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A Rational Framework for Post-Flood Road Network Condition Recovery

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Abstract: Heavy precipitation events can lead to widespread flooding and prolonged inundation of road pavement which in turn would weaken its structural performance and accelerate its deterioration. A major challenge for road authorities is to prepare a suitable and swift recovery programme to restore the road network in the event of flood-related disruptions. Furthermore, widespread damage caused by flooding and other competing needs for recovery resources imposes additional constraints. The situation is exacerbated by the uncertainty and complexity of the post-flood situation. To address this challenge, a methodology for the formulation of a strategic post-flood pavement recovery programme based on life cycle analysis is proposed in this paper. The resultant road conditions associated with the choice of work standards, the timing of implementation, as well as funding constraints were evaluated in a case study and a cost-effective recovery programme was formulated. The case study also demonstrated the use of output data to assist road administrations in strategic decision-making. This study serves as a guide for road administration to develop a post-disaster recovery programme and provides insights for further research into post-disaster management of infrastructure systems.

Keywords: Transport infrastructure; Transport management; flood, resilience, vulnerability, and contingency planning

1. Introduction

A safe and efficient road transport network is fundamental to connecting people, businesses and services and the associated infrastructure is often a country's largest publicly owned asset. However, due to the advent of more frequent and extreme weather events, road networks in many countries are being increasingly exposed to more frequent and higher impact floods that have a major effect on network serviceability (UN, 2009). The prolonged inundation of road pavement accelerates the deterioration of pavement condition and subsequently increases the maintenance costs (Amin et al., 2020). Research by Sultana et al. (2014) for example, has shown that a single flooding event can weaken the pavement structure by up to 50%. Flooding can also lead to substantial political, socio-economic, and environmental impacts (see Table 1). For example, at peak traffic times, flooding costs the UK economy around £100,000 per hour per major road affected (Pregnolato et al., 2017). It is therefore important that road authorities have the means to be able to provide and manage road networks that can maintain functionality during flooding and quickly recover afterwards (Li et al., 2019). To this end, the infrastructure emergency response is usually divided into two phases (Brandon, 2011):

- *Relief* concerns the re-establishment of the links within the road network, e.g., clearing debris and carrying out temporary repairs.
- *Recovery* considers the post-disaster condition of the road infrastructure and restoration of network serviceability. The recovery phase is often divided into an emergency recovery phase (ERP) and a comprehensive recovery phase (CRP) (Li et al., 2019). ERP prioritises recovering necessary connectivity for rescue operations and the basic needs of daily travel. CRP, on the other hand, deals with restoring the normal functionality and serviceability of the road network.

Table 1. Implications of flooding (Wang, 2018, Otero and Marti, 1995, Pregnolato et al., 2020)

Category	Implications of flooding
Road User	Road user vehicle-related costs (including greater fuel consumption and vehicle maintenance requirements) due to detours, reduced speed, poorer road conditions, queuing at the work zone, damage, and accidents (including loss of life). Road user travel time costs are associated with detours, waiting at work zones and reduced speeds.

Road Agency	Damage to highway grade, road pavement, street furniture, structures (e.g., drains and culverts) and other ancillary assets (e.g., electricity grid) necessitating maintenance or rehabilitation. Expenses associated with road closure/detours
Wider Economy	Loss of productivity Damage to private property Environmental damage

While there is a considerable volume of research on relief and short-term recovery (i.e. ERP), long-term recovery has received less attention (Çelik, 2016). Published studies on post-disaster recovery of infrastructure include the impact of weather (Martínez-Gomariz et al., 2018), resilience (Goldbeck et al., 2019, Li et al., 2019), recovery (Mallick et al., 2018, Amin et al., 2020, Kozin and Zhou, 1990), modelling and simulation of interdependent critical infrastructure systems (Ouyang, 2014), data-driven estimation of interdependencies (Monsalve and de la Llera, 2019), the restoration of networks (Monsalve and de la Llera, 2019) and climate risks to infrastructure (Dawson et al., 2018, Sasidharan and Torbaghan, 2021). A key objective, and challenge, for an effective post-flood road network recovery strategy is to prioritise the road maintenance appropriately to provide an acceptable level of road network serviceability while considering funding constraints (SCIRT, 2016). An optimised strategy involves consideration of the intervention choice, timing of intervention, sequence of treatment, target road condition, funding availability, and costs and benefits to stakeholders and the environment (see Table 1) (Robinson et al., 1998). These variables are interdependent. For example, an increase in funding can lead to better road conditions at an earlier time and provide increased benefit to the road user by lowering transport costs. There is also a need to consider the longer-term impacts of any road post-flood recovery plan on ongoing road performance and investment requirements and the consequential socio-economic impacts. There are, however, relatively few studies that consider all of these aspects (Goldbeck et al., 2019). For example, Khan et al. (2014) described an approach to identify post-flood maintenance and rehabilitation strategies by modelling the impact of floods on road pavement condition and Lu et al. (2020) investigated flood impact on road pavement performance. Work by both Amin et al. (2020) and, Chan and Wang (2020) focused on the resilience of road pavements from an engineering perspective. None of these studies considered the economic implications associated with flooding, nor the subsequent choice of appropriate maintenance strategies. Work by Kottayi et al. (2019) proposed an economic framework to support decisions regarding rehabilitation strategies that could be used by a road agency to counter the possible future impacts of climate change on road network deterioration. However, their approach did not explicitly address, flooding, the life cycle analysis of maintenance road use costs and benefits. On the other hand, Qiao et al. (2019) developed a life-cycle analysis approach to assess the road agency and road use costs associated with increased long-term road surface damage which might occur as a result of climate change impacts. However, they did not consider the immediate damage caused by flooding nor the associated maintenance strategies. There is therefore a need for approaches to support decision-making which can be used by road authorities to rationally identify short, medium (3-5 yrs.) and long (> 5 yrs.) term maintenance strategies for road networks subjected to flood damage.

To address these issues, the objectives of this paper are to develop and demonstrate, a theoretical framework for optimising post-disaster road condition recovery based on life cycle analysis considerations. The proposed framework allows road authorities, to prepare for, and determine, a post-flood optimum road network condition that considers budget constraints, the type and schedule of maintenance interventions and traffic levels. The proposed framework is illustrated through a case study of the Sioux Falls Road network located in South Dakota, USA.

2. Post-disaster recovery framework

The management of medium- and long-term road network condition recovery is challenging for road authorities as it requires consideration of several factors. These include network-wide damage, connectivity issues, accelerated pavement deterioration, the use of limited resources, an unknown scope of work, interface with other rebuilding programmes and the need to balance programme priorities (SCIRT, 2016). Such issues are dealt with as part of a road authority’s strategic and tactical asset management activities. Strategic asset management is concerned with long-term (> 5 years), network-wide decision making, whereas tactical asset management is to do with medium-term (3-5 years) planning at the road network to sub-network level (Robinson et al., 1998).

