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A preliminary investigation of the potential benefits of using the ASTRA Bridge for short-span bridge deck refurbishment projects in Switzerland

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ABSTRACT

How bridge refurbishment projects are performed requires a trade-off between the speed and cost of the project and the amount of traffic disturbances during the project. A possible way to help reach a better balance between these two extremes is the ASTRA Bridge developed in Switzerland. The ASTRA Bridge is a 236-meter long steel ramp system on wheels, which is placed on top of the bridge deck undergoing refurbishment to enable vehicles to continue to pass over the bridge while construction work progresses underneath. This study illustrates new refurbishment processes by using the ASTRA Bridge and presents the first quantitative analysis of the effects of using the ASTRA Bridge on the time, costs and traffic disturbances associated with bridge refurbishment. The bridge investigated is a short-span (50 m long) highway bridge requiring refurbishment of its superstructure. The analysis indicates that the use of the ASTRA Bridge resulted in reductions in duration and costs (14% and 3% for the example), and a substantial reduction in user costs (51% for the example). Although more analysis is required for different types of refurbishment projects, the initial results indicate that the ASTRA Bridge may become an integral part of future highway bridge refurbishment projects.

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ASTRA Bridge; construction automation; cost reduction; discrete-event simulation; highway bridges; infrastructure refurbishment; process modelling; traffic disturbances

1. Introduction

There is an increasing need for refurbishment to keep the continuously aging highway infrastructure in good condition, including its engineering structures such as bridges (Ellis, 2020). In the USA, for example, 64% of all highway infrastructures are not in good condition and 25% of all bridges need major repair (Ellis, 2020). In Germany, 10.9% of all bridges need major repair, and similarly, in France, 7% of all bridges show damages that could result in collapse (Calvi et al., 2019). Additionally, roads are increasingly being used at or near capacity, meaning the small perturbations in flow can result in significant consequences. For that reason, the total amount of congestion hours on Swiss highways has tripled since 2008 and the government forecasts that 20% of the highway network will be overloaded in 2040 (ASTRA, 2018b, ASTRA, 2020b). Increasing traffic volume and increasing needs to maintain the aging highway infrastructure present great challenges in highway refurbishment. Future refurbishment has to be performed in a way to optimally balance traffic disturbances and costs, not as it has always been done in the past (Müller, 2020). Improving the efficiency and effectiveness of refurbishment projects, is an important part of increasing the efficiency and effectiveness of road infrastructure asset management (Adey, 2019).

'Building under traffic' is the typical situation for the refurbishment of highways (Müller, 2020). Refurbishing highways requires track guidance, lane redirection and lane closures. These measures consume considerable road user time and money (Jann, 2019). One new technology that has considerable potential to improve the efficiency and effectiveness of road refurbishment projects through an improved balance between traffic disturbances and costs is the ASTRA[1] Bridge. The ASTRA Bridge is a 236-meter long 'bridge-like' steel ramp system moving on wheels. Its use enables vehicles to travel over the areas where work is being done and therefore it has the potential to help reduce traffic disturbances during highway refurbishment projects.

As the ASTRA Bridge is new, there is little research on the extent of traffic disturbance reduction that is possible during refurbishment construction processes. It is of stakeholder interest to investigate the extent of the possible reduction in traffic disturbances and change in refurbishment costs by choosing the ASTRA Bridge over the traditional highway refurbishment. This paper provides the first such results, which are on the effects of using the ASTRA Bridge during short-span highway bridge deck refurbishment projects in Switzerland. This study intends to conduct a preliminary study through process simulations to reveal the practical implications of using the ASTRA Bridge and the associated new refurbishment processes. The results would complement the body of knowledge on refurbishment project management and refurbishment construction

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processes by reflecting the realistic benefits of using new refurbishment technologies.

The investigation was done by simulating the construction processes with and without the use of the ASTRA Bridge with two labor resource scenarios: 1) refurbishment with the ordinary used labor resources (OLR) and 2) refurbishment with additional labor resources (ALR). The evaluation is done through the comparison of the simulated cost and time performance of the two processes under these scenarios. The simulation inputs include the duration and construction cost of each sub-process as well as the traffic user costs (i.e. cost of congestions, cost of accidents and cost of speed reduction). The simulation outputs include the total construction duration, the total construction cost and the traffic user cost incurred from the two processes. This research does not aim to propose suggestions on whether the development of the ASTRA Bridge is beneficial over its lifetime to balance out its investment and maintenance cost. However, this research focuses on showing the potential of using the ASTRA Bridge for individual projects where related construction and traffic user costs were investigated instead.

The remainder of this paper is structured as follows. Section 2 provides the context for this work with respect to recent innovations in highway bridge refurbishment processes and the description of the ASTRA Bridge. Section 3 explains how the simulations were conducted. Section 4 contains the results of the simulations and compares the bridge deck refurbishment with and without the ASTRA Bridge. Section 5 discusses the implications of the results and potential areas to improve future highway bridge refurbishment. The conclusions and future research work are contained in Section 6.

2. Point of departure

2.1. Innovations in road refurbishment processes

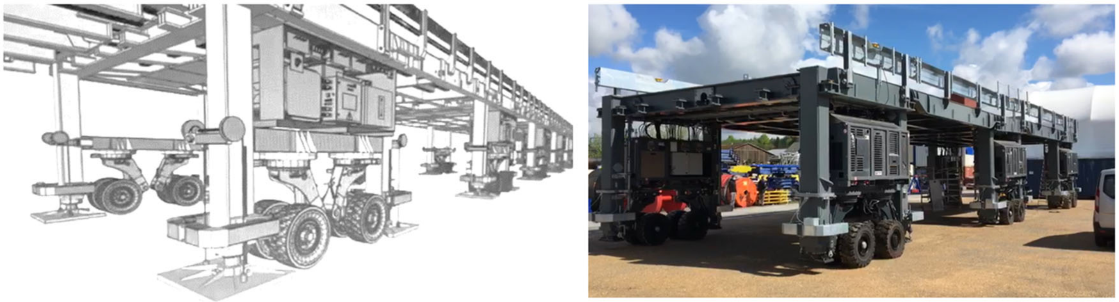
Using new technologies and processes in road refurbishment is not easy and normally requires a significant amount of time (George, Kaldany, & Losavio, 2019). Most technologies and construction processes used have been around for a long time, and there is a certain resistance to change. This resistance comes from increased risk and perhaps initially even increased cost of politically and economically important assets such as highways. Current construction processes can be done anywhere in the world at a reasonable price and the governments hesitate to take on the risks of innovations (George et al., 2019). Additionally, many construction workers and site managers view the use of new technologies and processes skeptically, due to the lack of training for workers, safety concerns and high implementation costs of new technologies and processes, etc.

Researchers and leading industry partners have recently made considerable advances that have potential to improve road refurbishment, including the advances in 3 D printing, digital tools, new construction materials and prefabrication solutions (Losavio, 2019; Shim, Dang, Lon, & Jeon, 2019). For example, the world's first 3 D printed steel bridge with a 12.5 m span was successfully built by a six-axis robot from a Dutch MX3D company, saving considerable labor time and efforts for project coordination (Losavio, 2019). To enhance the coordination of infrastructure refurbishment project information, a maintenance information management system was developed based on a 3 D information model in conjunction with a digital inspection system using image processing (Shim et al., 2019). A modular, prefabricated, and hollow road out of recycled plastic, the PlasticRoad project, was produced 70% faster with 4 times less weight than concrete elements (Davis, 2018). Similarly, the Rollpave project consists of a rolled-up prefabricated asphalt mat of around 3 cm thickness. With the inductive heating of the bottom side, the surface gets sticky and it can be rolled quickly on the roadway.

Similarly to speed up the refurbishment construction cycles, researchers have explored the use of new materials (Azizinamini, Rehmat, & Sadeghnejad, 2019; Zordan & Briseghella, 2007). For example, Ultra-High-Performance Concrete (UHPC) is concrete that contains steel fibers and three times more cement than normal concrete. In 2018, for example, UHPC developed at the Swiss Federal Institute of Technology Lausanne was for the first time used for a large highway refurbishment project in Switzerland. This protective and load-bearing concrete made additional waterproofing unnecessary for construction. It could quickly cure in 24 hours instead of 28 days, resulting in a total time saving of 6 to 8 weeks for a road refurbishment project. However, it is 20 times more expensive than common concrete (ASTRA, 2018a, Kron, 2019).

In addition to accelerating the construction process itself, research has progressed on improving traffic flow through construction sites. One example of this is the development of construction and traffic management plans for the I-15 Devore project, a fast-track urban freeway reconstruction project with high traffic volume in Southern California (Lee, Ibbs, & Thomas, 2005). In addition to improving plans, a more recent example of technology innovation is the steel ramp system named Fly-Over that was developed in Austria. It temporarily raises traffic 1.6 m over a bridge expansion joint so that the workers underneath can replace the joint quickly in a tight space (Rautter, 2018). The traffic-disruption-free design concept is similar to the ASTRA Bridge. However, the Fly-Over is intended only for the replacement of bridge expansion joints and it is not movable across the bridge. This ASTRA Bridge system overcomes the limitation. Due to its length and movability it can be used to enable all of the work included in bridge refurbishment processes.

Though traffic flow could be ensured by new systems such as the ASTRA Bridge, new systems developments remain expensive and the corresponding new processes were not fully investigated to show the benefits. There has been a lack of studies focusing on the evaluation of potential traffic disturbances reduction alongside the refurbishment construction processes and activities. The motivation of this research is therefore to address this knowledge gap and help



(a) Perspective view of the 3D prototype

(b) Perspective view of the physical prototype

Figure 1. The ASTRA Bridge in the prototype form (without ramps).

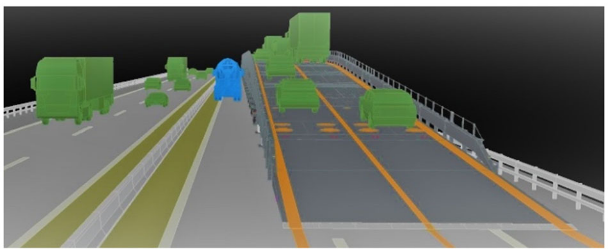


Figure 2. Schematic view of the ASTRA Bridge in use (with ramps).

infrastructure managers reduce traffic impacts through refurbishment process improvement.

