Life-Cycle Performance of Structures and Infrastructure Systems in Diverse Environments – Li & Frangopol (Eds)
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Sustainability-centered decision-making for interventions on existing concrete bridges

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ABSTRACT: This paper introduces a novel decision-making approach for interventions on existing concrete bridges, demonstrated through a case study of a bridge in the metropolitan region of Amsterdam. By redefining system boundaries, incorporating environmental impacts from traffic disruptions caused by structural and non-structural intervention activities, and by quantifying societal impacts in terms of additional costs for the users, this approach promotes a sustainability-centered decision-making for the early stages of determining measures for existing assets. The proposed methodology ensures that decisions regarding replacement, renovation, and/or traffic restrictions are not only technically sound but also aligned with broader sustainability goals, resulting in more balanced and transparent outcomes. The outcomes of the study underscore the importance of accounting for network-wide impacts and societal costs in advancing the sustainability of interventions on existing concrete bridges.

1 INTRODUCTION

The infrastructure in many European countries is aging and after decades of focusing on building new infrastructure the focus has shifted to sustainable maintenance and retrofitting solutions aimed at extending asset's service life. Historically, decision-making in the management of these infrastructural assets emphasized cost-effectiveness and short-term financial gains (Chen & Bai 2019), often overlooking broader societal and environmental impacts. Influenced by the growing demand for the integration of the Sustainable Development Goals (SDGs) into policy and practice, this paradigm has recently shifted towards more comprehensive evaluations that consider environmental impact. However, in the case of infrastructural assets like bridges and viaducts, such evaluations typically account only for environmental impact of the material production and construction phases of the asset itself, without considering impact of its full life cycle or overlooking its effects on the scale of the transportation network. The shortcoming of such approach has been made evident by recent studies (Kasuga 2023), which demonstrate that carbon emissions are significant throughout a structure's life cycle, extending beyond the production stage to include the use and maintenance phases. For existing structures, these emissions are primarily driven by maintenance activities and interventions, often requiring substantial materials and energy. Consequently, a holistic LCA framework must account for these extended impacts, integrating both embodied and operational carbon over the entire life cycle of the structure.

Studies such as (Haist et al. 2023) emphasize the importance of considering asset area system boundaries and accounting for both direct and indirect impacts and emissions. In the case of transport infrastructure, this includes accounting for the consequences of traffic congestion in the area under consideration due to construction activities. Therefore, a comprehensive evaluation of the accumulated environmental impact must also factor in system boundaries, taking into account the larger, interconnected context and all its potential impacts when evaluating

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the environmental effects of a project and assessing the overall impact throughout the asset's life cycle. This oversight becomes particularly critical in decision-making concerning interventions on existing assets in congested transportation networks. It is evident that choices regarding interventions for a specific asset will significantly affect traffic distribution and mobility network-wide. Therefore, a comprehensive evaluation of the accumulated environmental impact must also factor in system boundaries, taking into account the larger, interconnected context and all its potential impacts when evaluating the environmental effects of a project and assessing the overall impact throughout the asset's life cycle.

2 MULTI CRITERIA DECISION MAKING

To evaluate the aforementioned impacts, a novel methodology is proposed for sustainability-centered decision-making regarding measures to be applied to existing infrastructure assets. This methodology facilitates the consideration of the interdependencies arising from network topology and travel demand structures. By redefining system boundaries and incorporating environmental impacts from traffic disruptions due to construction and intervention activities — along with the societal consequences, quantified in terms of additional costs for users — this approach promotes more holistic decision-making, centered on sustainability in transport infrastructure. In the proposed methodology, it is recommended that the asset area system should be sufficiently large to ensure that any disruptions at the boundaries of the system do not significantly affect the accuracy of the evaluation or decision-making process. Typically, for deciding upon interventions on existing concrete bridges, the system will be chosen to encompass the part of transportation network that may be impacted by the proposed measures. This ensures that any indirect effects, such as traffic re-routing or congestion, are fully captured, and the evaluation accounts for the broader consequences of the intervention.