Maintenance needs are usually determined by considering both the functional performance of the road as seen by the road user and the engineering, or structural integrity, of the road pavement. The comparison of measured road conditions with predefined intervention levels indicates the shortfall in serviceability, or need for maintenance (Robinson et al., 1998). Pavement conditions can be measured in terms of road roughness, surface distress (e.g., rutting and cracking), structural capacity, pavement texture and friction (i.e., skid resistance). Amongst these, road roughness can be considered as a collective assessment of the pavement condition and is also the major determinant of vehicle operating costs (Robinson et al., 1998). Typically, road roughness values are observed to increase significantly following flooding (Khan et al., 2014, Sultana et al., 2016). Although some guidelines are provided to assist with the management of recovery operations, the uncertainty and complexity of the task often result in poor decision-making (ASEAN, 2020, Crown, 2018). The economic implications of maintenance and rehabilitation strategies however are rarely considered. Usually, one of three road recovery approaches, or strategies, are adopted. Namely responsive, build-back better or return to minimum service (Robinson et al., 1998, Lloyd-Jones et al., 2016, MacAskill, 2014). The strategies are shown schematically in Figure 1 and described below.

- *Responsive*: This is the most common practice in post-disaster road recovery whereby decisions are based on the defectiveness of the roads in the affected network (Robinson et al., 1998). Under this approach, improvement works are sequenced based on the road condition at the time of assessment. Since the recovery programme is not associated with any risk analysis or long-term plans, utilisation of resources is thus not maximised. Such condition-based prioritisation methods, however, usually lead to budget increases or further deterioration of road conditions (Robinson et al., 1998).
- *Build-back better*: In this strategy, damaged roads are re-constructed or sometimes realigned in the recovery stage (UN, 2015, World Bank, 2015). This approach can often reduce future vulnerability by providing re-constructed roads to a better standard and which are less susceptible to damage by future flooding. However, while network serviceability is improved rapidly, this approach demands high initial resources and long-term funding commitment. In some cases, short-

term recovery needs are solved but at the expense of long-term indebtedness (Lloyd-Jones et al., 2016).

- *Return to minimum service*: This approach focuses on returning the whole network to a minimum level of service and defers any substantial re-construction to a later stage. The approach aims to balance the use of limited funds, improve network resilience, allow funding to be released for other pressing needs and provide time for planning recovery activities (MacAskill, 2014). However, the approach requires comprehensive planning and thorough integration with a long-term recovery plan.

The appropriate choice of strategy depends on the amount and type of damage the flooding has caused to the road network, the budget available and the local socio-economic environment. To enable such factors to be considered within the management and selection of recovery operations we propose a rational approach based on life cycle analysis (LCA).

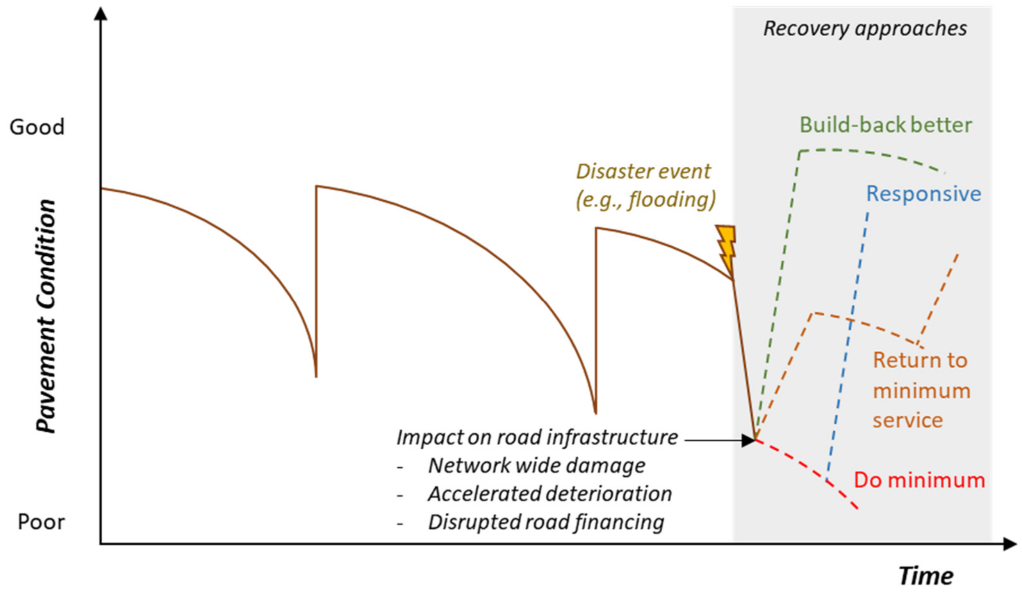


Figure 1. Common post-disaster road recovery approaches.

2.1. Life cycle analysis

The proposed framework, summarised in Figure 2, advocates the use of a life cycle analysis (LCA) approach to compare the economic implications of undertaking post-disaster road recovery strategies, such as those outlined above so that the most viable can be selected. The LCA process can be used to inform a road authority's policy and to support strategic and tactical road asset management (Robinson et al., 1998). At the strategic planning level of road asset management, LCA is used to inform policy by identifying the maintenance strategies and associated maintenance standards required to achieve desired performance targets, and the budget required. In such an approach, monies spent on reconstruction and maintenance are treated as investments, with financial returns, and the impacts of maintenance activities on the life of the assets and the resulting cost streams are considered. Recovery strategies are compared, over a given period of analysis, using economic decision rules that consider the cost and benefits accruing from the strategies. The most appropriate strategy is that with the greatest return on investment. Strategic planning requires a life cycle analysis of the cost of construction, maintenance, and the road use across the network. At the tactical level of road asset management, the measured conditions of individual road sections are compared with the selected maintenance standards to identify the required maintenance works. Economic decision rules are then used to prioritise the identified road sections for maintenance.

