Recommendations for Advanced Application & Guidelines for Bridge Authorities regarding Agency Needs

1. Introduction
In this project European partners from universities, research centers, road administrations, design offices and steel producers brought together their knowledge and experiences on steel-composite bridges. These bridges were not as commonly regarded only under the aspect of an efficient initial state and construction cost performance but over the entire lifecycle. On the one hand, during this long lifecycle bridges are designed for, degradation processes such as fatigue, corrosion and carbonation were regarded. On the other hand, inspection and maintenance were closely looked at in order to keep the bridges in good conditions. The functional quality was combined with the environmental and economic quality. By this holistic approach (LCA, LCC, and LCS) an assessment of the lifecycle was reached.

2. Conclusions from worked examples
Typical for the application range of concrete and steel-composite bridges in Europe three bridge types were identified according to the span length and their functionality. Small single span motorway bridges spanning nearly 35 meters using either composite girders or precast concrete girders were considered as bridges of type C2. Multi-span motorway bridges having a structural typology of continuous beam with a total length of 308 m distributed over nine spans were studied as bridges of type C1. Bridges of type A consisted of crossings of motorways spanning 40 – 50 m and allowed for comparisons between different abutment types (integral and seated bridges) and span distributions (single and two-span bridges). Span lengths up to 166 meters were reached by big motorway bridges and were assigned to type B1 with plate girder composite sections.

An extensive number of case studies was selected, assigned to the bridge types and studied in detail. The base of the analyses was the extensive data collection performed and compared for the different European countries involved. The detailed data compilation was integrated into a database. Bridges are designed for more than 100 years and the operation stage plays a central role. Special focus was given by compiling and comparing inspection and maintenance strategies. Standard scenarios were elaborated including frequencies, costs, traffic restrictions during the actions, equipment etc. For the maintenance scenarios average service lives of bridge elements were defined and necessary actions described. In addition,
two specific scenarios were elaborated and studied: a) the lack of money scenario and b) the prolonged life scenario. For both of these scenarios further assumptions were made and an adapted frequency of maintenance actions assumed.

The case studies were designed following the requirements of codes and rules. The material quantities determined were further used in lifecycle costs and lifecycle environmental analyses. Bridges immediately start to deteriorate after entering into service. In order to keep the bridges above a required condition, inspection, maintenance and rehabilitation actions are necessary. With each intervention environmental and economic impacts are caused and need to be taken into account. Hence, the structural performance must be known as environmental and economic analysis directly depend on it.

For the lifecycle environmental analysis, a system boundary was set, including all stages over the complete lifecycle of the bridges, from raw material extraction to the end-of-life, considering also the recycling. Seven indicators of environmental performance were regarded and the inputs determined.

Lifecycle costs were regarded from design to the end-of-life of the bridges. In order to compare past and future cash-flows with those of today several methods were compared. A yearly discount rate was set to 2% in the LCC for the 100-year service life in the standard and lack of money maintenance scenarios and for 130-year service life in the prolonged life maintenance scenario. Lifecycle social analysis was regarded considering user costs apart from direct measurable costs. These user costs are costs caused by maintenance operations leading to traffic congestion or disruption of the normal traffic flow. User costs were divided into traffic delay costs and vehicle operating costs.

The established database, the analysis of lifecycle performance, the lifecycle environmental and economic analyses were all together integrated in the holistic approach to the aforementioned and selected case studies.

The following conclusions can be provided for each bridge type:

- **Case A - Crossings of motorways**

For crossings of motorways the environmental impacts of the material production and the operation stage dominate by far the lifecycle. In general, a reduction of these impacts is achieved for the integral bridge solution. For crossings of a motorway a big benefit was registered for the integral as the maintenance of bearings and expansion joints is avoided and therewith traffic congestion reduced.
In terms of LCC, the integral steel composite solution (A1) is costly in terms of initial investments relative to the concrete counterpart. It was deduced that the composite steel solution (case study A3) is better than both its concrete equivalent (A2) and the integral solution A1 when considering the initial costs. On the other hand, the integral bridge gave reduced operating costs as it avoids the need for maintenance actions concerning expansion joints. The integral bridge requires less maintenance and therefore leads to less traffic disruption and reduced user costs. However, the traditional steel composite bridge gains slight favourability in the overall analysis.

LCA considering alternative maintenance scenarios showed that the lack of money scenario resulted in reduced emissions in all impact categories for the concrete bridge whereas the integral and traditional composite bridges had some increments as well as decrements in the different impact categories. The prolonged life scenario resulted in higher environmental impacts in all three cases.

LCC considering the alternative maintenance scenarios resulted in a more or less similar economic implications in the concrete bridge (A2); while for the integral bridge and the traditional composite bridge, both the lack of money and prolonged life scenario incurred additional costs as compared to the standard scenario.

