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Decision of Construction Technology from a Sustainability Aspect, Life Cycle Analysis Based on Transport and Construction

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In the case of the different types of construction processes, an important aspect from the sustainability point of view is the organization of construction, the total construction time and cost, and their influence on CO_2 emissions. In this study, in the case of construction projects, we examine the impact of the decided technology on the environmental impact. We take into consideration the aspects of transport and construction organization. Using life cycle analysis methods, we present the comparison of alternatives and sustainable solutions. Discrete event simulation is used to determine the CO_2 emission rate under different maintenance approaches. In the simulation model, a 2 x 2 lane I2 type bridge is simulated with altered traffic lines according to the different scenarios of maintenance. In the case of a half-track closure, the capacity of a 2 × 2 lane road is reduced by half, while the capacity of a 2 × 1 lane road due to alternating traffic directions is reduced by more than 50 %. The extent of the reduction depends on the length of the closed section, which greatly affects the emptying time. According to the results of the simulation, the CO_2 emission might be lower in the case of narrowed traffic alteration than in the case of half-track closure, but the maintenance timeframe is also an important factor.

1. Introduction

The CO_2 emissions present a major problem. The annual CO_2 emission was in 1940 4.85 Gt, and in 2022 37.49 Gt (Tiseo, 2023a), indicating an increase of more than seven times. Buildings' global carbon dioxide footprint plays a major role in the environmental burden. It was in 2021 3,417.4 Gt of CO_2 (Tiseo, 2023b). The environmental burden of bridge construction and maintenance has been described in a previous publication (Eisinger et al., 2022) using the Life Cycle Analysis methodology. The application of CE-LCA in a circular economy model has shown the importance of customizing the model in different industries (Ngan et al., 2021). For example, in the case of green building projects, the Joint Management Body has been linked to LCA, which is a new area of investigation in the construction industry (Alzarooni et al., 2022). The application of LCC methodologies in the construction industry is limited (Gluch and Baumann, 2004), so authors often develop their own models (Arulnathan et al., 2023). In the previous study, we investigated the environmental impact of the construction of a bridge and its irregular and regular maintenance. The aim of the study was to compare the environmental impact of the irregular and regular bridge maintenance models. It cannot be denied that regular maintenance over the life cycle of a bridge (100 y), including the environmental impact during its construction, is lower than irregular maintenance. This study has been extended to five different types of bridges in a later study (this study is under review), which concluded that the environmental impact of an integrated bridge (I2) is the lowest when it is maintained in a regular way. A similar comparative study has been carried out by Munoz and co-authors, who compared the environmental loads of different bridge types. The motivation for the present study was to improve our previous model by including the environmental load of traffic during the construction (upgrading) and maintenance of bridges in our model and to determine the associated CO_2 emissions (Social Cost of Carbon). Construction projects also have a direct impact on people's well-being, with adverse effects known as social costs (Çelik et al., 2017). In this study, we examine the environmental impacts of traffic generation during the construction and reconstruction of one type of bridge (I2). This provides a more accurate

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picture than the previous model to investigate the environmental burden from the life cycle of bridges. Eight types of SCC calculations for water infrastructure were performed by Matthews et al. and co-authors, comparing trench and no-ditch methods (Matthews et al., 2015). Cantuarias-Villessuzanne et al. (2016), in their social cost-benefit analysis, concluded that GHG emissions will decrease due to the diffusion of hydrogen technology, and the price of hydrogen cars will be lower due to regulation. This positive trend will become socio-economically profitable.