Moreover, it is crucial to recognize that during the decision-making, depending on the stage of this process, different problems must be solved at each stage, each under particular constraints that vary in terms of information availability and the justification of effort, with less information and lower effort in the early stages, and more information and greater effort becoming justifiable in the later stages (Smits 2019). In particular, at the early stages of deciding on measures to keep infrastructure assets operational, the primary concerns are determining the general approach and identifying the technical concepts to be considered. This stage typically focuses on broad strategies, such as identifying whether replacement, renovation, or other structural or operational interventions are needed, and selecting the best fit for the asset's service life extension. As the decision-making process progresses to later stages, like preliminary or detailed design, the focus shifts to refining these strategies with more detailed data and technical solutions (Mohammadi & Amador Jimenez 2022). At these stages, more detailed data are integrated into the decision-making process, and this is where the use of advanced analysis tools comes into play, offering a clearer understanding of how proposed measures can be optimized for the specific system boundaries considered. This transition from general to detailed decision-making underlines the dynamic nature of infrastructure management, where initial decisions set the foundation for more refined and technically sophisticated solutions later in the project cycle.

The proposed approach centers on decision problems common in the early stages of determining measures for existing assets. It aims to ensure that both structural (e.g., replacement or renovation) and non-structural (e.g., traffic restrictions) measures are not only technically feasible but also aligned with overarching sustainability goals, promoting balanced and transparent decision-making. As such, the method employs non-aggregative evaluations that consider a limited number of criteria of critical relevance during conceptual decision stages for existing bridges. It also involves a simplified parametrization of measures, such as typical retrofitting or replacement designs that can be established with limited amount of information and limited effort. By assessing distinctly different conceptual scenarios and evaluating their performance across all criteria, with outcomes presented individually for each criterion rather than consolidated into a single weighted score, the method provides a transparent, understandable basis for decision-making. The criteria proposed to be considered for sustainability-centered decision-making in the context of interventions on existing concrete bridges include: direct and indirect total life cycle costs, direct and indirect environmental impacts over the asset's life cycle (e.g., expressed in CO_2 equivalents), and both short-term and long-term availability of the bridge for traffic (e.g., expressed in duration of accessibility disruptions). These factors represent economic, environmental, and societal performance levels that must be incorporated into a decision-making framework focused on a holistic, sustainability-centered approach.

3 METHODOLOGY FOR EARLY STAGE DECISION-MAKING PROBLEMS

The methodology application is exemplified through a case study of an existing bridge in the metropolitan region of Amsterdam in the Netherlands. By redefining the system boundaries and incorporating in the environmental impact, arising from traffic disruptions due to construction and intervention activities, along with societal consequences of those disruptions, quantified in terms of additional costs for users, holistic decision-making is facilitated.

The bridge in question is the Schinkelbridge located in the A10 (see Figure 1), this motorway is the ring road around Amsterdam, and thus a critical link in the infrastructural network. The Schinkelbridge is one of the busiest bridges in the area (and the Netherlands as a whole): on average 233,600 motorized vehicles cross the Schinkelbridge every day (Rijkswaterstaat 2021). The bridge consists of 3 concrete girder spans of 40 meter and a single steel span of 30 meter, resulting in a total length of 150 meters, however for this study only the concrete spans are considered.

For the purposes of this study it is assumed that the concrete bridge decks no longer comply with the applicable standards and regulations and a decision needs to be made regarding which intervention technique should be applied. The intervention(s) should result in a structure that last for another 75 years. With this 75 year period an assumption is made on increased structural requirements over time: with ever increasing traffic loads and new insights in the structural behaviour of concrete comes increased performance requirements, this is illustrated in Figure 2.