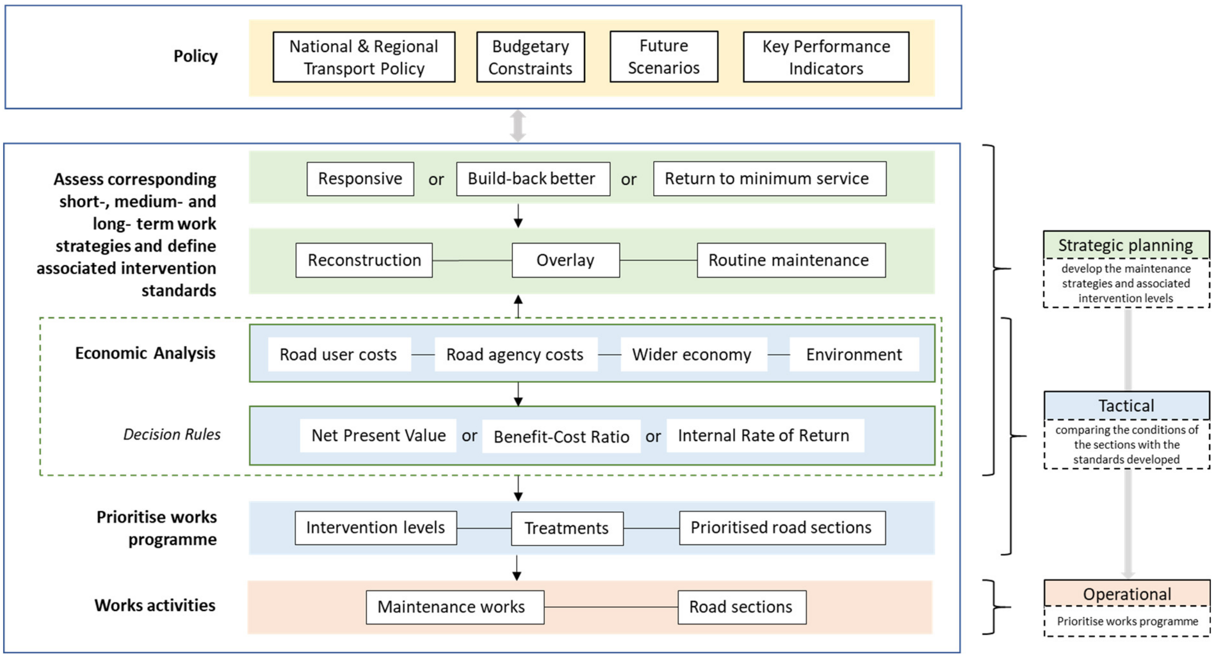


Figure 2. The theoretical framework for identifying the most appropriate post-disaster road recovery programme is based on economic considerations.

LCA is potentially a complex process and for large road networks, many investment options usually need to be considered. Therefore, the use of computer-based models is usually necessary. Several such models are available and include the Roads Economic Decision Model (RED) (Archondo-Callao, 1999), the New Approach to Transport Appraisal (NATA) (DfT, 2009), the Life-Cycle Cost Analysis Primer by the US Department of Transportation (FHWA, 2015), Deighton Total Infrastructure Management System (dTIMS) (Henning et al., 2006) and the Highway Development and Management Model (HDM-4) (Schutte, 2008). These tools are similar in that they consider the costs to the road authority of building a road to an initial standard and the ongoing maintenance costs required to maintain the road to prescribed standards and the costs to a road user of using the road maintained to these standards. Of these, HDM-4 is the most widely used and accepted model worldwide and indeed the models used within RED and dTIMS are the HDM-4 models (Robinson et al., 1998). HDM-4 is the World Bank's de facto standard for road investment appraisal and is used by potential donor recipients, to demonstrate the scale of returns on road investment (UKCDR, 2021). The use of HDM-4 worldwide is widely reported in the academic literature for a variety of applications. These include the strategic analysis of road investment in Bosnia and Herzegovina (Čutura et al., 2016), the UK (Odoki et al., 2013a) and Morocco (Bannour et al., 2019); assessing the impact of climate on road maintenance requirements in Australia (Chai et al., 2014) and the UK (Anyala, 2011); and to assess both national road networks (Deori et al., 2018, Jorge and Ferreira, 2012) in India and Portugal and, local ones (Thube, 2013, Odoki et al., 2013a) in India, Indonesia and the UK.

2.2. Economic decision rules

As part of the LCA approach, several decision rules could be used to evaluate the economic benefits of road investment strategies. The three most commonly used ones are the Net Present Value (NPV), the Benefit-Cost Ratio (BCR) and the Internal Rate of Return (IRR) (Robinson et al., 1998). NPV is the most widely used decision rule and is the difference between the discounted benefits and costs over the analysis period. It is defined as follows (Robinson et al., 1998):

$$NPV = \sum_{n=0}^{N} \frac{B_n - C_n}{\left(1+\left(\frac{r}{100}\right)\right)^n} \tag{1}$$

Where N is the number of years of analysis, B_n is the benefits accruing in year n, C_n is the costs accruing in year n, and r is the discount rate.

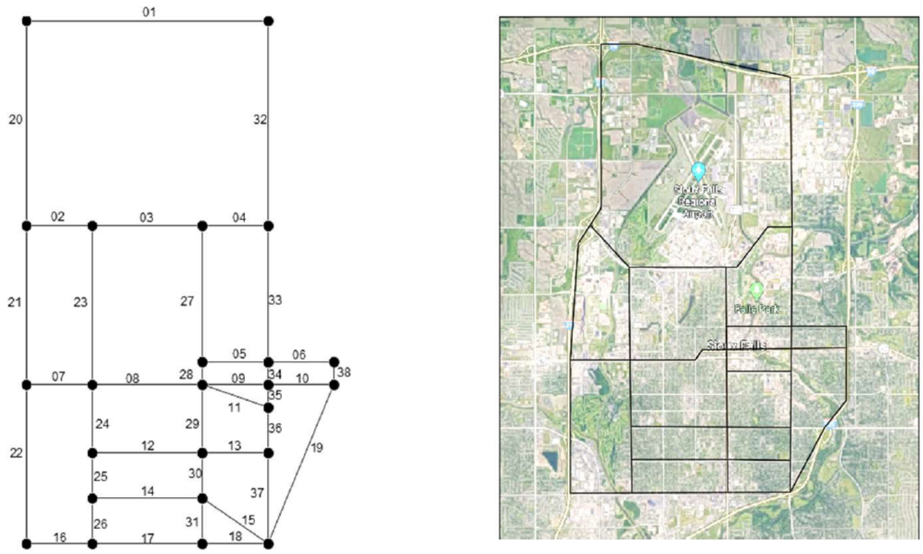
NPV measures the economic worth of an investment and a positive NPV suggests that the investment is justified economically. A variation of NPV, i.e., the NPV/cost ratio, is sometimes referred to the NPV as a decision rule since a large investment will usually have a larger NPV than a smaller one and would therefore always be chosen. This can be problematic when investment options are compared under budget constraints. The NPV/cost ratio, on the other hand, can be considered to be the magnitude of the return expected per unit of investment and is, therefore, a measure of the efficiency of an investment (Robinson et al., 1998). Typically when a government aims to maximise return on capital the NPV measure is adopted, but when there are several alternative investments to consider under budget constraints, NPV/cost is usually used (Robinson et al., 1998). The BCR is the ratio of discounted benefits and costs accruing over a given period of analysis and is defined via equation 2 (Robinson et al., 1998, Kim et al., 2021). The investment with the highest BCR, amongst those considered, should be chosen. The IRR is the discount rate at which the present value of benefits and costs are equal (Sasidharan et al., 2020), i.e. NPV = 0 and is determined by solving the equation 3 for *r*:

$$BCR = \sum_{i=0}^{n-1} \frac{b_i/c_i}{\left(1+\left(\frac{r}{100}\right)\right)^i} \tag{2}$$

$$IRR = \sum_{i=0}^{n-1} \frac{b_i-c_i}{\left(1+\left(\frac{r}{100}\right)\right)^i} = 0 \tag{3}$$

3. Case study

To demonstrate the application of the proposed approach, a road network based on the classical Sioux Falls Road network located in South Dakota, USA was used (Stabler, 2016). The central part of the city's road network is designed as a grid system and most residents of Sioux Falls travel and commute by car. The chosen network contains 38 road links with a total length of approximately 80 km (see Figure 3). The response to a significant flooding event in 2019 that resulted in prolonged closures of the interstate networks was modelled.