(a) Case study for the social cost of carbon bridge construction and regular maintenance

(b) Case study for traffic diversion of the motorway integrated bridge in Hungary

Figure 1: Main case study illustrations

In this study, we will calculate the Social Cost of Carbon (Figure 1a) for a bridge type (I2). While in North America the social cost is taken into account before the conclusion of construction contracts (Gilchrist and Allouche, 2005), in Hungary, this factor is not taken into account. This latter fact motivated our study: would the client be influenced in his choice of bridge type if he knew the social cost involved? Therefore, in the current study, SCC is defined due to traffic diversion (Figure 1b) during bridge construction and bridge rehabilitation. The US federal government has used SCC estimates for more than 80 policy evaluations with an estimated value of $1 trillion. Celik and co-authors developed their own model for SCC estimation, defining the social cost associated with housing construction by phase (Çelik et al., 2019). However, as research has progressed and data and computing have improved, new challenges and opportunities have emerged (Rode et al., 2021). Several ways of calculating SCC have been adopted. Nordhaus built a new conceptual framework in his model, presenting a new estimate of the social cost of CO_2 emissions (Nordhaus 2014). The concept leads to important results, both in terms of economic analysis and climate policy. Many studies define it in terms of the amount of CO_2 emitted per 1 t of the atmosphere and the associated damage (Dietz, 2012). A simplified formula is also used to define SCC, which increases the nonlinear structure of CO_2 emission potential (Tian et al., 2019). Integrated Assessment Models (IAMs) are often used to assess SCC (Wang et al., 2018). As IAMs models span multiple disciplines, they consider complex phenomena in a complex approach. They include environmental economics, climate science, energy systems, infrastructure, conflict, and even education and health.

2. Materials and methods

The concept of our research is to present the advantages and disadvantages of different maintenance approaches of I2 type bridges regarding the social cost of carbon emission during a regular maintenance time period. As our previous study showed, during regular maintenance, the environmental impact is lower than in the case of irregular maintenance during the lifecycle of I2 type bridges.Discrete event simulation is used to determine which scenario is the best solution in terms of CO_2 emissions during the maintenance period. The main feature of the discrete-event simulation model (DES) is that the state variables change only at discrete points in time. That is, they change only in a discrete set of points in time. In this respect, the DES method is the opposite of continuous simulations since, here, the time jumps from one scheduled event to the next rather than continuously spinning. Events integrated into the simulation can schedule additional events. Simulations are essentially simplifications of reality, focusing on the system as a whole. Simulations are most often performed using software that has been developed specifically for a particular purpose. The aim of a simulation is to represent reality as closely as possible and provide valuable information to the user. The correct implementation of these processes can improve the efficiency of the individual processes and perform optimization tasks.In addition to striving for simplicity, simulation models should be detailed enough to mimic reality as closely as possible (Buics and Balassa, 2020). The specification of different parameters in simulation software is essential, as they allow the software to illustrate each case in the most realistic way. These applied frameworks ensure the description and operation of the models (Prateek, 2015).According to literature in the territory of the European Union in 2018, transport is responsible for 25 % of all CO_2 emissions. Within transport emissions, road transport is the largest emitter passenger transport is responsible for 45 % of emissions, and goods transport for 29 %. According to EU 443/2009 no. decree "On the determination of emission requirements for new passenger cars within the framework of the Community integrated approach to reduce the carbon dioxide emissions of light commercial vehicles" sets the CO_2 emissions of newly marketed passenger cars at a value of 130 g/km.In the case of a given road cross-section, it is a problem to determine the CO_2 emissions. However, the CO_2 emissions of vehicles are closely related to the consumption of the vehicles, so in the process of creating the model, an average value can be calculated. It is not a problem with the method that it is difficult to collect information about the composition of the vehicle fleet in a given location.

The simulation experiments carried out with the model highlighted the need to examine different situations in relation to bridges and overpasses. These situations are closely related to the types of interventions required during the life cycle of bridges. In the present study, Discrete Event Simulation software was used to simulate how efficiently traffic can flow during maintenance in the case of I2 type bridges during various circumstances. The discrete-event simulation also helps to find the strengths and weaknesses of different traffic flow alternatives.

3. Calculation

The following simulation model is the first step of more detailed research, and as such, it contains several constraints which serve as limitations at this stage. The average speed CO_2 emission data are used in the simulation based on the results of the previous research. In the case of vehicles, traffic constraints like traffic jams or higher or lower traffic frequency based on the time of the day can also alter the average speed. For this, an interval in speed was introduced.