A total of four different intervention techniques are investigated for purpose of scenario analysis:

- Deck Replacement (A_1): For this intervention technique the effects are considered of the complete demolition of the existing deck and its subsequent replacement. The abutments and intermediate pillars are not replaced in this scenario. In this scenario the entire bridge is unavailable for a total of 90 days as the decks of all spans are replaced. It is assumed that this measure will only have to be performed once and no further interventions are needed prior to the end of its service life.
- Permanently reduce traffic load (A_2): This intervention technique is based on the NEN 8701, a Dutch standard for the assessment of existing structures. In this standard it is stated that the normative load can be reduced when signage is used that restricts the maximum (axle) load. For this intervention scenario the maximum load is set to 50 tons maximum. Based on Weigh-in-Motion (WIM) measurements this is roughly 16% of all trucks. This intervention is applied once and is assumed no further reductions are necessary.
- Strengthening deck using FRP (A_3): For this intervention technique the effects are considered of strengthening the beams of the deck with FRP. Strips of FRP are applied along the beam length at the supposed critical cross-sections. During the application of the intervention (a period of 30 days) the maximum axle load limited to 8 tons, however the bridge remains available for traffic. Based on WIM data this is means that 56% of all trucks have find an alternative route for this time period. It is assumed that the adhesive used to apply deteriorates over time. This in combination with the assumed increase in performance

Figure 1. Schinkelbridge in The Netherlands.

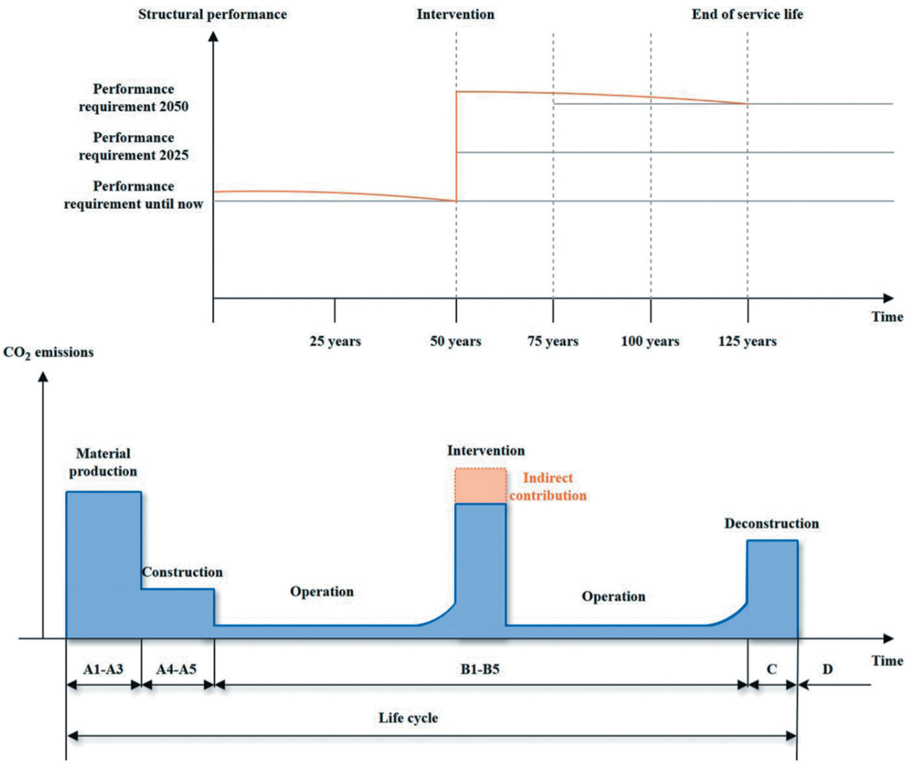

Figure 2. Effect of intervention on structural performance adapted from Kasuga (2023).

requirement over time leads to a replacement of the FRP every 25 years, for a total of 3 interventions over a period of 75 years until the end of the structures service life.

– Strengthening deck using external prestressing (A_4): This intervention technique is the strengthening of the bridge by applying external prestressing. These are, similarly to the FRP, placed along the beams of the bridge at critical cross-sections. During the application of the intervention (a period of 30 days) the maximum axle load limited to 8 tons, however the bridge remains available for traffic. Based on WIM data this is means that 56% of all trucks have find an alternative route for this time period. For this intervention technique a second strengthening intervention is foreseen due to the increase of the performance requirement over time for a total of 2 interventions over 75 years until the end of service life.