The social analysis (LCS) proved that the integral and the composite bridge share similar characteristics for the alternative maintenance scenarios. In both bridge types, the lack of money scenario lead to reduced user costs and the prolonged life scenario caused an increase in the user costs. However, for the concrete bridge (A2), both alternative scenarios, standard and prolonged life, resulted in a comparatively higher user cost as compared to the lack of money scenario.

To conclude, it appears that for such short spans, integral abutments could be preferred to usual abutments (with bearings and expansion joints). Also the choice between a concrete bridge and a steel-concrete composite bridge is governed by the importance given to user costs and therefore to the position of the bridge in the transport network.

- **Case B - Big motorway bridges**

Similar conclusions on the lifecycle environmental analysis can be drawn for the big motorway bridges. As before, the material production and the operation stage dominate the lifecycle, here again. Once more, the social aspects of the LCA prove that the night shift is considered favorable in reducing the impacts on user cost. The user costs calculated for the two different working shifts on the same bridge resulted in a difference of almost 1.5 million €. The application of the different scenarios to this case study reveals that the “lack of money”
The scenario has lower user costs at the end than the standard scenario while the “prolonged life” scenario has the higher user costs.

- **Case C1 - Multi-span motorway bridges:**

It was observed from the lifecycle environmental analysis that the stages of material production and operation dominate all impact categories. In terms of processes, the production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage the impacts are mainly caused by traffic congestion.

In terms of Lifecycle costs, it is evident from the case studies that the steel composite bridge exhibited preferable characteristics. The Initial cost and operation costs for the steel composite bridge were found to be less than its concrete counterpart. The steel composite bridge gained favourability in the end-of-life stage, as well, due to the abundant recycling possibilities with steel. Once more, the social aspects of the LCA prove that the night shift is favourable in reducing the impacts on user cost.

Assessing alternative maintenance scenarios, it was found that the lack of money scenario led to lower impacts on the environment in both the steel composite bridge and the concrete bridge. Moreover, it was concluded from both the LCC and LCS analyses that lower operation and user costs, respectively, are achieved with the “lack of money” compared to the standard maintenance scenario for both bridge types. The effort made to prolong the service life of the bridge with the “prolonged life” scenario lead to an increase of impact in all environmental categories. The operation costs and user costs were also increased as the service life is prolonged except that lower LCC value were obtained for the post-tensioned reinforced concrete bridge in the “prolonged life” scenario albeit the longer service life of the bridge.

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- **Case C2 - Small single-span motorway bridges:**

In this case study for small motorway bridges, it was observed from the lifecycle environmental analysis that the stages of material production and operation are by far dominating all impact categories. In terms of processes, the production of construction materials throughout the lifecycle and traffic congestion due to work activity, are the main causes of environmental burdens in the lifecycle analysis. For the operation stage, the impacts are mainly caused by traffic congestion.
In terms of Lifecycle costs, it was evident that the initial cost for the steel composite bridge is higher due to material and construction costs. Moreover, the operation costs are more or less similar for the two bridge types namely, steel composite bridge and its concrete counterpart. However, the steel composite bridge gains slight favourability at the end-of-life stage owing to its abundant recycling possibilities.

The social aspects of the lifecycle prove that the night shift is favourable in reducing the impacts on user cost. It has been seen that the overall results are improved when carrying out maintenance work at night. Night shift work provides reduction of impacts owing to the fact that traffic count is lesser at night. The user costs calculated for the two bridge types are comparable for the given traffic volume.

Case D - An innovative integral bridge over a motorway.

Case D1 – Corrosion protection: Hot-dip galvanization (thickness 300 µm) and no renovation is considered during whole life cycle of the bridge;

Case D2 – Corrosion protection: Organic protection coating and complete renovation of the corrosion protection in year 33 and 66 of the life cycle of the bridge;

Case D3 – Corrosion protection: Hot-dip galvanization (thickness 200 µm) and application of an organic corrosion protection in year 66 of the life cycle of the bridge;

In case study D, it was observed from the lifecycle environmental analysis that the stages of material production and end of life dominate all impact categories. The alternative that used conventional coating resulted in higher impacts on the environment and users due to repeated maintenance operations on the steel girder’s corrosion protection layers. It has been seen that the overall results are improved the most carrying out maintenance work at night. Night shift work provides reduction of impacts owing to the fact that traffic count is lesser at night.