2.2. ASTRA bridge

The Federal Roads Office of Switzerland (ASTRA) designed and developed both a 3 D and a physical prototype (Figure 1). It consists of modular steel ramp elements on wheels, which can be freely moved through work zones. A schematic view of the ASTRA Bridge in use is shown in Figure 2. The traffic is raised by 3.6 m and the refurbishment work is conducted underneath it. One lane allows undisrupted traffic flow and the other lane is used for the construction logistics. The ASTRA Bridge is primarily designed for bridge refurbishment purposes such as resurfacing of the decks or replacement of road/bridge expansion joints. Due to the limited space underneath it, the ASTRA Bridge system is not suitable for bridge replacement which requires more complex logistics space support and work coordination.

The physical prototype of the ASTRA Bridge is 236 meters long and weighs approximately 1’200 tons. The overall ramp system consists of 18 portals, 19 inter-segments, and 2 access ramps, which are connected by large bolts. All portals and ramps include an aggregate for an independent drive system. Specially manufactured safety barriers, which can be folded down during transport, are mounted to the portal. The use of the ASTRA Bridge requires a minimum curve radius of 1’000 m, no obstacles, and a minimum road width of 11.70 m. It is therefore most suitable for highway refurbishment projects. It is also designed to carry 40-ton vehicles in parallel. The bearing capacity of the structure on which the bridge will be used must be determined in each case. The weight of the ASTRA Bridge and the concentrated loads of the supports require careful calculations of the ground bearing loads before implementation. The ASTRA Bridge enables construction laborers to work under the ‘bridge’ for a span of 100 meters. The remaining 136 m of the length is taken up by the access ramps. The area underneath the access ramps is used as a stand-by room for machines. The internal clearance area of 3.1 m by 5.2 m allows the most common construction equipment and machines to work under the ‘bridge’. The ASTRA Bridge is movable in every direction to flexibly cover the designated work zones. However, the longitudinal joints between the work zones after each move will need to be addressed to ensure the strength of the pavements.

The ASTRA Bridge is designed to reduce the amount of night work, congestion, and accidents during refurbishment. The total cost including storage space and system development is approximately 20 million CHF. The assembly of the ASTRA Bridge can be done within 14 hours over one night (preferably from Saturday to Sunday in Switzerland). The elements are installed by pneumatic cranes and 28 workers. Elements are transported with low-capacity loaders. During its operation, the ASTRA Bridge is set on large built-in plates and the vehicles can cross the ‘bridge’ at 60 km/h on two lanes. No lane closures and almost no traffic guidance is required.

After completing construction work in a 100-meter-long refurbishment work zone, the ASTRA Bridge can move longitudinally to the next work zone each night within a few hours. It can move at a maximum speed of 0.5 km/h. During movement, no vehicles are allowed to pass on the ‘bridge’, but vehicles can pass in the logistics lane. The operation and movement of the ASTRA Bridge are controlled by radio and an integrated GPS from a control station at the end of the ramps. When the ASTRA Bridge is implemented in highway refurbishment projects, the extent of the possible reduction in traffic disturbances is still unknown. Without such knowledge, it remains challenging to decide if the new refurbishment process involving the ASTRA Bridge should be used instead of the traditional refurbishment process.

2.3. Knowledge gap

Researchers and leading industry partners have developed new construction materials such as UHPC and new construction systems to ensure continuous traffic flows for road and bridge refurbishment projects. Although these new materials and construction systems were demonstrated in

Figure 3. The Uerke Bridge (in a Google Street View).

corresponding case studies to partially show the potential of improving the refurbishment project performance in terms of cost and time savings, there is little research on investigating the traffic disturbances reduction during refurbishment projects and the overall cost- and time- saving potential by using a new construction system such as the ASTRA Bridge.

Decision makers need information about the extent of the possible reduction in traffic disturbances and the cost- and time- saving potential to facilitate their decision-making processes on choosing the most beneficial refurbishment construction system and processes. The potential of using the ASTRA Bridge for highway refurbishment projects, particularly the potential of reducing traffic disturbances during refurbishment processes, has not yet been investigated. To address this knowledge gap, this study first illustrates the new highway refurbishment processes by using the ASTRA Bridge and then evaluates the processes to give an initial indication of the potential reduction in traffic disturbances together with overall cost- and time- savings allowed from the new processes.

This study provides the first such evaluation results, which are on the effects of using the ASTRA Bridge during short-span highway bridge deck refurbishment projects in Switzerland. Being a complementing element to the current body of knowledge in infrastructure refurbishment, the results serve as a preliminary indication of the potential of the ASTRA Bridge, which allows stakeholders (e.g. road authorities in Switzerland) to understand the effects of using the ASTRA Bridge for future highway bridge refurbishment projects.

3. Evaluation

The evaluation of the ASTRA Bridge was done in this paper by comparing and contrasting the construction processes with and without using the ASTRA Bridge. The processes for maintaining the decks of short highway bridges (<50 m in length) were modelled using Business Process Model and Notation (BPMN)[2] diagrams. To quantitatively evaluate the potential of using the ASTRA Bridge, the modelled processes were simulated in different scenarios using the discrete event simulation software BIMP[3]. The cost and duration of each task in the processes were estimated using normal or triangular probabilistic distributions and these simulation input data were obtained from experts and reports (details shown in Section 3.3). It was assumed that the duration of the same task per meter of highway width remains equal in both processes. The simulations enabled estimates of the overall cost and time of the refurbishment project.

3.1. Short span highway bridge

Bridge deck refurbishment on short span highway bridges usually requires four to seven months. The work is normally performed between April and October in Switzerland. To provide some context, a typical bridge deck replacement project costs approximately 1 million CHF. During the project, four workers are scheduled for the project during the day, and no more than eight workers are scheduled during the night, including truck drivers. Additionally, six external workers are assigned to the site for the waterproofing and installation work, and the construction site is supervised by a foreman, a site manager, and a project manager.

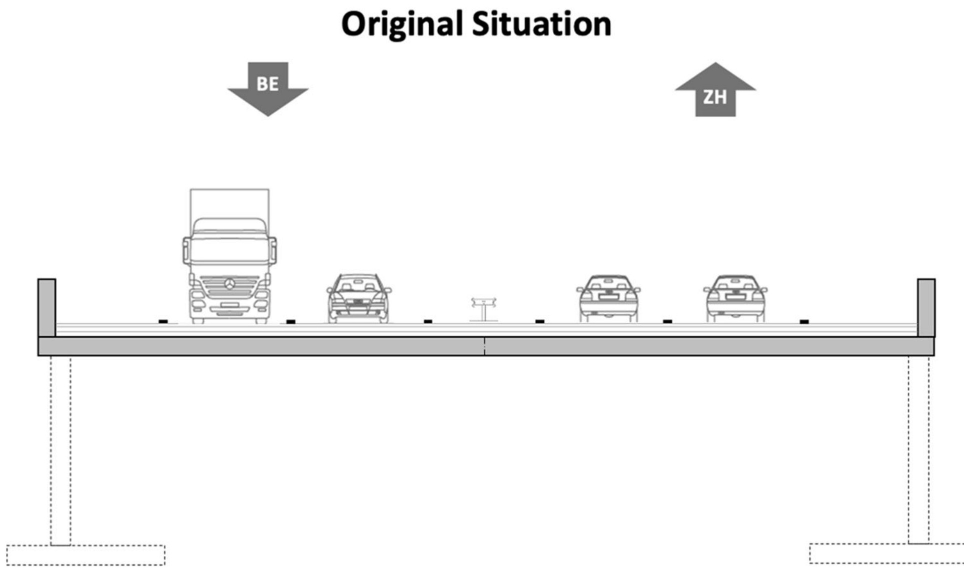
For the evaluation in this paper, the Uerke Bridge (shown in Figure 3) was used. The Uerke Bridge is 14.3 meters long and is located on a four-lane highway in Kölliken, Switzerland. Its last bridge deck refurbishment was in 1998. The construction processes that would be used for the refurbishment are well-documented.

3.2. Bridge deck refurbishment processes

Bridge deck refurbishment processes were defined in this study to contain the construction tasks concerning the roadway segments, bridge edges, and central strips. The main construction tasks of the traditional and the ASTRA Bridge processes are similar, and contain the following four layers:

1. the planning layer, which includes planning tasks and key decisions of the project manager, site manager, and owner,
2. the core layer, which includes the main interfaces between the construction phases to refurbish the bridge deck and the major resources on the site[4] (i.e. the daytime worker, nighttime worker, and user),
3. the construction layer, which includes installing scaffolds, safety barriers, corbels, noise protection walls, and insulation which is conducted by a specialized insulation team, and,
4. the detailed layer, which includes the specific steps for each task in Layer 3.

The BPMN diagram of Layer 1 is the same for both processes, which is shown in Figure A.1 in the Appendix. The BPMN diagrams of the other three layers are provided in the supplementary files.



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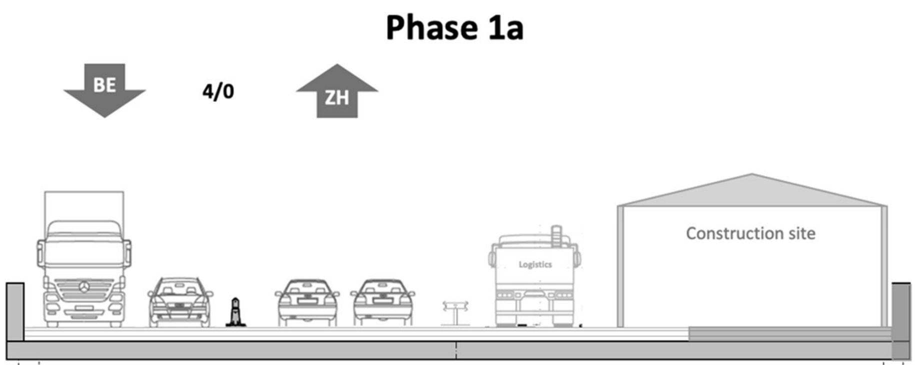

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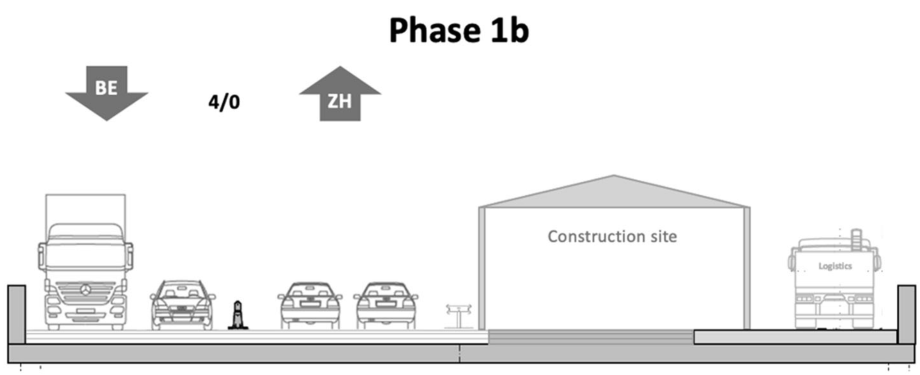


(c)

Figure 4. Construction phases for the traditional process of bridge deck refurbishment. (a). The original traffic situation on the examined highway bridge with driving directions to the city of Bern (BE) and city of Zürich (ZH). (b). The traffic situation during construction phase 1a when the traditional process of bridge deck refurbishment is used. The outer right side of the bridge is refurbished. A weather protection tent was used in this project. (c). The traffic situation during construction phase 1 b (inner right side) when the traditional process of bridge deck refurbishment is used. (d). The traffic situation during construction phase 2a (outer left side) when the traditional process of bridge deck refurbishment is used. (e). The traffic situation during construction phase 2b (inner left side) when the traditional process of bridge deck refurbishment is used. (f). The traffic situation during construction phase 3 (central strip) when the traditional process of bridge deck refurbishment is used.