These four intervention techniques are assessed using the following criteria:

- Economic impact: The direct costs (expressed in Me) following from construction activities, using sources such as Wipf et al. (1987) (adjusted for inflation) as cost key figures. In addition, indirect costs are calculated based on vehicle loss hours following from any detours necessary as a consequence of the intervention.
- Environmental impact: The direct emissions (expressed in Mkg CO_2-eq) following from materials used, construction activities, and waste treatment, using the Dutch National Environmental Database (Stichting NMD 2024)). In addition, indirect emissions are calculated based on the additional transport distance from any detours necessary as a consequence of the intervention.
- Societal impact: The short term (1 year) and long term (10 year) availability of the bridge-for all traffic (expressed as hinder in a % of time).

Since the proposed approach is intended for use in early-stage decision making, no elaborate designs were developed for any of the four scenarios described, relying instead on best practices and expert judgment estimates.

The system boundaries for the evaluation of the case study Schinkelbridge are chosen to encompass the Amsterdam ring road and the access routes surrounding it. By including these surrounding roads, indirect effects such as traffic re-routing and congestion are fully accounted for, enhancing the reliability of the decision-making process and ensuring more sustainable outcomes. Additionally, this system boundary choice is supported by sensitivity studies that demonstrate how expanding the system boundaries improves the robustness and accuracy of the impact assessments. This ensures that the evaluation captures the full scope of potential impacts such as traffic re-routing or congestion, are fully accounted for, providing

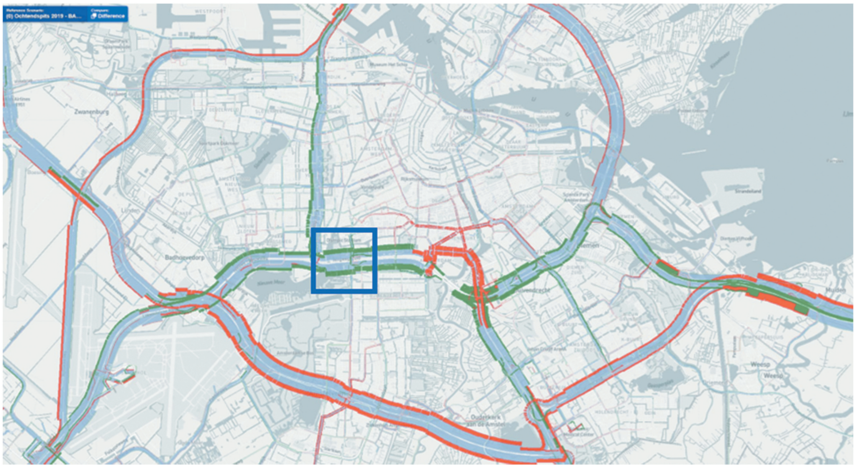

Figure 3. Traffic flow results as a consequence of closing the Schinkelbridge (blue square).

a comprehensive view of the broader consequences of interventions within the transportation network.

4 NETWORK IMPACT AND RESULTS

Both economic and environmental impact criteria consider indirect effects following from traffic being rerouted due to construction activities. These effects are assessed using a traffic flow model and publicly available traffic intensity data (such as INWEVA from Rijkswaterstaat (2021)). The traffic flow model used is extensively described in Lohman et al. (2023), and also applied in van der Tuin et al. (2023). All cases are compared to a reference (base) traffic flow model without any interventions. Changes in travel time and traveled distance as a consequence of the interventions is then taken into account in the various evaluating criteria, see Figure 3.

In Table 1 the changes in traveled distance and travel time for both cars and trucks are presented. The four columns represent traffic as is (Base), traffic when the entire bridge is inaccessible due to a full deck replacement (Full close), traffic when all trucks over 50 tons have to take a new route (16% of trucks), and traffic when the bridge is temporarily inaccessible to trucks with an axle load over 8 tons due to strengthening measures (56% of trucks). These effects are incorporated in indirect economic impact using cost key figures from Significance (2013) and the CNR (Comité National Routier 2020).