Table 1 shows the time required for traffic-disturbing maintenance and construction operations for the types of bridges examined in the simulation. In this scenario, the I2 type bridge has 2 x 2 traffic lanes both on the bridge and under the bridge. In the case of maintenance, traffic flow can be altered in three different ways, according to Table 1. During maintenance, the bridge can be either entirely closed, moving the traffic to a different direction under the bridge, or traffic can be altered to move either only one side of the bridge or narrowed to one lane on both sides of the bridge. In each scenario, different numbers of days are required to finish the maintenance tasks until which the traffic is altered and affected in a certain way.

Table 1: Assumed traffic disruption effect of bridge renovation in individual traffic lanes, measured in days

I2	1 y	5 y	10 y	30 y
On bridge	closed	closed	closed	closed
	0 days	0 days	0 days	11 days
	half-track	half-track	half-track	half-track
	7 days	12 days	14 days	23 days
	narrowed	narrowed	narrowed	narrowed
	5 days	11 days	12 days	60 days
Under bridge	closed	closed	closed	closed
	0 days	0 days	0 days	0 days
	half-track	half-track	half-track	half-track
	0 days	9 days	9 days	30 days
	narrowed	narrowed	narrowed	narrowed
	3 days	23 days	23 days	70 days

Impeding traffic generates two types of "costs". The vehicles cannot travel on their usual route, they use an alternative route, which on the one hand, increases the mileage, and on the other hand, due to the increase in traffic, the time spent waiting in traffic increases.In the case of the examined bridge type, according to the assumption, the traffic moves on a 2 × 2 traffic lane, both on the bridge and under the bridge. Each roadway has a stop lane, to which the traffic lanes can be moved in the event of a diversion so that traffic can use two lanes at a reduced speed.

In the simulation model of Figure 2. the above-mentioned 2 x 2 bridge is simulated with altered traffic lines according to the different scenarios of maintenance. If the bridge is completely closed due to maintenance, the traffic flows on an alternate way under the bridge from one side to another. If the traffic is narrowed, the traffic can flow through the bridge in a reduced way, while if half of the bridge is closed and the direction of the traffic is alternated from time to time, then the reduction of the flow is even greater.

During the simulation, it was determined what maintenance operations were necessary at each intervention time and to what extent they disturbed the traffic. Regardless of the congestion, a certain loss of time is suffered by all road users during the renovation period shown in Table 1. If the traffic lanes are saturated even during normal operation, the loss of time increases even further. The second time element mentioned earlier in connection with the bridge renovations, which result from the increase in traffic in the surrounding areas, depends greatly on the construction environment. In the case of urban and inland bridges, this can be significant depending on the road network, while in the case of highways and outlying roads, this is less common.

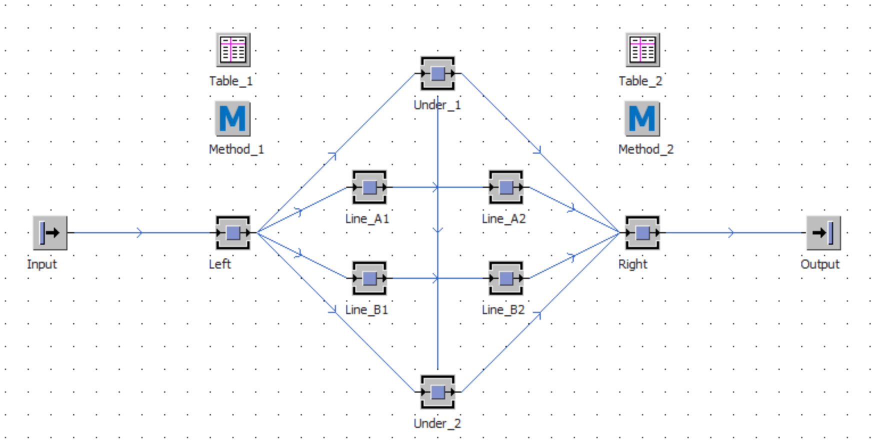


Figure 2: Simulation model of bridge construction and regular maintenance

4. Results

Table 2. shows the results of the simulation regarding CO_2 emission in different scenarios and time periods. In each time period, the bridge can be completely closed, or traffic movement can be half-tracked or narrowed, also, traffic can flow under the bridge half-tracked or narrowed.