(**a**) (**b**)

Figure 3. Comparison of (a) model network and (b) Sioux Falls map

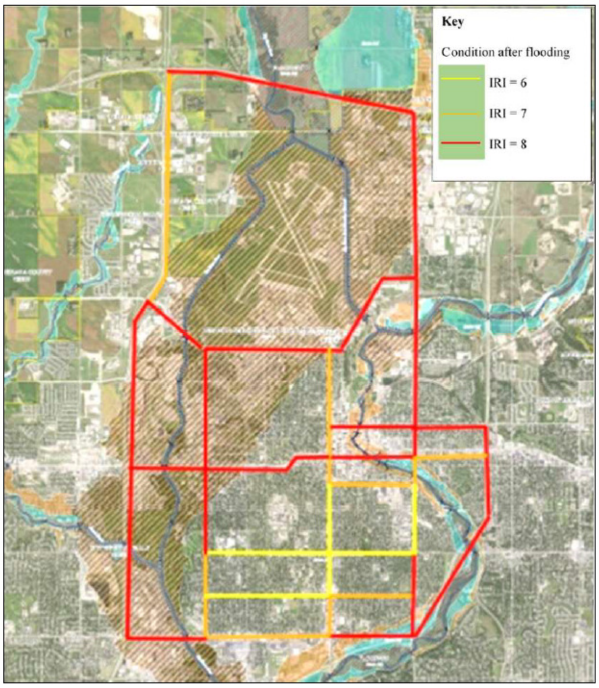


Figure 4. Post-flooding Road Condition, source (FEMA, 2020)

3.1. LCA using HDM-4

HDM-4 was chosen for this study to carry out the LCA given its wide acceptance and use for similar purposes worldwide (see Section 2.1). The HDM-4 program contains four models that it uses to predict the life cycle of road pavement performance and the ensuing road use costs as a function of user-defined road maintenance/improvement standards (or strategies). The models are associated with road deterioration (RD), road works effects (RWE), road user effects (RUE) and socio-economic and environmental effects (SEE). A schematic of the HDM-4 LCA process incorporating the models, together with a summary of the required inputs is shown in Figure 5. HDM-4 calculates the economic benefit of each strategy in terms of the economic decision rules described in Section 2.2.

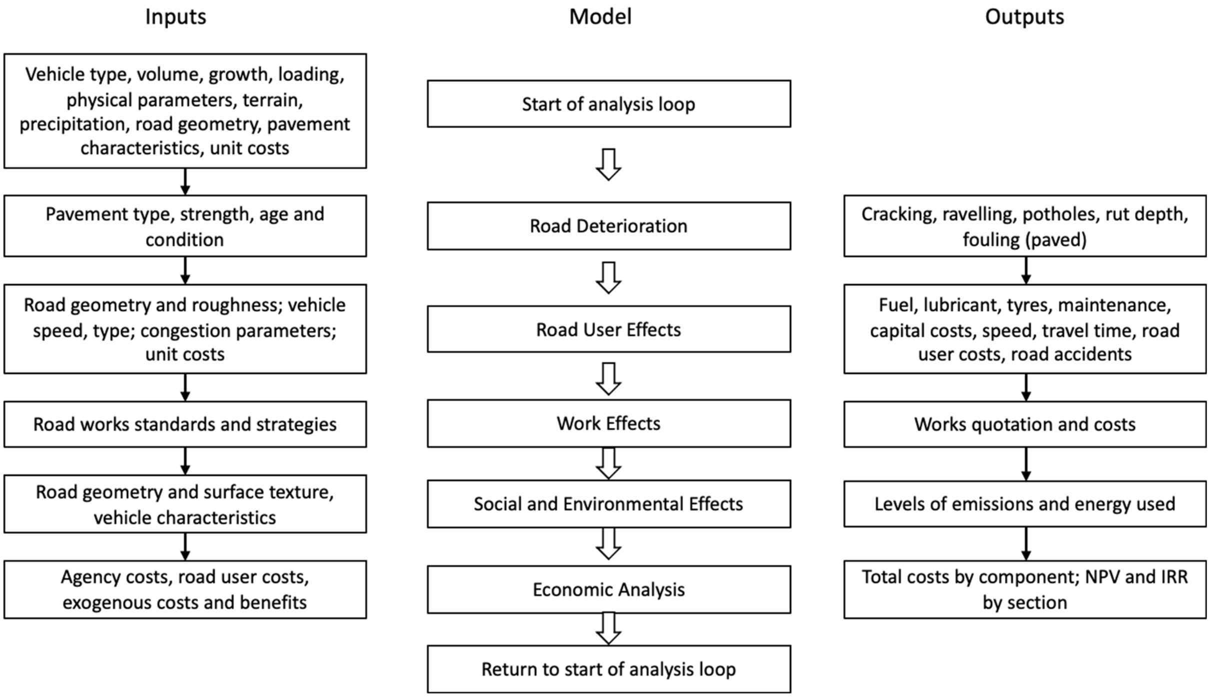


Figure 5. Life cycle analysis by HDM-4, source (Odoki and Kerali, 2006).

The RD model consists of various configurable equations which simulate the deterioration of a large variety of road pavement types. The equations account for the major factors which influence deterioration, including traffic loading, the initial structural design of the road, material type, climate, drainage, and maintenance. For each road pavement type, there are separate equations to account for the main distress types, namely cracking, edge wear, potholes, ravelling, roughness, rutting and skid resistance. RWE is associated with determining the effect of the chosen maintenance and rehabilitation strategies on road conditions during a road section’s life cycle. RUE concerns the impact of these strategies on-road use costs (see Table S1). Specifically, road user costs are determined from computed average road roughness (see Section 2) and traffic levels. Road user costs are made up of vehicle operation costs (VOCs), travel time costs and costs to the economy of road accidents. VOCs include fuel consumption, tyre wear, oil, spare parts, depreciation, interest, crew hours and overheads. Travel time costs are associated with the value of passenger time and cargo holding, and delay times associated with road works. Road accident costs include those to do with the loss of life, injury to road users, and damage to vehicles and other roadside objects. The SEE model is associated with energy consumption and vehicle emissions.