The effects of the interventions on travel distance and travel time also represents an environmental effect and as such in taken into account as indirect environmental costs using emission figures from the NMD. It should be noted that for the environmental impact an electrification of road vehicles is assumed over time following the work of Krause et al. (2020). Combining this with the (direct) emissions following from the necessary materials and labor necessary for the inventions total emissions are obtained, as shown in Figure 4. Interesting findings here are the fact that emissions from the execution of a full bridge deck replacement are nearly 1:1 with emissions of traffic following from a 30 day bridge closure. Granted these indirect emissions depend greatly upon the availability of alternative routes and the intensity of the traffic passing over the bridge. Considering the severity of the indirect emissions for a 30 day bridge closure it should come as no surprise that a permanent detour due to load restrictions, even if for a small population of trucks and with significant electrification over time, has considerable consequences for the emissions until the end the bridge's service life.

Table 1. Effect bridge closure on traffic flow.

	Base	Full close	16% *of trucks*	56% *of trucks*
Travel distance cars (M km/day)	21.76	21.88	21.76	21.76
Travel distance trucks (M km/day)	4.49	4.53	4.50	4.51
Travel time increase cars (Hours/day)	0	2559	0	0
Travel time increase trucks (Hours/day)	0	824	132	461

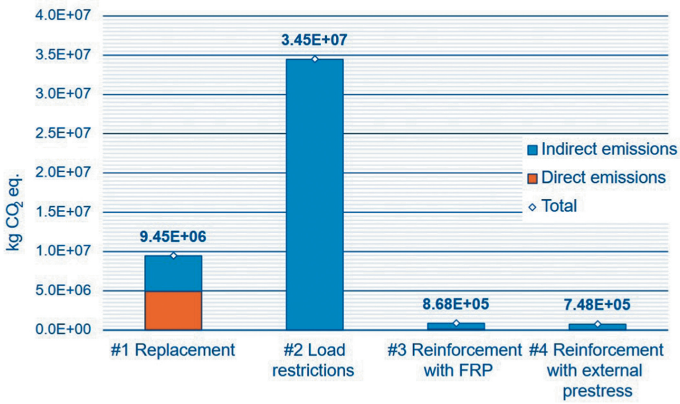

Figure 4. Environmental impact from all four interventions.

In Table 2 and Figure 5 results for all four intervention techniques in terms of economic-, environmental- and societal impact is presented. Generally, a full replacement is considered to be more expensive and polluting than strengthening measures, and this also follows from the results of this case study. The real standout intervention technique however is limiting the traffic load. Usually when considering environmental effects of an intervention only the material production, construction and deconstruction stages of the asset's life cycle are considered (stages A and C), and the use stage (stage B) is often neglected. From this perspective a solution like reducing the maximum traffic load of a bridge may seem like a sound solution, with low initial economic and environmental impact. However, by redefining the system boundaries new insights are obtained about the societal consequences. As shown in the results, the indirect impact cannot be neglected, in fact the indirect costs for the proposed traffic limitation surpass the direct costs of the deck replacement in this scenario in just over two years' time.

In the case of the Schinkelbridge the strengthening solutions seem to provide the best results. Because of the simplifications made in the process of this approach these results should not be taken as a definitive ranking, but rather input for preliminary decision making and consequently moving on to a more advanced design making model. These require more input but allow for weighing the consequences of various design choices to reach an optimal design.

The presented methodology applied to the Schinkelbridge case study demonstrates its effectiveness in supporting early-stage decision-making in infrastructure interventions. By redefining the system boundaries to encompass the Amsterdam ring road and surrounding secondary roads, the methodology effectively captures both direct and indirect impacts due to traffic re-routing and congestion, and holistic evaluation highlights the importance of incorporating environmental and societal impacts alongside economic considerations. It is evident that neglecting societal (availability) aspect, which can only be evaluated in the broad asset area system and focusing solely on direct economic impact would lead to suboptimal decisions, possibly prioritizing traffic restrictions as an optimal solutions. The analysis of four intervention scenarios revealed that strengthening measures, such as using FRP and external prestressing, offer the most favorable balance of economic, environmental, and societal

Table 2. Results Schinkelbridge.