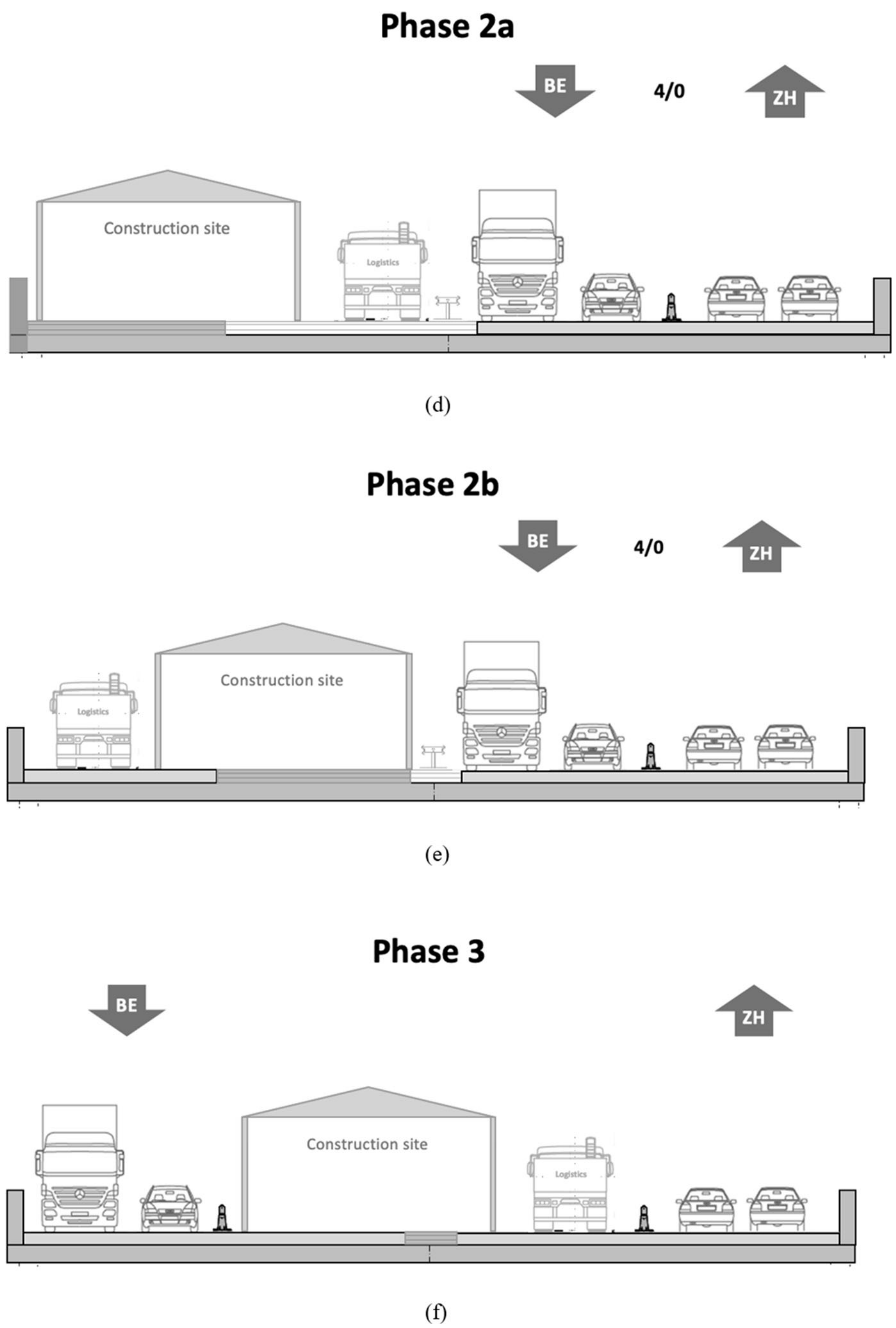


Figure 4. Continued

3.2.1. The traditional process

The traditional process is defined as the standard process in Switzerland for maintaining highway bridge decks when the ATSRA Bridge technology is not used. The traditional process is divided into three construction phases based on the Swiss traffic control and construction staging plan, i.e. the 4/0 plan suggested in the SN 640885 standard (VSS 2015). An overview of the 4/0 plan about how to divert traffic next to the work zones is shown in Figure A.2 in the Appendix. The three construction phases for the traditional process of bridge deck refurbishment are illustrated in Figure 4. The construction site moves along with diverted traffic flow. The traffic is guided to four narrow lanes that are adjusted from the original two lanes. Strong rainfall, extreme temperature, or strong winds prevent certain construction work. During summer, rainfall is often a problem for installing insulation, sealing, and mastic asphalt. A weather protection tent is useable in the traditional process to save 10 days of waiting time in one season, however, the continuous movement of the tent requires considerable assembly and disassembly time and cost. A simplified BPMN diagram of the traditional process, which consists of 150 tasks, is shown in Figure 5.

In the BPMN diagram of the traditional process, three key decisions are modelled using the probability-based exclusive gateways:

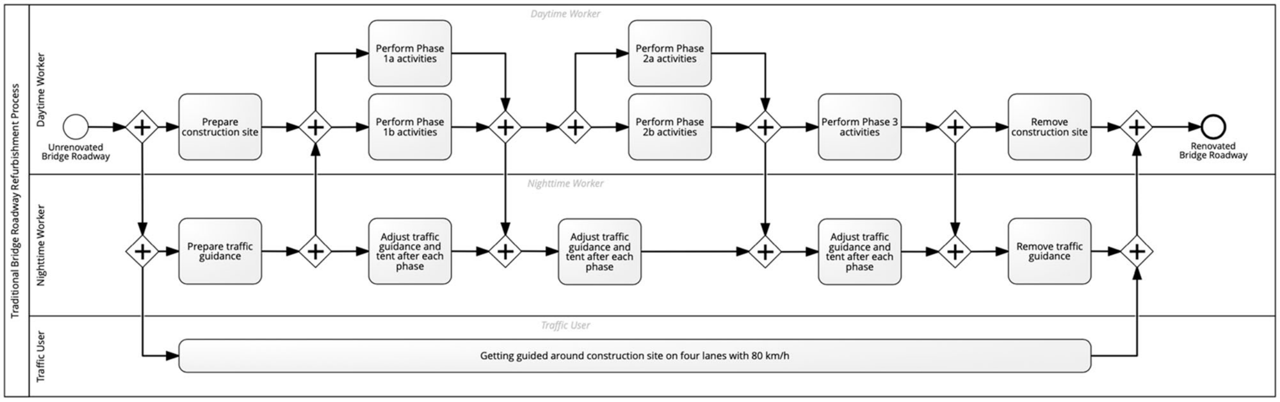


Figure 5. Simplified BPMN diagram of the traditional process of bridge deck refurbishment.

1. decision on whether to build a new central strip crossing next to the construction site or use a preinstalled one, on which the costs related to the traffic guidance are dependent;
2. decision on whether to build or replace noise protection walls according to the noise protection wall requirements in the Network Status Report (ASTRA, 2018b);
3. decision on whether to build a weather protection tent or not depending on the local weather conditions.

3.2.2. The ASTRA bridge process

The ASTRA Bridge process contains four construction phases (illustrated in Figure 6), which are subdivided into nine subphases with a total of 250 tasks. A simplified BPMN diagram of the ASTRA Bridge process is shown in Figure 7. The number of nighttime tasks is reduced in the process diagram for the ASTRA Bridge process as it only includes a limited number of required traffic guidance, assembly, disassembly, and the movement of the ASTRA Bridge. The assembly and disassembly tasks of the ASTRA Bridge are conducted by one assembly team of 28 people during one night. The assembly and disassembly tasks of the weather protection tents are not modelled in the process diagram because the ASTRA Bridge by nature provides weather protection and therefore the tents are not needed. The curing tasks of mastic asphalt are included in the ASTRA Bridge process because the ASTRA Bridge cannot move sideways before the road surfaces are hardened. During the movement of the ASTRA Bridge, no traffic flows are allowed on top of it; however, the movement takes only a few hours.

3.3. Cost estimation

Compared to the process duration estimation, which was based on simple and direct time estimation for each modelled task, the process cost estimation required more detailed cost information. Three of the most important cost types were considered for this study, i.e. construction cost, labor cost, and user cost. The notations of cost variables and parameters are described in Table 1.