3.2. Optimisation

HDM-4 uses an optimisation process to determine, under budget constraints, the optimal investment (i.e., maintenance/renewal) strategy for each road section. This is achieved by first determining the NPVs for each alternative strategy for each road section and then searching for the combination of all such strategies that maximise the economic benefit under the given network budget constraint (Kim et al., 2021). For this work, HDM-4's incremental benefit/cost ranking approach was used for the optimisation. The incremental NPV/cost is defined as (Weather Atlas, 2020):

$$E_{ji} = \left[\frac{\left(V_{NP_j} - V_{NP_i}\right)}{\left(C_j\right)}\right] \qquad (4)$$

where E_{ji} is the incremental NPV/cost ratio, *VNPj* is the net present value of the selected investment alternative *j*, *VNPi* is the net present value of the designated base alternative *i* and *Cj* is the capital cost of the selected investment alternative *j.*

HDM-4's incremental benefit/cost approach ranks the alternative investment strategies for each road section in the road network in order of the largest E_{ji}. The method then chooses the strategies with successively lower incremental NPV/cost ratios, ensuring that no more than one alternative per road section is chosen. During the process, the algorithm ensures that the cost of the chosen strategy does not exceed the remaining budget. If the cost of the strategy causes the budget to be exceeded, it is not considered. The process continues until the budget is exhausted. Further details of the approach can be found in Weather Atlas (2020).

3.3. HDM4 configuration and calibration

To improve the accuracy of the default relationships used in the RD, RWE, RUE and SEE models, the models can be configured and calibrated to local conditions (Bennett and Paterson, 2000).

Configuration

For this work, configuration involved defining the input data used by HDM-4 for strategic analysis. To this end, all road sections were assumed to be constructed of asphalt mix on asphalt pavement and the initial values of road condition (roughness and structural condition) were based on research which suggests that the condition of the road following a flood of that modelled in Sioux Falls may cause the condition of the roads in the vicinity to vary between poor to very poor, depending on the level of occurred flooding. The extent of flooding was estimated from a flood risk map obtained from the US Federal Emergency Management Agency (FEMA) (FEMA, 2020) (see Figure 4). Accordingly, and using a widely accepted system for the categorisation of road roughness according to road condition (Robinson et al., 1998), values of the roughness between 6m/km (poor road condition) and 8m/km (very poor road condition) were assigned to road sections in the network (see Figure 4). As a result, the network would need to be reconstructed. The quality of road construction quality before the flood event was assumed to be good.

Road classes and geometric characteristics were taken from (GOOGLE MAP, 2020, UKCDR, 2021) and climate characteristics represent the humid continental climate with frequent thunderstorms experienced by Sioux Falls (Weather Atlas, 2020). Traffic flow patterns and associated speed–flow relationships were calculated using data from (SIUOXFALLS.ORG, 2020, South Dakota DOT, 2020).

Calibration

Three levels of calibration are recommended, depending on the purpose of the HDM-4 analysis (Bennett and Paterson, 2000).

- *Level 1* is to do with determining the model input values which most affect the model outputs. Usually, this involves utilising the default values in HDM-4 together with expert opinion and data obtained from desk studies. Level 1 calibration is suitable for strategic analysis, such as that described herein, and was therefore used entirely for all input parameters.

- *Level 2* calibration uses data from the field to tailor to the local environment the predictive relationships which have the greatest influence on model outputs.
- *Level 3* concerns major field surveys allied to experiments that refine the existing predictive relationships or formulate new ones.

All road sections were assumed to be constructed of asphalt mix on asphalt pavement and the default RD model equations and associated calibration factors for this type of road pavement construction were used and calibrated to consider the local humid continental climate. Similarly, for the calibration of the RWE model equations, the study used HDM-4's default equations, calibration values and road condition improvement parameters that are appropriate for the selected maintenance and rehabilitation strategies, when applied to an asphalt road pavement (see Table S2).

As far as the RUE model is concerned, the main purpose was to provide a representative number and mix of vehicle types so that HDM-4's vehicle operating cost models could be appropriately calibrated. The focus was given to the calibration of models associated with capital costs, fuel consumption, vehicle maintenance and speeds. To this end, the vehicle fleet was based on the National Fleet template provided in the HDM-4 programme (South Dakota DOT, 2020), updated and augmented by data given by Morosiuk et al. (2004). These data were also used to inform HDM-4's SEE model. The values used are given in Table S1. Further details of the HDM-4 models and their configuration and calibration can be found in Odoki and Kerali (2006), Bennett and Paterson (2000), Morosiuk et al. (2004), Bennett and Greenwood (2004).

3.4. Investment strategies

The works standards shown in Table S3 were defined to represent the post-flood recovery stage and the steady-state maintenance phases respectively. The standards are based on those suggested by PIARC (2006), Odoki et al. (2013b), Evdorides et al. (2012). It should be noted that two reconstruction standards were analysed. These relate to roads carrying different levels of traffic (i.e., a thicker reconstructed road is proposed for roads carrying 30,000 vehicles per day compared to those carrying less than this amount). In both cases, following reconstruction, the roughness of a road was assumed to return to 2 m/km (i.e., the road condition was assumed to be very good (Robinson et al., 1998)).

The life cycle analysis was carried out for 15 years following the occurrence of a flooding event. Given the resource availability, severity and damage associated with the flooding event, the first five years were considered to be a suitable timeframe for carrying out post-flood recovery works (to findings of Evdorides et al. (2012)). Thereafter, it was assumed that typical maintenance policies would be used for the remaining 10 years of the analysis period.

3.5. Intervention strategies

To compare different recovery approaches 16 strategies were considered, as summarised in Table S3. Each strategy considered the need for reconstruction to occur once within the five-year recovery period. The purpose of specifying the various timing alternatives was to provide sufficient options so that where the ideal improvement/maintenance work could not be implemented in the year due to budget constraints, there would be a possibility for the intervention option to be selected in another year (Morosiuk et al., 2006).

3.6. Budget constraints

To simulate possible post-flooding resource limitations, the implications of budget constraints were also analysed using four budget scenarios shown in Table S4. For a given budget constraint and the intervention options defined above, HDM-4 can determine an optimised works programme (or section alternative) for each road section using the optimisation process described in Section 3.2. Under the unconstrained budget scenario (S0), the capital expenditure in the 1st year was computed using HDM-4 to be US$145M, indicating a surge in funding requirement in the first year. Based on this, three additional budget scenarios were developed. Budget scenario S1 simulated a high funding condition, with a budget constraint of US$60M per year throughout the 5-year recovery stage (i.e., approximately 40% of the unconstrained first-year budget). Budget scenario S2 was a medium funding scenario, with an annual budget constraint during the recovery stage of US$40M (i.e., two-thirds of the annual constraint of S1). Budget scenario S3 simulated a low funding scenario but with the provision of a national government, or international aid, during the 1st year of US$ 40M. The budget constraint for the remaining years was set at US$ 20M (i.e., one-third of the annual ceiling for S1). For all scenarios, an unconstrained budget was adopted for the 10 years following the post-disaster recovery period.

4. Results

Based on the LCA performed using HDM-4, the effects of the intervention strategies (see Table S5) are summarised in Figure 5. It can be observed that the timing of the interventions had a great influence on road conditions in the form of roughness. For example, it may be seen from Figure 5 that if reconstruction was deferred by one year without a thin overlay, the average IRI of the network would increase to about 9 m/km in year two, and 12m/km in year five with consequential increases in road use costs by approximately 8.3%. These IRI values represent very poor road conditions (Múčka, 2017). On the other hand, if a temporary thin overlay was applied in the first year, the average IRI could be maintained at 6 m/km (i.e., fair condition) until year five.