Table 2: Total CO_2 emission of vehicles during bridge renovation in individual traffic lanes

I2	1 y	5 y	10 y	30 y
On bridge	closed	closed	closed	closed
	0 kg CO_2	0 kg CO_2	0 kg CO_2	2,420 kg CO_2
	half-track	half-track	half-track	half-track
	1,540 kgCO_2	2,640 kgCO_2	3,080 kgCO_2	5,060 kgCO_2
	narrowed	narrowed	narrowed	narrowed
	1,100 kgCO_2	2,420 kgCO_2	2,640 kgCO_2	13,200 kgCO_2
Under bridge	closed	closed	closed	closed
	0 kgCO_2	0 kgCO_2	0 kgCO_2	0 kgCO_2
	half-track	half-track	half-track	half-track
	0 kgCO_2	1,620 kgCO_2	1,620 kgCO_2	5,400 kgCO_2
	narrowed	narrowed	narrowed	narrowed
	540 kgCO_2	4,140 kgCO_2	4,140 kgCO_2	12,600 kgCO_2

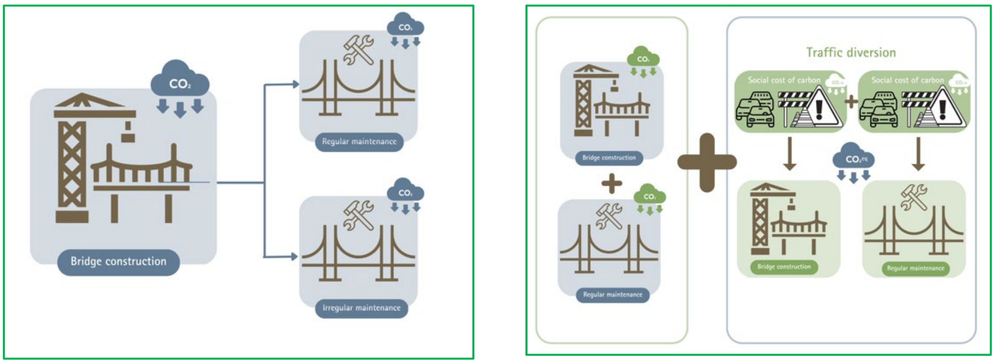
According to literature in domestic practice, the ideal value of the capacity of traffic lanes is 2,000 J/h, which is almost unattainable due to traffic problems, weather, and road conditions. For real traffic, 80 % of this - 1,600 J/h - is the value for the typical 2 x 2 traffic lane per lane. However, it should be taken into account that this value should be regarded as the tolerable traffic volume because the following distance is minimal between vehicles. The free flow speed associated with the previously mentioned value is 115 km/h.

In the case of a half-track closure, the capacity of a 2 × 2 lane road is reduced by half, while the capacity of a 2 × 1 lane road due to alternating traffic directions is reduced by more than 50 %. The extent of the reduction depends on the length of the closed section, which greatly affects the emptying time.

Taking into account the data of the examined bridge type according to Table 2, one can see that, while in case of shorter time periods on the bridge, traffic alteration results in less CO_2 emission, but in case of longer maintenance periods altering the traffic to a different route result in less CO_2 emission.