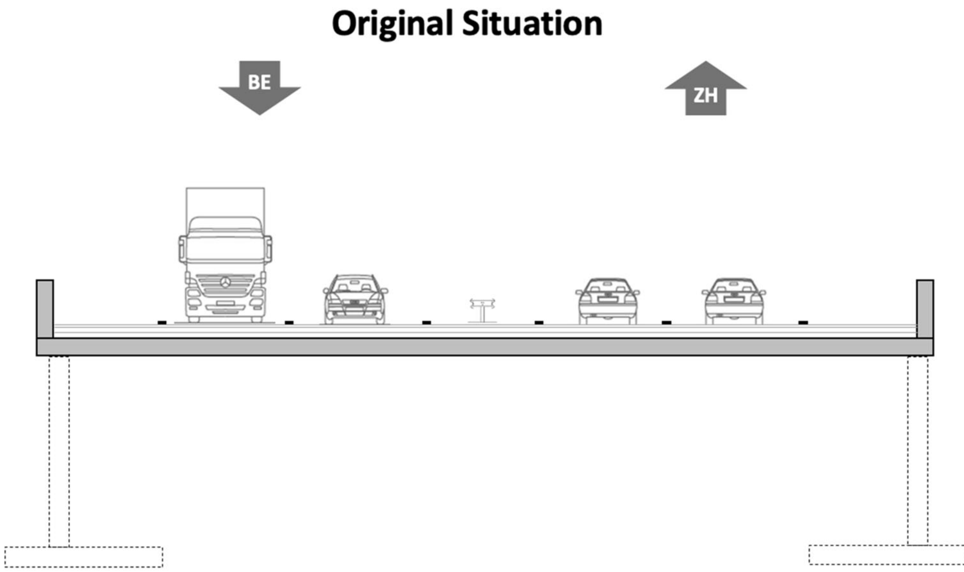
3.3.1. Construction cost

The costs of each task in the two processes were estimated using expert opinion collected from the first author's multiple site visits, historical documentation, the price figures in Switzerland and Swiss traffic standards. The inflation rate of 11.1% (BFS 2020) and the adjusted value-added tax in Switzerland were accounted for deriving the values of costs for the year 2020 to be compatible with the year 1998 (i.e. the year of the latest refurbishment of Uerke Bridge decks). The specific costs concerning the operation, assembly and disassembly of the ASTRA Bridge were provided by ASTRA. The acquisition cost and maintenance cost of the ASTRA Bridge itself and traditional construction equipment were removed from the simulation modelling, which will ensure the consistent comparison between the new process and traditional process only focusing on the refurbishment construction activities. It is noted that the ASTRA Bridge is provided in Switzerland for projects for free by ASTRA. Therefore, the construction costs in this study include the operation, assembly, and disassembly costs.

For short-span highway bridges, the ASTRA Bridge only needs to have a total of 160-meter length of portals and ramps. Traffic guidance cost was estimated based on the standards and the market price of the respective year. Swiss standard SN 640885 (VSS 2015), particularly the 4/0 traffic guidance plan, was used to estimate the costs related to installing the signal posts and markings. The lengths of required markings and steel crash barriers in each construction phase were estimated for each decision path in the process. The list of the values used for cost estimation is provided in the supplementary files.

3.3.2. Labor cost

Each worker was assigned to an individual timetable, either daytime (08:00-17:00, e.g. insulation team) or nighttime (23:00-6:00, e.g. nighttime worker) timetable, to record and track their working time consumption in the simulated processes. The traffic users were assigned to the 24/7 (0:00-24:00) timetable. The hourly cost of labor was derived from literature (details provided in supplementary files). The crew size was assumed to be at least two workers as is standard practice in Switzerland. The labor cost for Uerke Bridge refurbishment



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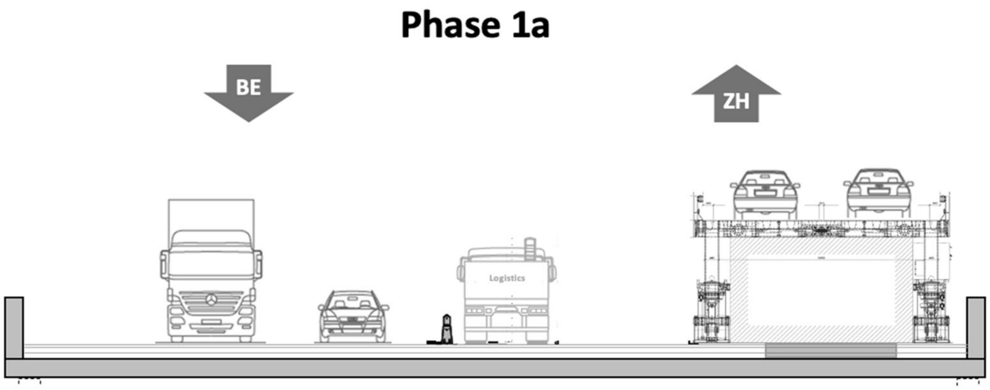

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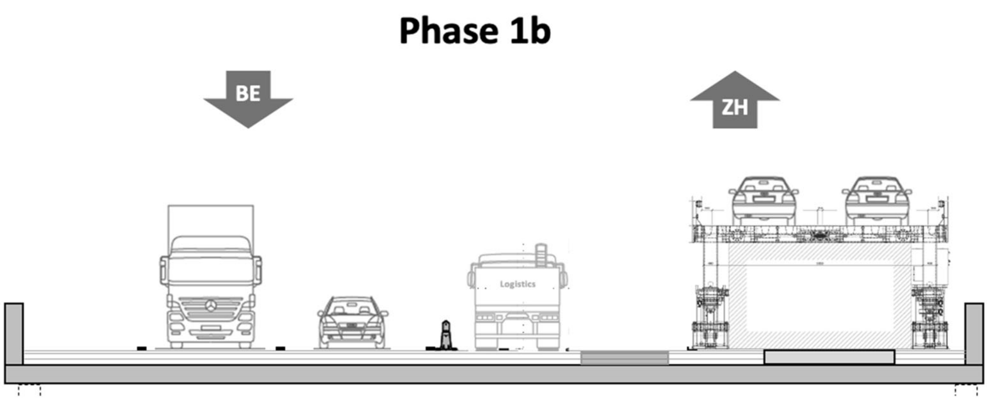
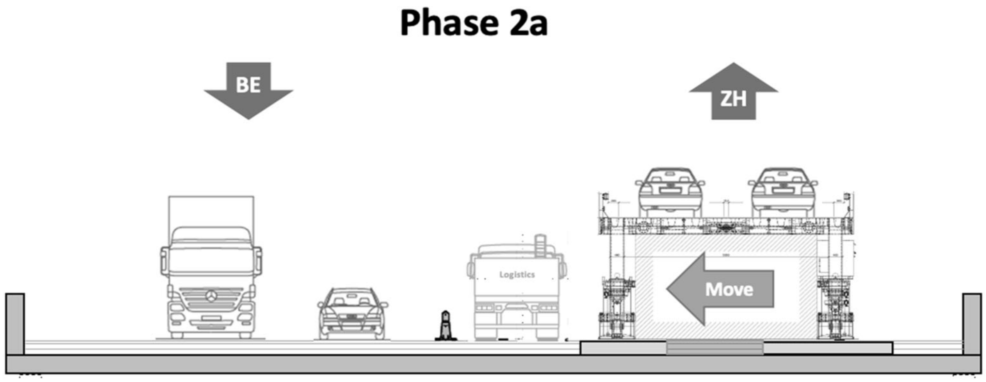


(c)

Figure 6. Construction phases for the bridge deck refurbishment process when using ASTRA Bridge. (a). The original traffic situation on the examined highway bridge (same as Figure 4(a)). (b). The traffic situation during construction phase 1a when ASTRA Bridge is used starting on the outer right side of the bridge. (c). The traffic situation during construction phase 1b when ASTRA Bridge is used. The part next to the ASTRA Bridge is refurbished. (d). The traffic situation during construction phase 2a when ASTRA Bridge is used (i.e. The ASTRA Bridge is moved within maximum one hour during the night. During this time cars need to be guided alongside the ASTRA Bridge.). (e). The traffic situation during construction phase 2b when ASTRA Bridge is used. (f). The traffic situation during construction phase 2c when ASTRA Bridge is used. (g). The traffic situation during construction phase 3a when ASTRA Bridge is used. Movement to the left side of the bridge crossing the prepared central strip. (h). The traffic situation during construction phase 3b when ASTRA Bridge is used. (i). The traffic situation during construction phase 4a when ASTRA Bridge is used. (j). The traffic situation during construction phase 4b when ASTRA Bridge is used.



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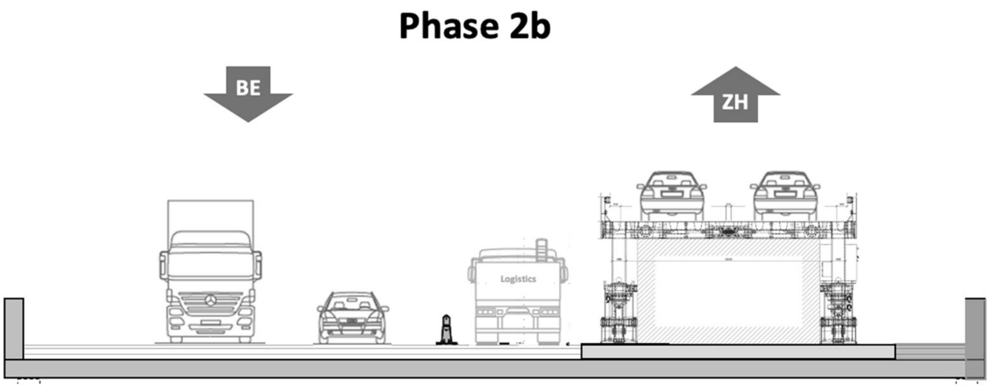

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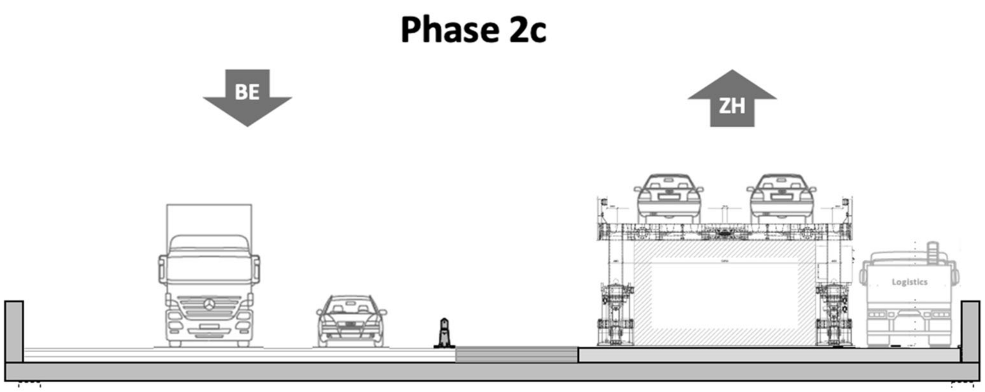

(f)

Figure 6. Continued

project was further confirmed by the experienced experts from the construction site and was attached to each task.