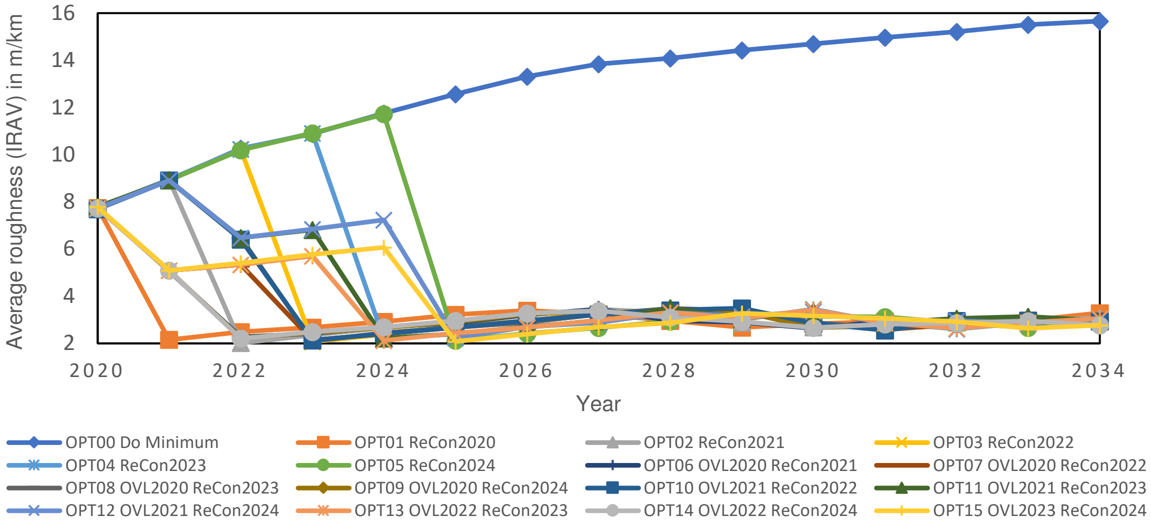


Figure 5. Effect of intervention options on road roughness weighted by section length

The optimum section alternatives were determined by HDM-4 based on the calculated incremental NPV/cost ratio, subject to the pre-defined budget constraints (Morosiuk et al., 2006). For illustration, the chosen alternative scenarios for road sections 11 to 20 are presented in Table S5. It can be observed that, when funding was abundant, the economic analysis would initiate reconstruction for road sections with more severe damage and higher traffic volumes (i.e., AADT). However, when the budget constraints are more stringent, the HDM-4 suggests temporary improvement and deferred reconstruction for the damaged road sections.

Figure 6 shows the average network road condition (in terms of road roughness) predicted by HDM-4 following work programme optimisation for each of the four budget scenarios. From Figure 6, as expected, the unconstrained budget scenario would result in the most rapid improvement of road condition, with average network roughness decreasing from approximately 8 m/km to approximately 2 m/km (i.e., from poor to very good condition) after the first year. The high budget scenario would result in an average roughness of less than 4 m/km (fair/good condition) occurring after two years; while the low budget scenario would result in the same average condition being achieved after three years. It can also be seen that with extra funding in the first year, the time required to reach an IRI of 4m/km could be reduced to one year after the flooding event.

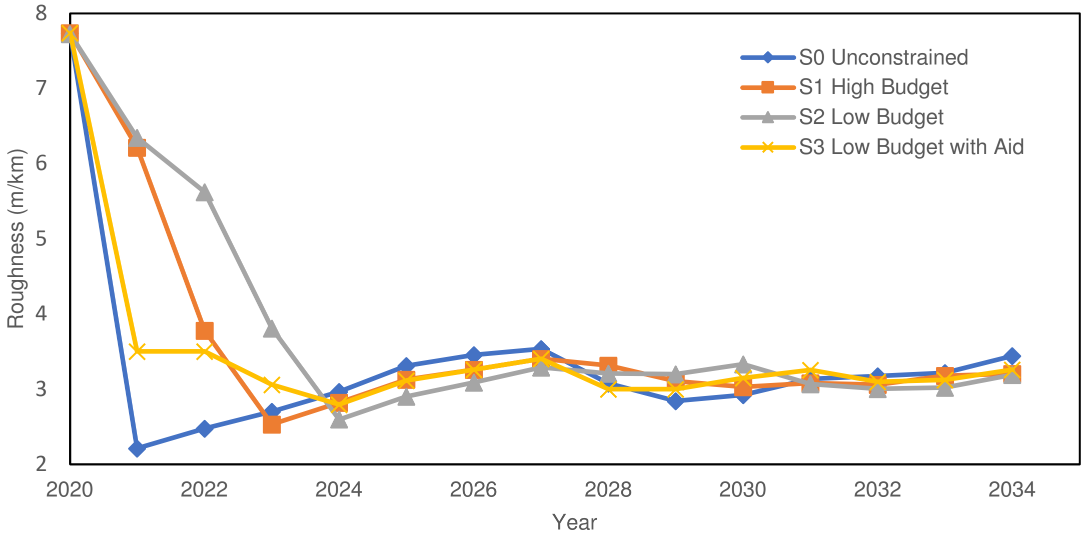


Figure 6. Average network roughness based on budget scenarios, weighted by section length

Figure 7 shows the predicted road roughness for the four budget scenarios for each road section in the network at the end of 2020, 2022 and 2024. These key indicators and diagrams obtained from the analysis could help the road authorities to determine the best recovery plan (e.g., which road sections within the network should be prioritised for maintenance investments and to what level should they be maintained). The road agency costs associated with reconstruction and maintenance for each of the four budget scenarios are shown in Figure 8. This type of information could be particularly useful for a road agency to help to develop an affordable recovery programme in the event of significant flooding where there is likely to be network-wide damage and a very large demand for funding for various recovery operations and relief efforts.