	Profit Direct *Me*	Profit Indirect *Me*	Planet Direct *Mkg CO_2eq*	Planet Indirect *Mkg CO_2eq*	People Short term *Hinder %*	People Long term *Hinder %*
Deck replacement	10.5	11.6	4.98	4.48	24.7	0.3
Traffic limitations	0.7	352	0.00	34.5	8.0	8.0
Strengthening with FRP	1.4	4.1	0.15	0.72	3.1	0.1
External prestressing	1.1	2.7	0.07	0.68	3.1	0.1

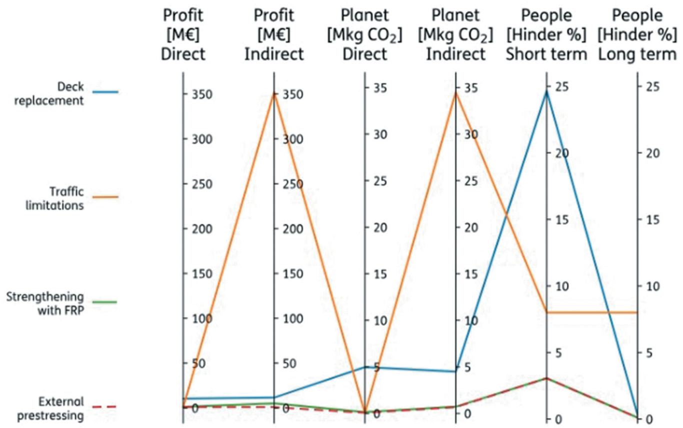

Figure 5. Analysis scenarios for all four interventions.

outcomes. Interestingly, the traffic load reduction intervention, while initially appearing cost-effective, results in substantial indirect societal costs, surpassing direct costs in the long term. Hence, it is evident that neglecting societal (availability) aspect, which can only be evaluated in the broad asset area system and focusing solely on direct economic impact would lead to suboptimal decisions, possibly prioritizing traffic restrictions as an optimal solutions.

To further contextualize these findings an alternative scenario is assessed in Figure 6 under a set of simplified assumptions. The Schinkelbridge experiences some of the highest traffic volumes of all bridges in The Netherlands. Assuming a bridge with a third of the traffic (78,000 motorized vehicles per day) and scaling the added travel distance and travel time linearly it would take nearly 10 years for the costs of traffic limitations to catch up to the direct and indirect costs of a deck replacement. Additionally, over this time span the environmental impact of the traffic limitation is at only 40% of the deck replacement. This represents a very feasible scenario of where a bridge is nearing the end of its service life or planned to be replaced in the next decade for functional reasons and an issue is detected with the bridge.

These findings underscore the value of the methodology as an early-stage decision-making tool, providing valuable insights that inform more advanced design processes. Although the analysis was conducted with limited information and effort—relying on a traffic model as a supporting tool—the methodology proves effective for evaluating intervention options. It accelerates early-stage decision-making and provides valid arguments for decision-makers to justify their choices. While further detailed analysis is required to optimize the final design, this approach lays a strong foundation for subsequent developments.

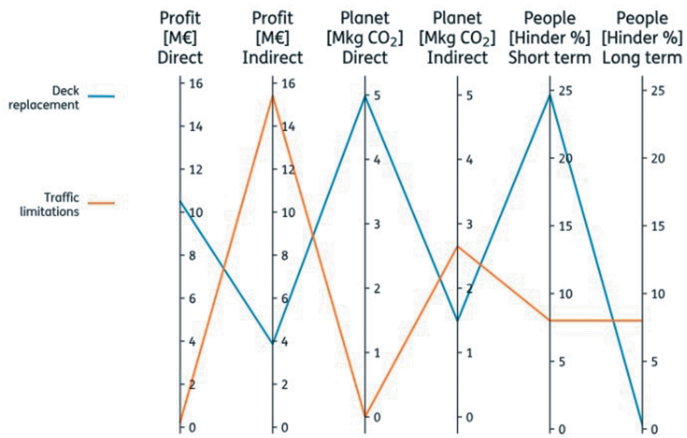

Figure 6. Analysis scenarios for lower traffic intensity and only a 10 year window.