3.3.3. User cost

The user cost was broken down into three sub-types: cost of congestion, accidents, and speed reduction. The selection of the three sub-types was based on how users can be affected by the use of the highway infrastructure (Adey, Burkhalter, & Martani, 2020). User cost that already occurs on days without construction work was not included. Other sub-types of costs, such as psychological, CO2 emission and noise costs, were not included as they were not expected to differ considerably between the two processes. However, these are important aspects to be considered in simulation models focusing on the detailed dynamics of the whole refurbishment project ecosystem. Values and the descriptions of the user cost variables are provided in Table 1. Each of the costs is elaborated as follows:

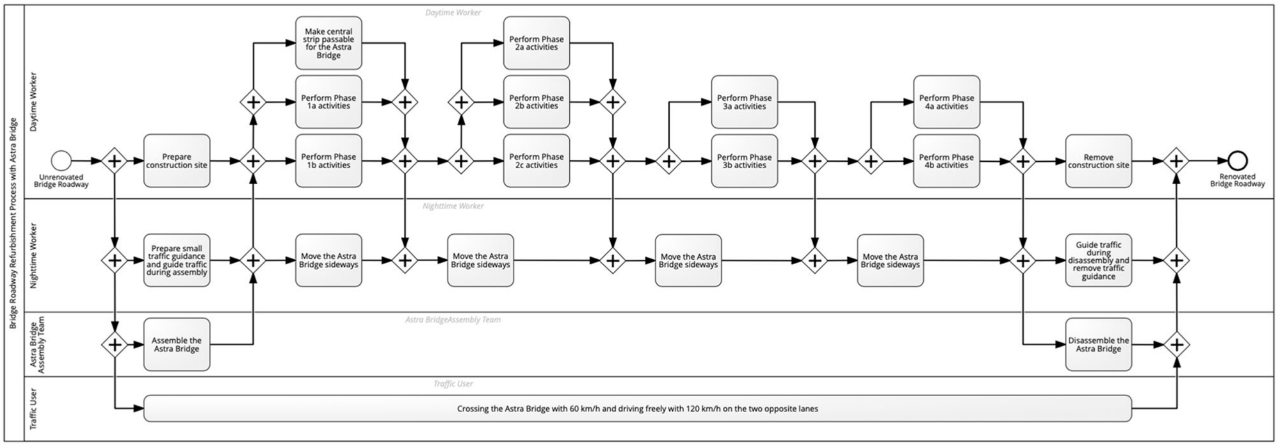

Figure 7. Simplified BPMN diagram of the ASTRA Bridge process of bridge deck refurbishment.

(1) Cost of congestion. The cost of congestion was approximated using Eq. (1), assuming all construction sites cause the same congestion per meter length of traffic disturbances. Although some researchers have developed more detailed equations to evaluate the cost of congestion, such as Rashidi, Waller, and Axhausen (2020), Eq. (1) provides a simple, approximate and appropriate initial estimate. In Eq. (1), the total average length of traffic guidance, L^G, for a user to pass, consists of the average straight length along the construction site and the average length of traffic guidance before and after it. Using the Swiss standard SN 640885 (VSS 2015), a total average length of traffic guidance per highway direction of 725m is required for the traditional process and 200m required for the ASTRA Bridge process (i.e. 400 m on one side, 0 m on the other side):

$$C^T_{Congestions} = T \cdot c^T_{hour} \cdot \frac{D^C_{Swiss}}{52 \cdot P^{UC}_{Swiss}} \cdot L^G \cdot \frac{d^T}{24} \qquad (1)$$

(2) Cost of accidents. The cost of accidents was approximated using Eq. (2), which takes into consideration the cost of property damage, the cost of injury, the cost of fatality, together with the cost of congestions caused by accidents on the two or the four lanes. It was assumed that 10% of all accidents cause congestion on the four lanes in the traditional process, e.g. if a truck crosses the central stripe towards the opposite highway bridge lanes. This accident was, however, not considered in the ASTRA Bridge process, and it was assumed that there was difference in the the probability of workers. The costs were multiplied with a factor of 1.5 (a conservatively estimated value) to take into consideration the missing emergency lanes at the construction sites and the resulting higher risk of having accidents:

$$\begin{aligned} C^T_{Accidents} = {} & T \cdot L^G \cdot d^T \cdot (C^P_{Accident} + C^I_{Accident} \cdot d^I_{Accident} \\ & + C^D_{Accident} \cdot d^D_{Accident}) \\ & + T \cdot c^T_{hour} \cdot D^C_{Accident} \cdot 1.5 \cdot (2 \cdot 0.1 + 0.9) \end{aligned} \qquad (2)$$

(3) Cost of speed reduction. The cost of speed reduction was approximated using Eq. (3). The traditional process requires a speed reduction to 80 km/h on all four lanes, however, the ASTRA Bridge process requires a speed reduction to 60 km/h only on two lanes. The usual speed limit of 120 km/h on Swiss highways was used as a reference to the reduced speed. The length of the speed reduction passage should exceed the traffic guidance length by 0.3km (VSS 2015). Besides, the acceleration and deceleration time losses were evaluated for the two processes, depending on the type of vehicle. For example, a heavy truck passing the ASTRA Bridge with 60 km/h needs to decelerate by 20 km/h if it originally passes with a speed limit of 80 km/h. These values were chosen according to the Swiss Federal Road Authority's feedback during the ASTRA Bridge prototype testing phase. According to ASTRA (2020), the 4-hour rush time per day was used in Eq. (3) based on the fact of the 28% of daily traffic on Swiss highways (i.e. 4 = MOD(1, 0.28) + 1):

$$\begin{aligned} C^T_{Speedreduction} = {} & T \cdot d^T_{Uerke} \cdot c^T_{hour} \cdot \left(\frac{L^G + 0.3km}{\frac{80km}{h}} \right. \\ & \left. + \frac{0.28km \cdot 2}{\frac{100km}{h}} - \frac{L^G + 0.28km \cdot 2}{\frac{120km}{h}} \right) \\ & \cdot \left(1 - 0.28 \cdot \frac{5}{7} \cdot +0.059 \right) \end{aligned} \qquad (3)$$

In addition, estimating user cost using Eq. (3) required the following two assumptions:

(a) All users pass and arrive at the construction site exactly at the specified speed limit. In reality, however, some users often cautiously decelerate to less than the required speed limit and some do not even reduce speed. Based on the past project experience using the Fly-Over ramp,

Table 1. The notations of cost variables and parameters for cost estimation.

Variables	Description	Value	Unit	Source
C^T	The total user cost incurred from the case bridge refurbishment project.	Sum of variables	CHF	–
$C^T_{Congestions}$	The user cost incurred from the additional congestions near the construction site.	Sum of variables	CHF	–
$C^T_{Accidents}$	The user cost incurred from the additional road accidents near the construction site.	Sum of variables	CHF	–
	The user cost incurred from the speed reductions near the construction site.	Sum of variables	CHF	–
c^T_{hour}	The average user cost per vehicle per hour	23.29	CHF/h	(VSS 2009)
$C^P_{Accident}$	The average user cost incurred from the property damage.	44, 800	CHF	(VSS 2013)
$C^I_{Accident}$	The average user cost incurred from an injury event.	327,100	CHF	(VSS 2013)
$C^D_{Accident}$	The average user cost incurred from a fatality event.	3,255,200	CHF	(VSS 2013)
d^T_{Uerke}	The average daily traffic at Uerke Bridge in 2018 in both directions.	75,339	Vehicles/d	(SASVZ 2018)
D^U_{Swiss}	The average yearly traffic within the Swiss highway network.	$27.7*10^9$	Vehicles	(ASTRA, 2020b)
D^L_{Swiss}	The length of the Swiss highway network.	1,859	km	(ASTRA, 2018b)
d^T_{Swiss}	The average daily traffic on the Swiss highway network ($d^T_{Swiss} = \frac{D^U_{Swiss}}{365*D^L_{Swiss}}$).	40,823	Vehicles /(km*d)	Calculation
D^C_{Swiss}	The yearly congestion time due to the operation of construction sites within the Swiss highway network.	387.5	h/year	(ASTRA, 2020b)
D^A_{Swiss}	The total number of accidents on the Swiss highway network.	7,801	Accidents	(ASTRA, 2020a)
D^{CA}_{Swiss}	The total congestion caused by accidents on the Swiss highway network.	2,835	h/year	(ASTRA, 2020b)
$D^C_{Accident}$	The average congestion caused by one accident ($D^C_{Accident} = \frac{D^{CA}_{Swiss}}{D^A_{Swiss}}$).	0.36	h	Calculation
$d^P_{Accident}$	The number of car accidents causing property damage per km.	$0.42*10^{-6}$	Accidents/km	(VSS 2013)
$d^I_{Accident}$	The number of injuries from car accidents per km.	$15.74*10^{-8}$	Injuries/km	(VSS 2013)
$d^D_{Accident}$	The number of fatalities from car accidents per km.	$0.32*10^{-8}$	Fatality/km	(VSS 2013)
$P^C_{Accident}$	The percentage of highway car accidents occurring next to the construction sites.	7%	–	(Krümmel & Klinke, 2012)
$P^P_{Accident}$	The ratio of the probability of car accident near a construction site to that of a normal condition	200%	–	(Krümmel & Klinke, 2012)
P^{UC}_{Swiss}	The percentage of highway infrastructure under construction in Switzerland ($P^{UC}_{Swiss} = \frac{P^C_{Accident}}{P^P_{Accident}}$)	3.5%	–	Calculation
T	The refurbishment construction duration including 1 week of public holidays	Variable	Weeks	Simulation results

users tend to decelerate the first day after such a system is assembled.

(4) The traffic disturbances caused by highway bridge deck refurbishment is indifferent to the length of the bridge. In reality, however, it is noted that short-span highway bridge refurbishment will cause slightly more traffic jams per meter length than long-span highway bridges.