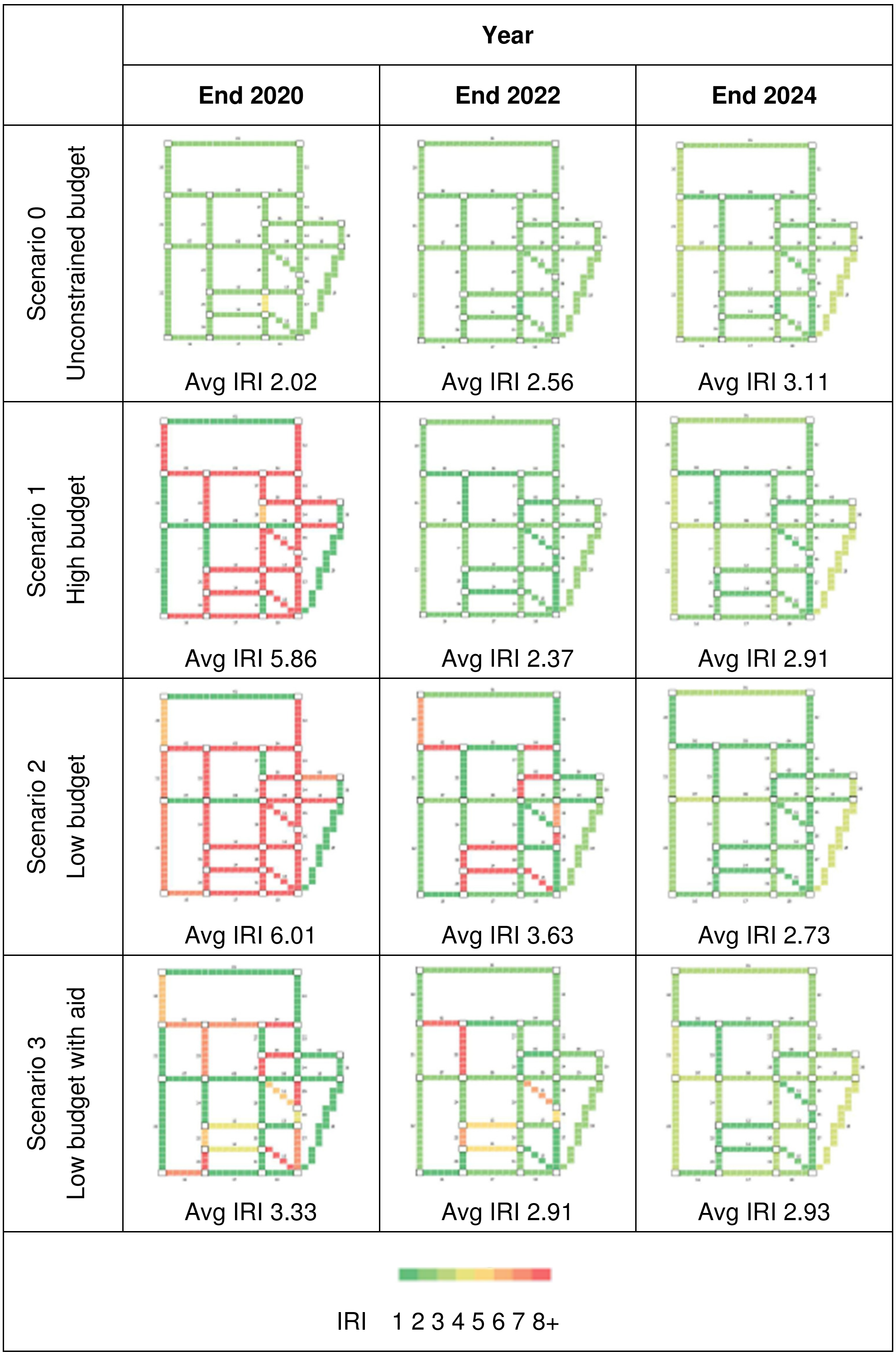


Figure 7. Network conditions for different budget scenarios

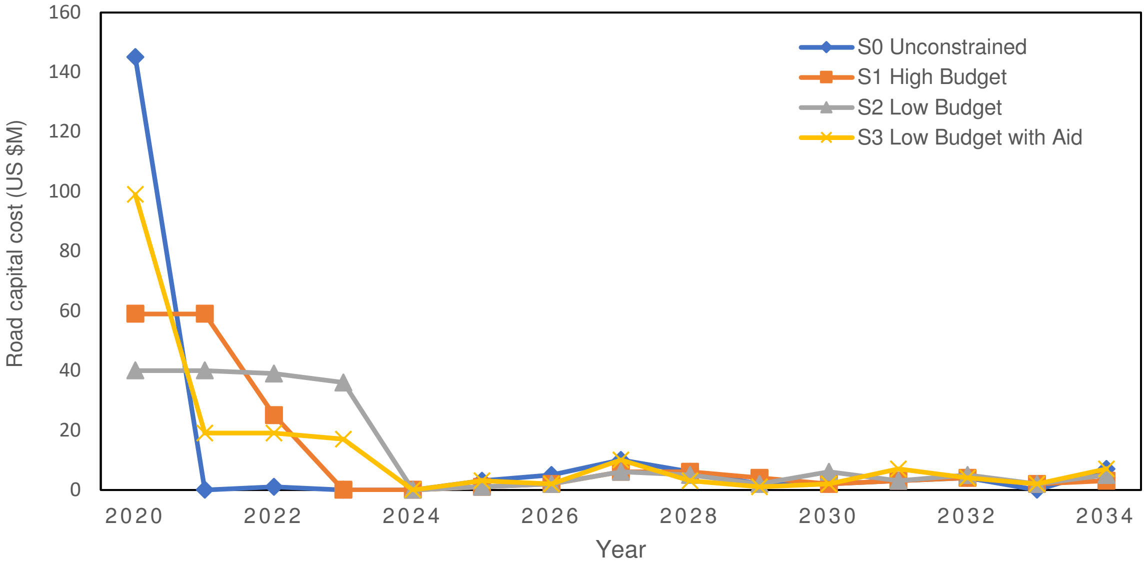


Figure 8. Capital cost stream for different budget scenarios

5. Discussion

The paper proposed an approach which can be used by a road agency to facilitate the judicious selection of road reconstruction and maintenance strategies within a post-flood road pavement recovery programme. The approach is based on life cycle costs analysis that considers road agency and road user costs and benefits. When applied to a case study on the Sioux Falls Road network, based on the optimum section alternatives, it was observed that immediate reconstruction was the optimum intervention option for a majority of road sections. For other road sections, deferred reconstruction, or an overlay, were also appropriate, especially under budget constraints. The traditional approach usually considers that immediate reconstruction (build back better) is the best approach, however, this study revealed that there is not necessarily a simple universal best solution. Rather, the strategy for each road section should be assessed based on its characteristics, and the needs of the road agency and road user, with due consideration of the constraints and conditions for determining the optimum intervention option.

It was also observed that, for some road sections, the option with the highest relative NPV was not the same as the one with the highest incremental NPV/cost ratio. An inspection of the cost streams for these sections revealed that, while an intervention option had a high NPV, the capital input (i.e., road agency cost) for that option also tended to be high. As mentioned above, in these circumstances the

NPV/Cost ratio is a better measure of investment efficiency. This observation demonstrates that choosing an appropriate economic indicator is important for proper prioritization of the invention options.

A summary of the key indicators for the case study is presented in Table S6. Budget scenario S0 provided the largest decrease in IRI in the first year. However, this required a surge of funding which could be difficult to achieve in practice. On the other hand, budget scenario S3 presented a more feasible recovery option. Based on these indicators, a road administration would be able to choose a recovery approach that was f suited to its budgetary circumstances.

The reliability of the study relies on accurate input data, such as the initial road condition, traffic volume, discount rate, road user costs and road agency costs. These are all important in the modelling process for the proper computation of the economic indicators. For example, traffic volume data will have a significant impact on the analysis results because HDM-4 employs road deterioration models which rely on traffic data for predicting the magnitude of individual wheel loads and the number of times they are applied and thereby future road performance.