5 CONCLUSIONS

This paper underscores the importance of incorporating environmental impacts from traffic disruptions and societal costs arising from the additional burdens placed on users of transport networks in sustainability-centered decision-making for existing concrete bridges. The proposed novel methodology emphasizes the consideration of these effects and implements a non-hierarchical and non-aggregative evaluation methodology along with the redefinition of system boundaries in intervention decisions. To support these evaluations, the method utilizes a large-scale digital twin system, which is essential for assessing mobility consequences that can, to a case-specific degree, accumulate significantly over time. A case study the use of this approach in evaluation of various intervention techniques for a bridge that serves as a crucial transport artery in a busy highway in The Netherlands. The evaluation reveals that long-term societal costs can completely overshadow seemingly high initial costs. However, it is important to consider contextual details as the same overshadowing solution can still be a viable solution given a different set of transportation network characteristic and system boundaries. While other multi-criteria decision-making methodologies exist, the presented methodology uniquely presents an option for early-stage decision-making where complete technical details of the various intervention solutions are not yet available.

REFERENCES

Chen, L. & Bai, Q. 2019. Optimization in Decision Making in Infrastructure Asset Management: A Review. In Applied Sciences 9(7): 1380, 2019.

Comité National Routier, 2020. EUROPE STUDIES - The Dutch road freight sector in 2019. https://www.cnr.fr/en/netherlands-dutch-road-freight-transport-sector-2019

Haist, M. et al., 2023. Nachhaltiger Betonbau - CO2 Bilanzierung über den Bauwerkslebenszyklus (German) [Sustainable concrete construction - CO2 balancing over the building life cycle]. In Bauphysik Kalender 23: 337–347, 2023.

Kasuga, A. 2023. Impact of carbon neutrality on structural concrete—Not a risk but an opportunity. In Structural Concrete 24(2): 1725–1736, 2023.

Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., Prenninger, P., Coosemans, T., Neugebauer, S., & Verhoeve, W. 2020. EU road vehicle energy consumption and CO2 emissions by 2050 — Expert-based scenarios. In Energy Policy 138, 2020.

Lohman, W., Cornelissen, H., Borst, J., Klerkx, R., Araghi, Y. & Walraven, E. 2022. Building digital twins of cities using the Inter Model Broker framework. In Future Generation Computer Systems 148: 501–513, 2023.

Mohammadi, A. & Amador Jimenez, L. 2022. Decision Support Systems for IAM. In Asset Management Decision-Making For Infrastructure Systems. Springer, Cham. https://doi.org/10.1007/9783-030-97614-9_5

Rijkswaterstaat, 2021. INtensiteit WEgVAkken (INWEVA) (Dutch) [(Traffic)Intensity (on) road sections]. https://data.overheid.nl/dataset/40045-intensiteit-wegvakken–inweva–2021 (accessed: 01-09-2024).

Significance, VU University Amsterdam & John Bates Services 2013. Values of time and reliability in passenger and freight transport in The Netherlands. Report for the (Dutch) Ministry of Infrastructure and the Environment, 2013.

Smits, J. 2019. The Art of Bridge Design: Identifying a design approach for well-integrated, integrally-designed and socially-valued bridges. In A+BE | Architecture and the Built Environment 9(3): 1–212, 2019.

Stichting NMD. Nationale Milieudatabase (Dutch) [National environmental database]. https://milieudatabase.nl/nl/database/nationale-milieudatabase/ (accessed: 16-05-2024).

van der Tuin, M., Spruijtenburg, D. & Zhou, H. 2022. Vehicle dispatching in macroscopic transport models: modelling Demand Responsive Transit. In Transportation Research Procedia 72: 25732580. 2023.

Wipf, T.J., Erickson, D.L., & Klaiber, W.F. 1987. Cost-Effectiveness Analysis for Strengthening Existing Bridges. In Transportation Research Record 1113: 9–17, 1987.