3.4. Discrete event simulations

Discrete event simulations were used to evaluate the two processes using BPMN and the Signavio platform. During the simulations, a Future Event List (FEL) with timestamps was created using the BIMP Simulator (Ullrich & Lückerath, 2017). The duration of each task, the hourly cost, the timetable were assigned to daytime and nighttime workers who conduct associated construction tasks in the modelled processes. The probabilities of decisions were modelled using probabilistic distributions. As each simulation produces a different result depending on the chosen decision, simulations could be done multiple times for multiple process instances to provide an average value for cost and time performance. One week of summer holidays was added to the process duration results. The simulations also output the waiting time for each modelled task, which could help indicate how some processes can be optimized by adding resources to reduce or remove such waiting time. In other words, the waiting time on tasks indicated where main bottlenecks exist.

Discrete event simulations were chosen over the other methods, such as the critical path method, as they allow full consideration of the labor resource usage for the calculation of the costs (AbouRizk & Halpin, 1990; Ji & AbouRizk, 2018; Chen, Adey, Haas, & Hall, 2020). This study does not intend to develop mathematical methods for solving for the parameters of selected distributions and the goodness-of-fit testing for construction data as this is beyond the main scope of this research. However, appropriate probabilistic distributions have been chosen based on the triangulation of the data sources to be the realistic input for simulations. The simulations were built for the ASTRA Bridge process and the traditional process respectively under two labor resource usage scenarios: 1) refurbishment with ordinary labor resources (OLR) and 2) refurbishment with additional labor resources (ALR). 15 process instances were simulated in the discrete event simulations, as it is sufficient to test the statistical significance of the performance of the processes (Jenkins & Quintana-Ascencio, 2020). The simulations were followed by a set of sensitivity analysis to show the performance of using the ASTRA Bridge if the assumptions vary. Under OLR scenario, for example, a sensitivity analysis was conducted to show the influence of variations in assumptions. Particular attention was paid to the reduction in travel speed due to the use of the ASTRA Bridge. Drivers may experience psychological insecurities when passing the new ramps.

For the OLR scenario, 4 daytime workers were scheduled for the case study project and 8 night-time workers including truck drivers were scheduled during the nighttime operations. A team of 6 workers was specifically scheduled to conduct the waterproofing and insulation work. The construction site was supervised by a foreman, a site manager, and a project manager. Two different traffic conditions were further considered for the OLR scenario: 1) maintaining the decks of the highway segments with a traffic volume of 40,823 vehicles per day when using the ordinary labor resource (OLR-SA), 2) maintaining the decks of the highway segments with a traffic volume of 75,339 vehicles per day when using the ordinary labor resource (OLR-UB). The two traffic conditions were simulated because they reflect two basic situations in which it was imagined that the ASTRA Bridge would be used for the Uerke bridge as a specific case and for other short-span highway bridges in Switzerland in general.

For the ALR scenario, the labor resource usage was adjusted to take into consideration the needs of additional labor in each phase of the processes. The simulation neglected the cost of additional workers in a queue, which means that these workers were only assigned for the process step when in need. They were viewed as a selective workforce that could be commissioned on demand by the site manager. Where to add additional workers was determined by the waiting time of the process step. Three sub scenarios for the ALR scenario were considered: 2 additional daytime workers, 4 additional daytime workers and a second insulation team.

4. Results

4.1. OLR scenario – refurbishment with original labor resources

Simulation results of the OLR scenario show that the ASTRA Bridge can improve the cost and duration performance of the deck refurbishment process of a short-span highway bridge in Switzerland. The time and cost of each process instance are summarized in Table 2. The total duration and the total cost resulted from the discrete-event simulations for the traditional process are comparable to the realistic figures from the past reference projects. Using the traditional process, bridge deck refurbishment took 19.1 weeks and cost 911 * 10^3 CHF on average. Using the ASTRA Bridge process takes 16.3 weeks and costs 882 * 10^3 CHF on average. The construction cost reduction was approximately 30,000 CHF (3%) and the duration reduction was 2.8 weeks (14%). The total waiting time on each task was used as an indicator to reflect how long a task waits for execution until the respective resource was available. The waiting time represented bottlenecks, which could be addressed to reduce durations. The waiting time in total from the traditional process was 3.4 weeks and that from the ASTRA Bridge process was 4.3 weeks.

The user cost and construction cost for the two processes are illustrated in Figure 8, considering the traffic situation at Uerke Bridge (i.e. 75,339 vehicles/day) and that of Swiss highways on average (i.e. 40,823 vehicles per day). The total average cost at the Uerke Bridge location using the traditional processes was 2.82 million CHF, and that using ASTRA Bridge was 1.82 million CHF. The difference was close to 1 million CHF. Considering the Swiss average traffic situation, the total cost of the traditional process at Uerke Bridge was 1.99 million CHF and that of the ASTRA Bridge at Uerke Bridge was 1.42 million CHF. The cost difference was in this case 0.57 million CHF. The detailed user cost composition from the two processes in the OLR scenario is shown in Figure 9. In general, the user cost for the average Swiss highway traffic volume (40,823 vehicles/day) was lower than that for the Uerke Bridge daily situation. The ASTRA Bridge process was, therefore, more useful for bridge refurbishment on highway segments with high traffic volume. In Switzerland, traffic volumes on highways range from low traffic in mountain areas to 137,000 vehicles per day in Muttenz, Hard (ASTRA, 2020b).

Table 2. Simulation results of the OLR scenario for both processes.

	Refurbishment process using the ASTRA Bridge in the OLR scenario			Refurbishment process without the ASTRA Bridge in the OLR scenario		
Process instance	Total duration [w]	Waiting time [w]	Total cost [10^3 CHF]	Total duration [w]	Waiting time [w]	Total cost [10^3 CHF]
1	19.1	3.3	883	16.3	4.5	884
2	19.0	3.3	883	16.5	4.8	917
3	20.0	3.1	890	16.2	4.3	883
4	20.1	3.8	930	17.1	4.5	889
5	18.4	4.1	885	17.1	4.6	924
6	18.4	3.1	919	16.1	3.7	853
7	19.3	3.5	931	16.1	4.0	875
8	18.0	3.6	928	16.3	4.0	860
9	19.3	3.0	882	16.0	3.8	836
10	20.3	3.0	882	16.1	4.4	855
11	20.3	3.9	949	15.7	4.2	900
12	17.4	4.1	896	16.5	4.3	883
13	18.4	3.3	953	16.6	4.7	874
14	19.4	3.1	897	16.1	3.7	850
15	19.4	3.2	926	16.6	5.4	945
Average	19.1	3.4	912	16.3	4.3	882

Note: [w] represents weeks.

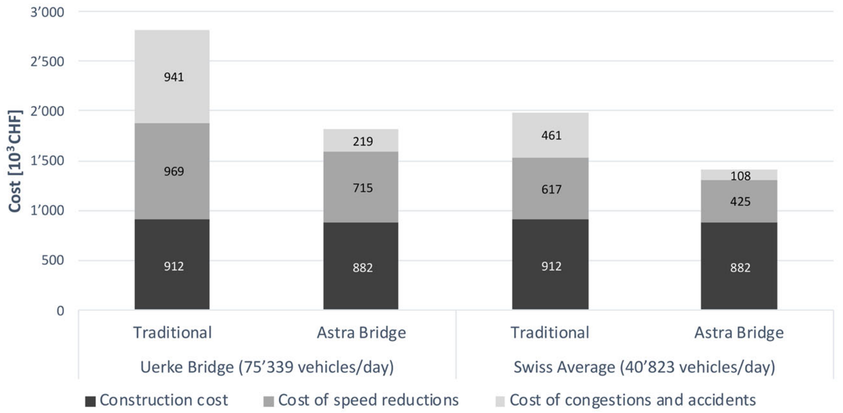

Figure 8. The construction and user costs (i.e. cost of speed reduction, cost of congestion, cost of accidents) for both processes in both traffic situations.

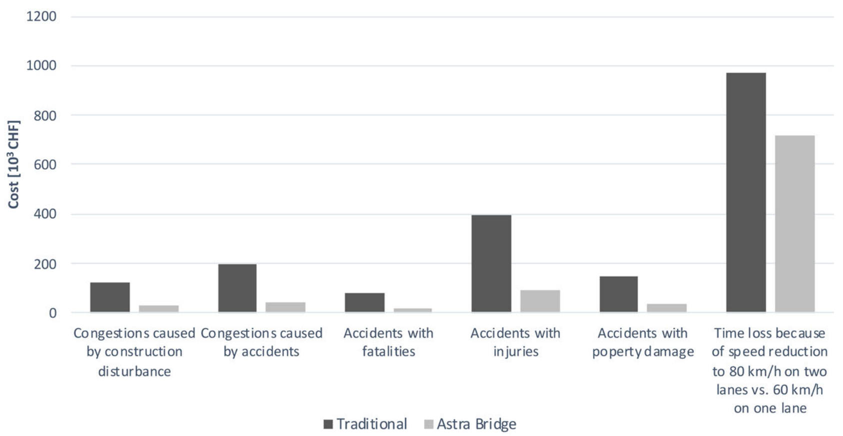

Figure 9. The detailed user cost composition for both processes in the OLR scenario.

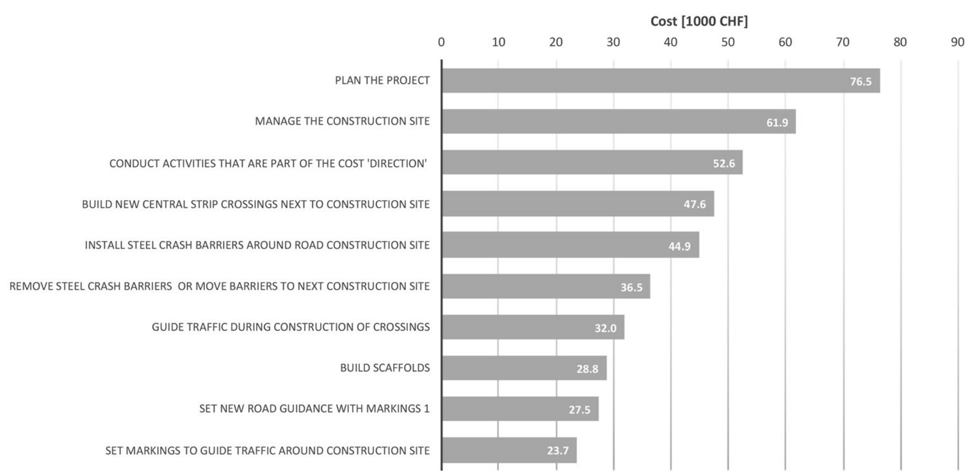

Figure 10. Top 10 tasks featuring high cost in the refurbishment process without using ASTRA Bridge.