5. Discussion

Life Cycle Analysis (LCA) is a comprehensive and systematic approach used to assess the environmental impacts of a product, process, or system throughout its entire life cycle, from raw material extraction to disposal. When applied to bridge construction, LCA provides valuable insights into the environmental sustainability and efficiency of bridge projects with a holistic assessment as it considers the entire life cycle of a bridge, including the extraction and processing of raw materials, manufacturing, transportation, construction, maintenance, and eventual demolition or disposal. By assessing the full life cycle, LCA avoids the potential pitfalls of focusing solely on a particular phase of bridge construction, providing a more accurate and comprehensive understanding of its environmental impacts.LCA also enables the identification and quantification of various environmental impacts associated with bridge construction. These impacts may include energy consumption, greenhouse gas emissions, air and water pollution, resource depletion, and waste generation. By quantifying these impacts, LCA helps prioritize areas for improvement and guides decision-making towards more sustainable alternatives LCA also allows for the comparison of different bridge design options, materials, and construction methods. It helps in evaluating the environmental trade-offs among various alternatives, enabling engineers and decision-makers to make informed choices that minimize the overall environmental burden. LCA can highlight the potential benefits of using sustainable materials, incorporating renewable energy, or adopting innovative construction techniques. In this paper, LCA was carried out during the previously performed bridge construction and maintenance studies in the first step for the type I2 bridge (Figure 3a). In this calculation, only CO_2 emissions and costs were analyzed during regular and irregular maintenance. In the present study, the CO_2eq from the traffic load during construction and regular rehabilitation of the I2 bridge was calculated for different traffic management scenarios (Figure 1a). In future studies, we would like to combine the results obtained so far not only for the I2 bridge but also for the other four bridge types (reinforced precast concrete bridge with 2 supports, reinforced precast concrete bridge with 4 supports, steel-concrete composite bridge with 2 supports, steel-concrete composite bridge with 4 supports,). Our aim is to extend the LCA not only with the costs and CO_2eq during bridge construction and renovation but also with the associated traffic load costs and CO_2 load. This will give us a more accurate picture of the type of bridge with the lowest costs and CO_2eq when considering construction, regular renovation (100 y), and traffic load data. Our model has several limitations. Several parameters are not taken into account: environmental impacts and economic processes. It also raises the question of how the result changes if we consider an LCA based on a different methodology or if we extend our approach to social cost benefit. These questions will be addressed in future work (Figure 3b).



(a) Case study for construction and maintenance of the motorway bridge in Hungary

(b) Case study for construction and maintenance and for social cost of carbon bridge construction and regular maintenance

Figure 3: Discussion case studies

6. Conclusion

Bridge construction serves the transport system, but it is usually significantly hindered during construction and to a lesser extent, during maintenance work. Sustainability must apply to the entire life cycle, including construction and maintenance. Due to the complexity of the transportation system, determining the cost of individual elements is a complicated task that requires a detailed examination of individual interventions in relation to the entire transportation system. The aim of this study was to improve our previous model by including the environmental load of traffic during the construction (upgrading) and maintenance of bridges in our model and to determine the associated CO_2 emissions, providing a more accurate picture than the previous model to investigate the environmental burden from the life cycle of bridges. Discrete event simulation was used to determine the CO_2 emission rate under different maintenance approaches. In the simulation model, a 2 x 2 lane

I2 type bridge is simulated with altered traffic lines according to the different scenarios of maintenance. According to the results of the simulation, the CO_2 emission might be lower in the case of narrowed traffic alteration than in the case of half-track closure, but the maintenance timeframe is also an important factor. In the future, this method will be applied to four other types of bridges. This will allow comparative analyses to be carried out to determine which type of bridge is the most environmentally friendly and sustainable to build and maintain. To this calculation, we will add the previous construction and maintenance calculations for the different bridge types. The results will then present a more comprehensive and thorough LCA analysis.

Nomenclature

D – Number of days of renovation
AVv – Average speed of vehicles
AVRv – Average speed reduction of vehicles
Tv – Average loss of time of vehicles
Al – Average load of bridge per day
AVCOv – Average CO_2 emission of vehicle/line crossing
AVCOr – Average CO_2 emission of vehicle/alternate route
Cmaxv – Total CO_2 emission of vehicles/line
Cmaxr – Total CO_2 emission of vehicles/alternate route

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