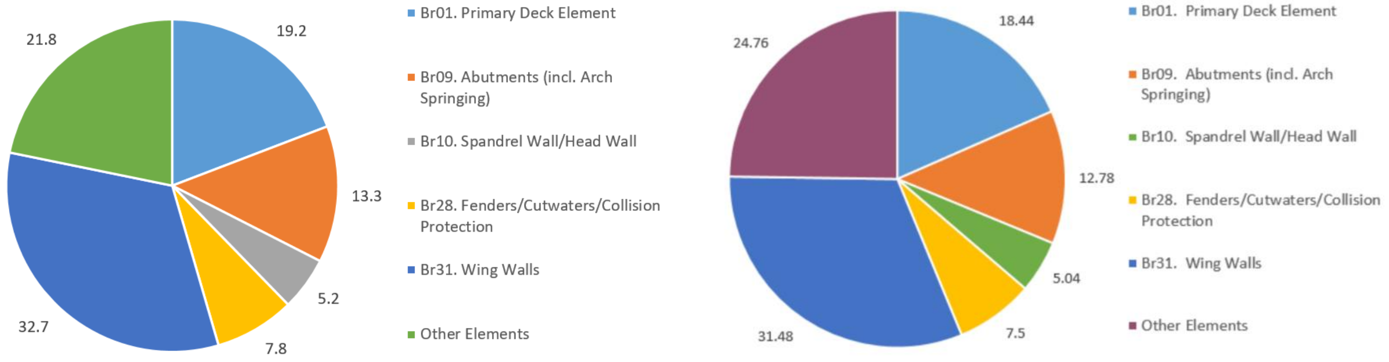
This section will investigate how the budget was spent in each of the four cases (the same as Section 4.1). Figure 5 shows which elements have been allocated the most capital for rehabilitation or replacement.

From the figure it is clear that the element which has been allocated the most in all four cases is element 31 which is the wing walls. This may be surprising as this element isn't deemed to be of very high importance to the bridge, however from further examination of the inspection information these elements have the worst extent and severity scores. In SAVI, elements that are in the worst condition take priority over the importance of the element.



(a) Budget of £1million a year

(b) Budget of £2 million a year



(c) £3 million a year

(d) £4 million a year

Figure 5: Pie charts showing the percentage of the budget spent on the rehabilitation/replacement of the elements. Each pie chart representing a different budget: (a) £1 million, (b) £2 million, (c) £3 million and (d) £4 million respectively.

4.3 Effect of change of element score

In order to consider the effect of engineering judgement on short term maintenance planning, this section will discuss two scenarios and compare them to the original data. First of all, take a £2 million budget a year and adjust the scores of the elements which are of very high importance. The score of these 8 elements was adjusted by increasing the extent and severity combination by one step, i.e. change a score of 3B to 3C, this is a minor change but this analysis will see how this effects the maintenance plan. For the original element data, 36.5% of the budget was spent on repair and replacement of elements of very high importance. For the adjusted scores this increased to 46.4%. This shows that a slight adjustment in scores at time of inspection has a large impact on how the budget is allocated to elements.

From Figure 5, it is clear that in all cases investigated, the majority of the budget was allocated to element 31 which is the wing walls. However, since this element is not of very high importance the adjusted scores show that the majority of the budget was re-allocated to element 1 which is the primary deck element.

5. Conclusion

This paper has provided an overview of the current literature around the area of maintenance prioritisation. It has focused on the SAVI software developed within the UK. A case study was then presented where bridges from the Southern division of DfI where taken as a representative sample. The several types of analysis that SAVI is capable of were applied to this data set and results were shown and discussed. First, under consideration was how the level of investment affects the short-term and long-term condition of bridges in the network. In the short-term, it showed that as investment increased so did the condition of the bridges. However, as higher levels of investment were reached the amount of bridges in the higher condition categories remained steady. In terms of the effect on the long-term condition, this study has shown that as the spend on maintenance increases so too does the condition with the biggest difference in condition observed in later years. an example was used to demonstrate the impact and importance of the time of the investment by considering an overall investment of £130 million over a 30-year period administered in different ways i.e. £3.5 million a year or an inconsistent investment where the amount increased by £1 million every 5 years. This has shown that a consistent investment had a impact on the condition than the alternative. Secondly, this study looked at how the budget was spent highlighting that the element that receives the most investment remains the same despite the changes in expenditure. This illustrates that a feature of SAVI is to focus on the elements which display the worse condition rather than the elements which are of higher importance to the bridge. Finally, the importance of inspector training was highlighted by implementing minor variations in condition records to reflect the impact of inspector bias. Therefore, consistent inspection records across the network is vital for accurate maintenance planning. This paper focused on the impact of various decisions on the maintenance plans for the bridge as a whole, a point of further work would be to investigate this further and look at the effect on individual elements.

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