The detailed distributions of the cost of the bottleneck tasks in both processes are illustrated in Figures 10 and 11. The cost distributions showed that the most expensive tasks were the planning and central strip crossing activities in the traditional process, making these tasks an ideal candidate for cost reduction by removing the central strip crossing activities as much as possible. Compared to the traditional process, the planning and assembly tasks are subject to the highest costs in the ASTRA Bridge process where the central strip crossing activities are no longer necessary.

Under the OLR scenario, a sensitivity analysis was conducted to reflect influence of variations of the speed limit. By changing the input values of the speed limit, the sensitivity analysis showed that the total cost reduction due to the use of the ASTRA Bridge decreased from 1 million CHF to 700,000 CHF if the users were supposed to drive past the construction site at a speed of 100 km/h on average instead of 120 km/h. As an extreme case in the sensitivity analysis, when all vehicles pass the ASTRA Bridge at a speed of 40 km/h, the total cost reduction by using the ASTRA

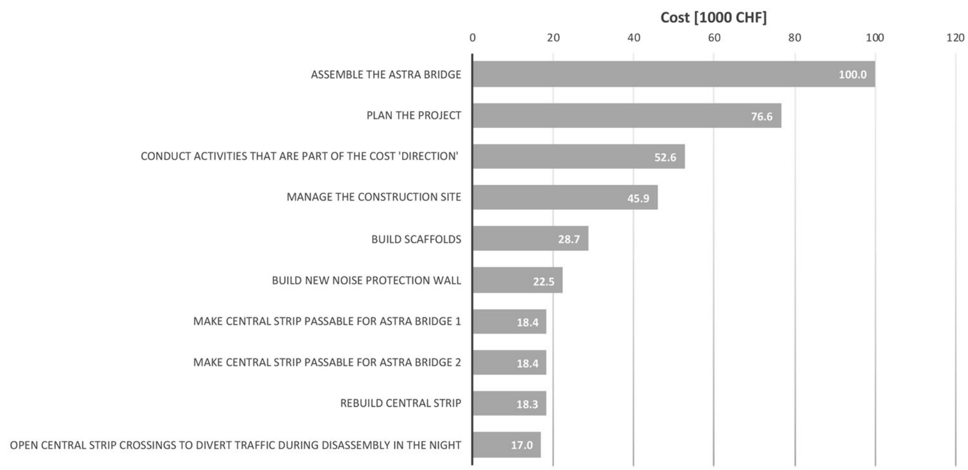

Figure 11. Top 10 tasks featuring high cost in the refurbishment process using Astra Bridge.

Table 3. Simulation results of ALR the scenario for both processes.

			ALR scenario		
		OLR scenario	Add 2 daytime workers	Add 4 daytime workers	Add 1 insulation team
Refurbishment process using the ASTRA Bridge	Total cost [10^3 CHF]	882	876	875	880
	Total duration [w]	16.3	15.2	14.2	15.6
	Duration savings [w]	0	1	2	0.4
	Waiting Time [h]	728	513	364	647
Refurbishment process without using the ASTRA Bridge	Total cost [10^3 CHF]	912	918	930	914
	Total duration [w]	19.1	17.5	16.9	17.5
	Duration savings [w]	0	2	2	1.6
	Waiting Time [h]	577	320	225	488

Note: [w] represents weeks, [h] represents hours.

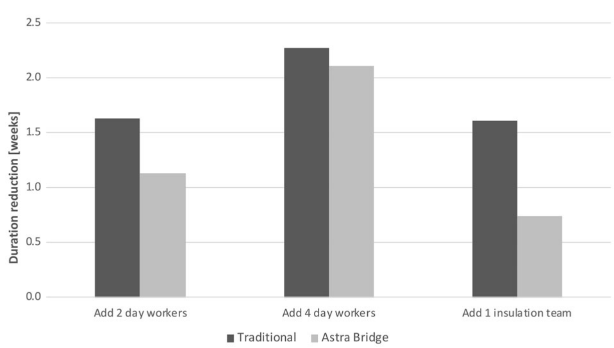

Figure 12. The reduced durations respectively in the two processes under the ALR scenario.

Bridge was only around 260,000 CHF. By changing the traffic volume per meter length of the construction site, the sensitivity analysis showed that the cost reduction was increased up to 1,300,000 CHF when the ASTRA Bridge was used for a much shorter span construction site. The sensitivity analysis showed that adjusted speed assumptions would result in different numbers, but that the ASTRA Bridge still brought a reduction in costs.

4.2. ALR scenario - refurbishment with additional labor resources

The simulation results of the ALR scenario are summarized in Table 3 and illustrated in Figure 12. Adding 4 daytime workers helped reduce the duration of the traditional process from 19.1 to 16.9 weeks without holidays. Similarly, the duration of the Astra Bridge process was reduced from 16.3 to 14.2 weeks. The differences in the total cost between the OLR scenario and the ALR scenario were however small.

The total duration of both processes was reduced by 2 weeks by adding 4 daytime workers to remove the waiting times on tasks. The addition of 2 daytime workers or adding 1 insulation team was more beneficial for the traditional process. For the ASTRA Bridge process, adding 4 or more than 4 daytime workers further enhanced the time efficiency of refurbishment work.

5. Discussion

In the two processes, main construction activities were modelled using BPMN diagrams and structured in four layers: the planning layer, the core layer, the construction layer and the detailed layer. Although the BPMN process models were sufficiently representative of the real-world processes to indicate the difference between them, it must be noted that the real-world processes are considerably more complex and are subject to considerable uncertainties such as labor strikes and extreme weather. Nevertheless, this study has provided the first quantitative indications that it is worthwhile implementing the ASTRA Bridge.

The Uerke Bridge project represents a common type of short-span highway bridge in Switzerland. The simulation results of how this project would run indicate the possible savings in terms of reduced construction, labor, and user costs for all the 2,441 Swiss highway bridges that are less than 50 meters in length if the ASTRA Bridge is used for the refurbishment of their decks. The exact evaluation of the user cost and the resulting reduced total cost, however, is dependent on the actual traffic volume and driving speed used on the specific highway bridge of a chosen location. Simulation results have to be validated using information collected from real world experiments. During the course of this study, no real world experiments were possible. Since the assumptions used in this study are based on expert opinion, historical documentation, and Swiss traffic standards, the simulation results remain justifiable and realistic to represent the performance of implementing the ASTRA Bridge for short-span highway bridges. Compared to the traditional process, the ASTRA Bridge process is likely to result in the following benefits:

(1) *A reduction of the duration of bridge deck refurbishment projects in the short-span highway bridges* (using Uerke bridge as a representative, a 14% reduction could be attained). Part of the reason is the elimination of the need to install several traffic guidance structures and the independence of construction work from bad weather conditions. In the traditional process, 6 out of 10 of the most expensive tasks are related to traffic guidance installation. However, it is worth noting that the ASTRA Bridge system is not completely weatherproofing. Due to the cross slope of the road, water may still flow into the construction area during heavy rain and therefore construction work could be halted despite the ability of the system to offer some protection from the elements.
(2) *A small change in the intervention costs* (For the Uerke bridge the reduction was 3%). On the one hand, the assembly and disassembly of the ASTRA Bridge during one night from Saturday to Sunday with 28 workers increased the cost. On the other hand, this additional cost was compensated by the reduction in the costs of traffic guidance. For example, the safety crash barriers, such as the Vario Guards, can be considerably reduced from 832m to 166m of steel crash barriers, assuming the central stips crossings are built right next to the construction area.
(3) *A significant reduction in user costs* (For the Uerke Bridge, the user cost was reduced by 51%). The user costs primarily come from the time loss due to the speed reduction, followed by the costs incurred due to the increased traffic accidents near the construction sites. Congestion costs directly caused by the construction site were relatively small, as the Swiss federal road authority has been putting in place considerable effort into refurbishment construction regulations to reduce the congestions. The main reasons for the reduced user cost in the ASTRA Bridge process, include that 1) only one highway side is disrupted; 2) construction site length is shorter and 3) reduced construction work duration. These facts in turn helped reduce the risk of congestion and accidents through speed reductions.

Some additional considerations when deciding to implement the ASTRA Bridge process for future highway bridge refurbishment projects are the following:

(1) The ASTRA Bridge has an operational lifespan of at least 20 years. The high development cost (around 20 million CHF) should be further justified by investigating the total reduction of user cost when it is continuously used in highway bridge refurbishment projects over a long period of time. The simulation results for the Uerke Bridge indicate that the benefits of using the ASTRA Bridge for 20 short-span highway bridges in Switzerland could compensate for the development cost. Assuming it is used on one short-span highway bridge per year, the break-even point is still possible within the lifespan of the ASTRA Bridge. For the 2,441 highway bridges of less than 50 meters in length in Switzerland, around 100 of them need at least one refurbishment project per year, assuming the average lifetime of the bridge deck is 25 years. The reduction of total cost and total duration at such a scale could be significant. The first author interviewed three construction professionals of the highway bridge refurbishment projects in Lausanne and two bridge engineers from ASTRA, whose feedback was consistent with this potential of the adoption of ASTRA at scale.
(2) Although the study focused on one example project in Switzerland, the BPMN process modeling and evaluation could be repeated using local labor and traffic data in other developed countries and similar improvement could be extrapolated to address their ongoing extensive demand in highway refurbishment. For example, most of the highways in the US and the rest of Europe were built in the 1960s and were not well maintained. 30% of all traffic jams have been incurred from construction sites in Germany and 15% in Austria (Fritsch, 2018, ASFINAG 2016). Specifically in Germany, there were 600 existing refurbishment construction sites on German highways in 2017 (Gassmann, 2017) and 1,909 km out of a total of 12,993 km of highways in Germany need refurbishment yearly (Speda, 2019, BMVI 2020). Using the ASTRA Bridge process for German highway bridges would reduce user cost by around 2.1 million CHF if the user cost reduction from the Uerke Bridge case study is proportionally allocated to similar projects in Germany using the same labor and traffic regulation data. Despite the fact that ASTRA has already registered the patent for the ASTRA Bridge in 34 different countries, adopting the ASTRA Bridge process internationally requires careful considerations as the adoption is subject to complex social-technical and cultural factors in a specific local context. For example, traffic rules, regulations, people's driving behavior and their acceptance of the new ramp systems will have an impact on the success of the adoption of the ASTRA Bridge. The benefits of using ASTRA

Bridge will have to be widely demonstrated and statistically proven on different types and sizes of highway bridge refurbishment projects to ensure a complete understanding of when and where it is best to use it.