The approach described in this paper can be used by senior decision-makers as an aid to develop policy and associated procedures for the strategic (long-term) management of the road network. The advocated approach allows appropriate consideration of the longer-term needs of the road network to the maximum benefit of all stakeholders and the environment. In regions prone to flooding, the approach enables the strategic planning estimates of road investment expenditure to be made which allows for improvements to the road network at the same time as making provision for future flooding events. Furthermore, the approach can inform post-flood recovery policy concerning road network resilience, the distribution of budgets to road sections within the road network and the allocation of resources amongst other types of damaged infrastructure (such as buildings). In the case of network resilience, policies can be adopted which utilise LCAs to gauge whether the road network has sufficient resilience in the event of routes being made impassable due to flooding. Concerning the allocation of resources amongst individual road sections, the most approach road maintenance and reconstruction strategies can be determined according to the requirements of the road agency (e.g. a responsive approach, return to minimum levels of service or build back better) (UNDP, 2011). Whilst this research has focused on the road pavement, as it is usually the costliest road asset, the framework could be extended to develop recovery strategies that consider multiple road asset types (e.g., street lighting, structures, traffic control systems). A number of approaches are possible. At the strategic level, a road agency might consider addressing asset types separately and prioritise asset types for intervention. In this case, an LCA could be carried out on an asset-by-asset basis. For example, the supply of lighting may be considered the greatest priority amongst all asset types. An alternative approach would be to group all the assets within a road section together when carrying out an analysis and to prioritise the maintenance of road sections, rather than just the asset type. This might be problematic as it would require consideration of the different rates of deterioration, costs, and benefits of the individual asset types within a road section to be considered. In the case of flooding, addressing road drainage issues is of fundamental importance, and it would therefore be sensible to address drainage issues at the same time as carriageway maintenance. Since most drainage maintenance is carried out routinely, it would be relatively straightforward to include the costs and benefits of improved drainage within an economic analysis that also included the road pavement.

The theoretical framework proposed within this paper can also be suitably adapted to determine optimal intervention programs for other linear infrastructure networks (e.g., railways and utilities), and for other road-related infrastructure such as street lighting, drainage, retaining walls, and traffic control systems. The rational and transparent process advocated allows the rationale for such policies to be conveyed to stakeholders clearly and transparently, thereby securing support for the policy.

5.1. Limitations and recommendations for further research

The case study serves as an illustration of the application of LCA in the post-flood recovery programme formulation. In the case study, a homogenous road section was assumed to stretch from node to node, including all traffic lanes. The traffic volume was assumed to be based on a pre-flood traffic survey with a constant growth factor. Traffic volumes on road sections however can change dynamically according to network accessibility. In future studies, components of network accessibility such as connection, movement, cost, time and comfort could be assessed (Brans et al., 1981). The effect of traffic diverting to other roads within a road network, or other modes of transport such as rail or water transport could also usefully be further investigated (Evdorides et al., 2012). For example, the closure of the Forth Road Bridge in the UK due to storms resulted in 42% of car users and 46% of bus users shifting to railways to travel for work, and additional rail services were introduced to account for the traffic demand (Sasidharan et al., 2021). The impact on the economic analysis of the potential for traffic to divert to another route, which might occur on road networks with multiple route alternatives could be addressed using appropriate traffic models. Such models can be used to replicate the ability of a road user to choose a different route (see for example (Jamous and Balijepalli, 2018)). This would allow for a better estimate of the traffic using a particular road section at any given time, and therefore improved estimates of road-induced deterioration on the network and associated road use costs.

Benefits and costs that are not generally not quantified in monetary terms, e.g. road safety, better social welfare, environmental effects, and traffic re-routing (Odoki and Kerali, 2006), were not included in the case study due to the unavailability of data which allow for the associated costs and benefits to be quantified.

Resource saved through deferral of road reconstruction allows funding to be invested in improving the resilience of the road network, such as upgrading drainage systems or providing improved flood defences.

It is recognised that an employed strategy can provide wider economic benefits which were not considered in this work. i.e., those other than the direct benefits associated with reductions in road use costs. These benefits include the socio-economic impact on the wider community of business development opportunities, access to education, health facilities and access to employment (John Hine et al., 2019). Such benefits and costs are particularly pertinent where network redundancy, or resilience, is low. Although the wider impact economic impacts of road investment are well known, often they are problematic to quantify in monetary terms and are therefore not included in traditional road investment appraisal approaches. More often they are included in multi-criteria analysis approaches to investment appraisal (Moran et al., 2017). Further work is therefore required to enable such benefits to be quantified in monetary terms so that they can be considered in a road investment appraisal together with the direct and indirect costs and benefits of maintenance activities considered herein.

It is also recognised that economic benefits can be gained from improving the resilience of exposed transport infrastructure (Koks et al., 2019) and studies could usefully be undertaken to explore methodologies to quantify the costs and benefits related to improving the resilience of road networks, particularly in disaster-prone areas.

6. Conclusion

Road surface flooding is a major challenge faced by road authorities worldwide as it can result in severe pavement damage, accelerated deterioration and an increase in maintenance costs. Furthermore, in many countries climate change has resulted in the increased frequency and intensity of storms that exceed the design capacity of road drainage infrastructure, resulting in an increased number and severity of flooding events. To facilitate the formulation of a post-flood recovery programme, this paper proposes and demonstrates for the first time a rational approach to select road reconstruction and maintenance investment options for a road network based on life cycle costing that considers road agency, road use and wider economic benefits and costs. The proposed framework can aid road agencies to identify the direct and indirect costs associated with candidate recovery strategies, thereby improving strategic and tactical management in the long and medium term respectively. Thus, improving the allocation of resources.

A case study set in Sioux Falls, USA, demonstrated that economically beneficial recovery programmes could be formulated using the proposed approach. The case study showed that under budget constraints, immediate reconstruction would not always provide the most economically beneficial investment choice. However, under these circumstances, appropriate maintenance strategies could be devised to achieve a reasonable average road condition over time. The selection exercise was based on the economic indicators calculated using the World Bank's HDM-4 tool. In particular, the use of incremental NPV/cost ratio in HDM-4's programme analysis was effective in the assessment of the intervention options under budget constraints. The relationship between the funding levels, intervention options, timing and the resultant network condition could be visualised using the output data from HDM-4. These parameters were useful in the decision-making process for road administration. Furthermore, HDM-4 could generate an annual works programme for use by road administrations or road agencies.

The case study considered life-cycle costs and benefits for road pavements only. The LCA demonstrated within this paper can be extended to other road assets, such as street lighting, drainage, retaining walls, and traffic control systems as well as to other linear infrastructure (e.g., railways and utilities). Deterioration models and costs benefit relationships for these assets can also be developed to provide a more comprehensive analysis of the road network. Furthermore, for road networks with multiple route alternatives, such as the Sioux Falls case study, traffic simulation could be used to model the ability of a road user to choose a different route (detour), allowing for a better estimate of the traffic using a particular road section at any given time.

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Data availability: The data employed to support the findings of this study are available in the public domain: https://github.com/bstabler/TransportationNetworks/tree/master/SiouxFalls.

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