In terms of the initial cost, i.e., production and construction costs, the three alternatives of corrosion protection lead to a relatively similar cost with slight favourability to the ordinary steel coating. And the end of life costs are the same for all the three alternatives. However, the first
alternative, 300 µm hot-dip galvanized steel, showed significant reduction in cost in the operation stage as there is no need for maintenance throughout the lifespan of the bridge. The second alternative, which required two full renovations - via organic coating - of the corrosion protection layers, resulted in higher operation costs. The third alternative, where by duplex coating scheme was adopted, is less costly than the second but still more expensive than the first alternative. In conclusion, it can be said that the hot-dip galvanization presents itself as the best alternative in terms of lifecycle cost.

Once more, the social aspects of the lifecycle analysis prove that the night shift is favourable in reducing the impacts on user cost. The user costs associated with D1 were found to be 29.8% and 11.9% lower than those for cases D2 and D3, respectively. Comparing LCC of the three alternatives with the user costs included, the hot-dip galvanized bridge is 21.3% cheaper than the one with the customary organic coating, instead of the 5.4% difference while not considering the user costs. It was also noted that the user costs make up for more than 65% of the total lifecycle costs.

- **Case E - An innovative composite bridge PRECOBEAM**

Contrary to the previous two cases, Case study E, put the focus solely to the bridge deck. The Precobeam solution, an innovative bridge construction method, was studied against a conventional composite bridge solution. As a result, it was observed from the lifecycle environmental analysis that the stages of material production and end of life stage dominated in all impact categories. The LCA resulted in a more or less the same impact on the environment for both cases with slight favourability to the PRECOBEAM solution in the ODP impact category. Life cycle costs were not evaluated for this case study.

Concerning the social aspects the night shift is more favourable in reducing the impacts on user cost. The user costs associated with case the precobeam solution were found to be significantly lower than those calculated for the traditional composite bridge.

3. **Recommendations for advanced application**

- Bridges should be treated individually at their location in the infrastructure network taking into consideration traffic management specific features and construction methods. In this type of approach, the presented examples should not be generalized. However, many lessons can be learned from the case studies, according to their particular features.

- It was shown that composite steel-concrete bridges can be competitive when compared to concrete competing alternatives if the comparison covers the entire lifespan of the structures being analysed. Under these conditions, the initial investment in the design stage will certainly payoff.
• Good knowledge of quantities, construction methods and their respective implications in traffic management are mandatory to obtain credible results in life cycle analysis.
• Reliable results in life cycle analysis are highly dependent on the best knowledge of material quantities, construction methods and their implications for traffic management.
• Good knowledge of traffic counting and evolution over time is advisable, since it affects all categories of life-cycle analysis.
• The discount rate should be carefully chosen to reflect the time horizon of the analysis, since all costs must be discounted to the present.
• The lifecycle performance of each bridge is mainly described by the performance of critical details. Good knowledge of the behaviour of the details during the entire lifespan of the bridge is essential.
• The holistic approach opens up for long-term investments such as HSS, self-weathering steel or post-weld treatment, as these pay off easily during the operation stage.
• The tool provided, allows great user flexibility. Unit costs and traffic management features can be changed to test multiple alternatives.

4. Guidelines for bridge authorities regarding agency needs

• Life-cycle analysis should contribute more effectively for the proposals ranking on bidding processes. We believe that the implementation of a bonus system for those proposals that prove to be most effective over the entire assets life cycle would be an encouraging measure for bidders.
• In the evaluation of the bidding proposals, analysis periods should be long enough to capture long-term differences in discounted costs among competing alternatives and rehabilitation strategies. These periods should encompass all maintenance and rehabilitation cycles as well as end-of-life disposal costs.
• Concession agreements with private sector could comprise designing, building, operating and maintaining infrastructure assets over their full life cycle.
• funding of private players who demonstrate their performance regarding sustainability
• encourage the implementation of LCCA-driven cost-effectiveness company ranking
• encourage the implementation of training programs for executives and experts of tendering authorities
• encourage the implementation of specific legislation to overcome the difficulties created by short term political cycles
• The social aspects of the lifecycle prove that the night shift work is favourable in reducing the impacts on user cost. In addition, it reduces reputational costs, particularly in tolled motorways.

• Life Cycle Assessment considering alternative maintenance scenarios showed that the lack of money scenario resulted in reduced emissions in all impact categories for the concrete bridge whereas the integral and traditional composite bridges had some increments as well as decrements in the different impact categories. However, it should be noted that this comes at the expense of degradation of the bridge which may ultimately lead to a decision to replace the bridge altogether.

• In some structures, where the design is governed by the seismic action, Life Cycle Costs of the steel composite solution may be lower than its concrete equivalent. Differences in substructure costs can be explained, generally, by the significantly heavier decks in concrete solutions, implicitly associated to higher inertial forces and, therefore, higher seismic stresses in columns and foundations.