6. Conclusions

The refurbishment of highway bridges requires making a trade-off between the speed and cost of performing the refurbishment and the amount of traffic disturbances caused by the refurbishment. Accelerating the work while reducing traffic disturbances are two intertwined goals of the development and implementation of new technologies. One of these new technologies is the ASTRA Bridge, a recently developed mobile modular ramp system. The ASTRA Bridge is a 236-meter long steel ramp system on wheels that are placed on top of the bridge deck undergoing refurbishment to enable vehicles to continue to pass over the bridge while construction work progresses underneath.

This paper conducted the first quantitative and preliminary analysis of the effects of using the ASTRA Bridge on the time, costs, and traffic disturbances associated with bridge refurbishment. The analysis was done using empirical data collected from the completed Uerke Bridge project in Switzerland and discrete event simulations. Two labor resource usage scenarios: − 1) refurbishment with ordinary labor resources (OLR) and 2) refurbishment with additional labor resources (ALR) - were simulated for both the traditional process and the ASTRA Bridge process. The Uerke bridge is considered to be representative of all of the 2,441 short-span (shorter than 50 m) highway bridges in Switzerland. The simulation results were considered to be reasonably accurate representations as to what they would expect and to provide stakeholders (e.g. road authorities in Switzerland) the first reference values about the effects of using the ASTRA Bridge during short-span highway bridge deck refurbishment projects.

The simulation results for the OLR scenario for the Uerke bridge showed that the ASTRA Bridge process reduced the total cost by 3%, the total duration by 14%, and the user costs by 51%. The total cost, including construction cost, labor cost, and user cost, was reduced by 1 million CHF from a total cost of 2.82 million CHF when the traditional process was used. The major bottlenecks (i.e. tasks subject to high waiting times for available labor resources) in the traditional process were found to be the reprofiling and insulation activities and that of the ASTRA Bridge process were reprofiling and removal tasks. When adding labor resources, the simulation results of the ALR scenario showed more cost and time improvement in the traditional process than in the ASTRA Bridge process. Considering the current increased refurbishment needs of highways and bridges in developed countries other than Switzerland, the cost and time efficiency of using the ASTRA Bridge would be more significant.

In future research, the ASTRA Bridge is intended to be used in a real-world test project and the related construction processes will be closely monitored and documented. The analysis effort should then be repeated using more detailed information and more detailed descriptions of the processes. In addition to focusing on bridge deck refurbishment, it is suggested to investigate the use of the ASTRA Bridge for other types of projects that may cause traffic disturbances. The BPMN simulation and process evaluation could also be repeated for bridge refurbishment projects in other countries taking into consideration the specific regional conditions, e.g. traffic conditions and labor resources.

Notes

1. Federal Roads Office of Switzerland is referred to as Bundesamt für Strassen (abbreviated as ASTRA) in its German translation.
2. Business Process Model and Notation (BPMN) is a graphical representation for specifying business processes in a business process model. The newest version BPMN 2.0 is released by the Object Management Group (OMG).
3. The simulation software BIMP can be accessed via https://bimp.cs.ut.ee/.
4. For both processes, the daytime workers are scheduled for deck refurbishment construction tasks, and the nighttime workers are scheduled only for preparing, adjusting, and removing the traffic guidance and the weather protection tents during the night.

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Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Some or all data, models, or simulation codes that support the findings of this study are available from the corresponding author upon reasonable request. Main data and models are saved in the supplementary files, which are provided via the link: https://bit.ly/3qgO7cL

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Appendix

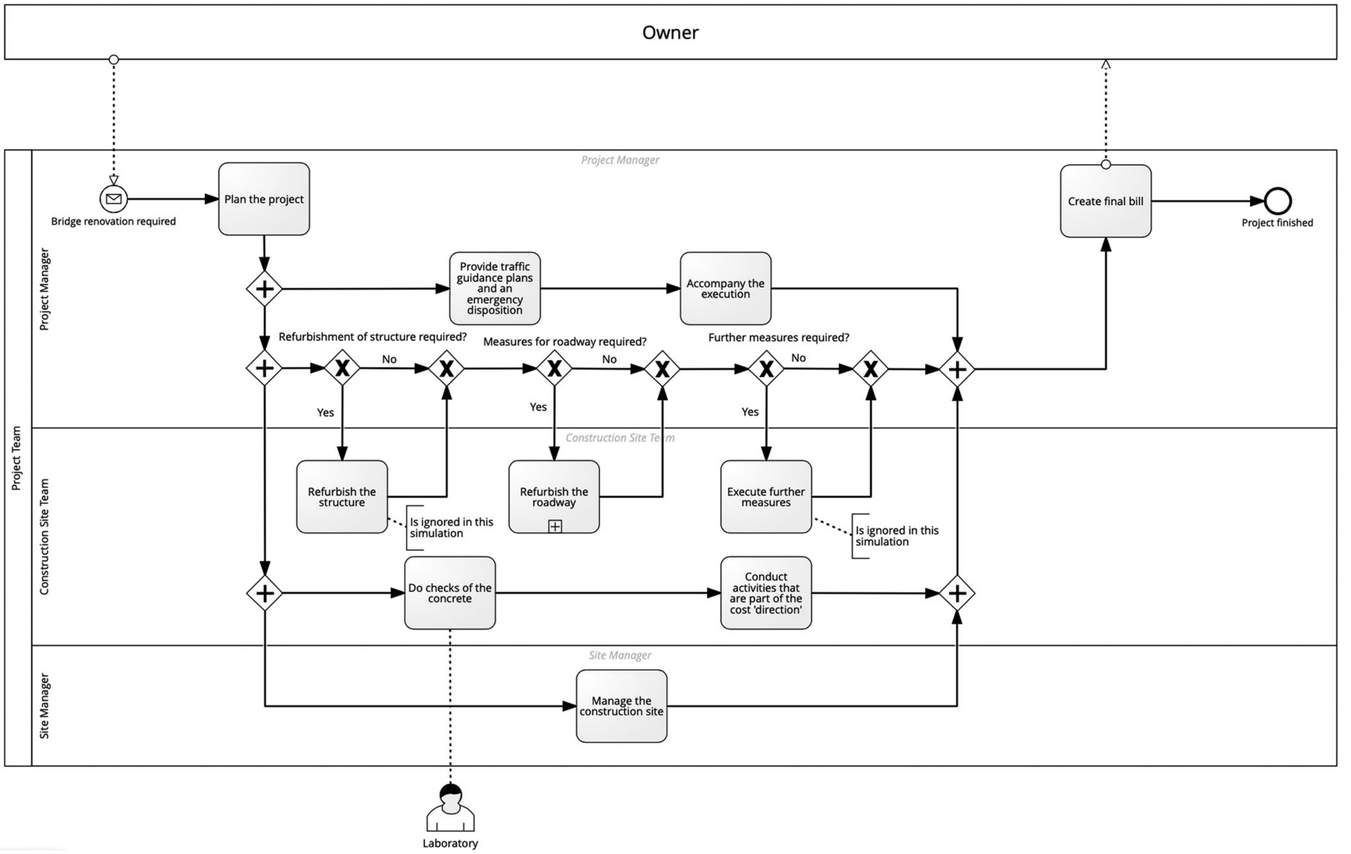

Figure A.1. The layer one process diagram which shows the process on a high level.

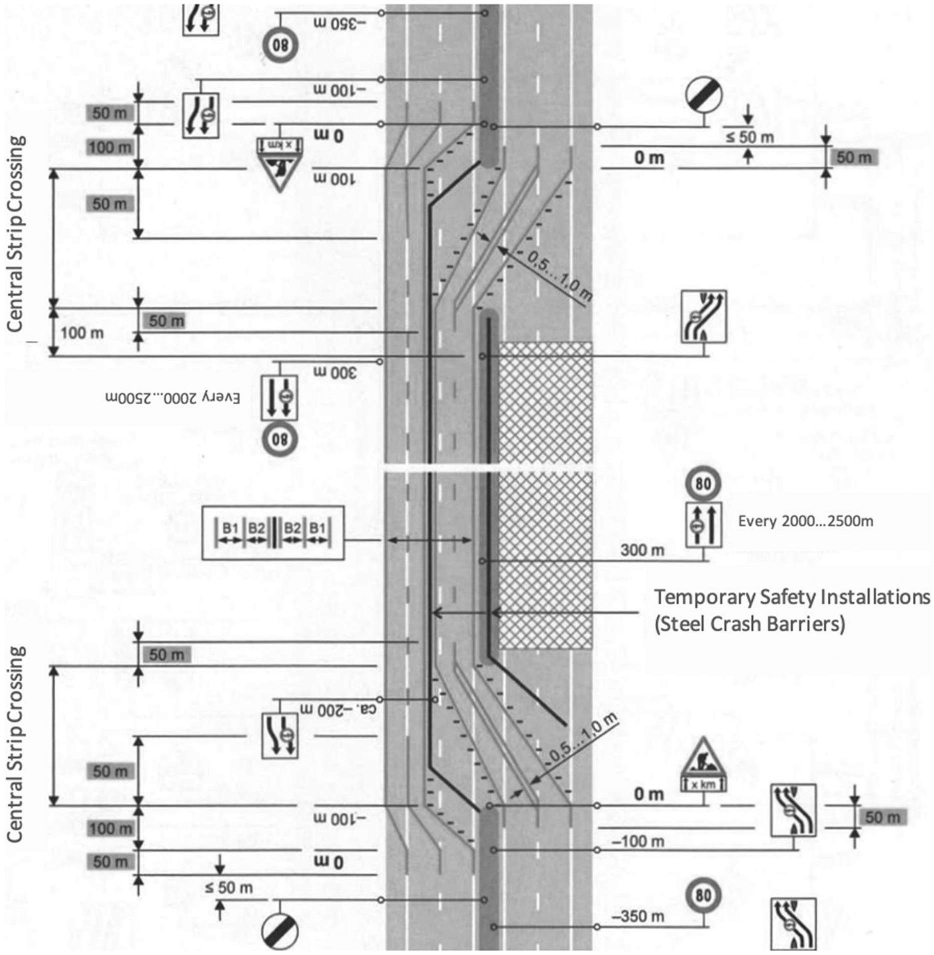

Figure A.2. The overview of the 4/0 traffic guidance concept based on the SN 640885 standard (VSS 2015).