A simplified design approach for small river crossings in African rural areas

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Summary

In many developing regions, small river crossings are essential for access to markets, healthcare and education. However, their design often faces difficulties due to limited resources, lack of infrastructure and insufficient engineering skills. Large, complex bridges are rarely feasible, making small-scale, practical solutions crucial for connectivity and local development. This paper presents a simplified methodology for the preliminary design of small river crossings, suitable for non-specialists such as contractors or local engineers. Offering easy-to-use calculations, design spreadsheets and practical guidelines, the approach reduces technical barriers and ensures safe and durable structures adapted to local needs. Developed as part of the I-FERME project, funded by the Politecnico di Milano and involving multiple scientific disciplines, this work promotes infrastructure development in remote areas and enables local actors to contribute to the progress of their communities.

1 INTRODUCTION

In rural areas, small river crossings are indispensable elements of transportation networks, providing critical connections to markets, healthcare facilities, and educational institutions. Despite their importance, the design and construction of these crossings often face significant obstacles. Limited financial resources, a lack of robust infrastructure, and the absence of specialized engineering expertise constrain the feasibility of traditional bridge solutions. Large, complex structures, while effective in other contexts, are frequently impractical in rural areas, where simpler and more cost-effective alternatives are essential to ensure connectivity and support local development.

The reliance of many rural communities on temporary or rudimentary crossings exacerbates the challenges. These structures are often poorly adapted to withstand seasonal flooding or changing environmental conditions, leading to frequent disruptions and safety risks. The situation highlights the urgent need for durable, low-cost solutions that can be implemented with the resources and expertise available locally [1]. This article builds upon the work conducted within the I-FERME (Intelligent inFrastructure dEsign foR a Multifunctional Efficient farm) project, an initiative funded through the Polisocial Award by the Politecnico di Milano. The project focuses on enhancing the efficiency of multifunctional farms in the Democratic Republic of the Congo (DRC) and sub-Saharan Africa. Its strategy includes developing simplified tools for preliminarly designing road infrastructure and support services for food processing and storage. These tools are optimized for local resources and needs, and made accessible to the involved communities and other target groups. While the proposed method offers a practical approach, it also presents certain limitations that will be examined throughout the paper.

2 PROPOSED METHODOLOGY

The simplified methodology for the preliminary design of small river crossings presented in this article demonstrates the project's commitment to delivering practical, scalable, and socially impactful solutions. By integrating straightforward calculations, well-structured design tables, and clear, user-friendly guidelines, this approach reduces technical barriers and enables local stakeholders to actively contribute to the sustainable development of their communities. This effort to lower technical barriers has also been supported by the creation and publication of a dedicated Massive Open Online Course (MOOC), aimed at introducing end users to the conceptual design of small river crossings and the practical application of the proposed tools [2].

2.1 Local context

The I-FERME project focuses on improving the efficiency of multifunctional farms in Sub-Saharan Africa, particularly in the DRC, through the development of simplified design tools for road infrastructure (small river crossings) and support systems for food processing and preservation (stand-alone solar power grids and solar/biomass powered cold storage units). These tools are optimized for local resources and needs, aiming to promote sustainable agriculture. The primary application context is the Mpangala agro-pastoral farm, located about 40 km from Kinshasa [3]. The establishment of this farm, a key site in the project, was originally promoted by the Catholic University of Congo and the Congolese Episcopal Conference.

In Sub-Saharan Africa, smallholder farmers contribute to about 80% of agricultural production. However, farm operations in the region face numerous challenges, as nearly 70% of farm tasks are carried out manually, with only 10% of farm operations mechanized. The lack of mechanization, alongside poor access to electricity further intensifies the difficulties faced by local farmers. Additionally, road infrastructure remains a critical barrier, with most regions having limited or poor-quality roads that hinder the transport of agricultural products to markets (Fig. 1).

In this context, the need for efficient and accessible infrastructure is vital. The Mpangala farm, located in an area with limited paved roads and access paths that are sandy and poorly maintained, exemplifies the challenges faced by farmers in rural DRC. To enhance accessibility, the project aims to support the design of small-scale river crossings that could improve vehicle access to remote farms like Mpangala, supporting both agricultural activities and marketability of local products.

The design tools presented in this paper were developed to be straightforward, flexible, and reusable by non-specialists, including university students and local engineers, ensuring their applicability in comparable developing contexts.

Fig. 1 Current river crossing structures at the Mpangala farm

2.2 Objectives and base hypoteses

The proposed methodology aims to offer a simplified approach for the preliminary structural design of small river crossings in areas with limited technical expertise and resources. It seeks to balance ease of application with safety, sustainability, and adaptability to local constraints. To this end, the methodology is based on key assumptions that simplify the design process while ensuring reliability and structural integrity.

The design focuses on small bridges with spans between 4 and 12 m, typically suited for rural or secondary roads. Priority is given to simple single-span structures with a single lane (between 2.5 and 4.5 m wide) and simply supported static schemes, as more complex systems would require a level of detail that goes beyond what can be effectively simplified. The design considers traffic loads typical of rural areas, including pedestrian traffic, light vehicles, and agricultural machinery. Specifically, following the approach proposed in [1], equivalent loads corresponding to a 20 t commercial vehicle, derived from an 18 t two-axle or a 32.5 t three-axle conventional vehicle, are considered [4]. The methodology also allows for the consideration of heavier traffic conditions, with loads up to 44 t, in accordance with alternative international design standards [5].

A key assumption is the use of locally available, low-cost materials such as ordinary reinforced concrete, solid timber, and steel. The design accounts for the variability in material quality by adopting conservative strength classes to ensure structural safety. Specifically, concrete is considered as class C30, reinforcement bars as B450C steel, structural profiles as S235 steel, and Ozouga timber (known as Niuka in the local DRC language) is selected as a commonly used material in Africa, particularly suitable for bridge construction [6].

Due to the complexity of soil conditions, foundations, and hydraulic design, the methodology limits itself to the preliminary design of the deck cross-section, advising users to consult specialized manuals [1] for the design of foundations and hydraulic considerations. The importance of conducting specific studies for foundation design and hydraulic phenomena is emphasized, as these aspects require more detailed analysis to ensure the reliability of the structure.

2.3 Preliminary design algorithm

The preliminary design algorithm, implemented in Microsoft Excel to maximize its usability even in resource-limited contexts, is divided into four main phases discussed in the following subsections.

2.3.1 Phase 1: Input of key parameters

The user inputs the key parameters in a spreadsheet provided with the MOOC [2]. Selectable variables include span length (4 to 12 m), bridge width (2.5 to 4.5 m), type of deck (transversely rigid deck such as reinforced concrete slab or composite steel-concrete slab, or transversely deformable deck such as timber plank), primary beam material (timber, steel, reinforced concrete), and loading scheme (vehicles up to 20 t or up to 44 t). The algorithm uses this data to estimate the self-weight of the deck and the stresses on the main beams, with a simplified approach that neglects the deck's contribution to longitudinal bending, thus reducing complexity in the early design phase. This strong assumption is also due to the frequent inability to provide an adequate shear connection between the beams and the deck, as demonstrated by the structural solutions shown in Fig. 1.

2.3.2 Phase 2: Automatic selection of section alternatives

Once the parameters are defined, the algorithm proposes different design solutions, considering the chosen materials and deck types. Options include rectangular and circular beams for timber, HEA and IPE profiles for steel, and reinforced concrete rectangular beams (Fig. 2). This flexibility allows for both deformable and rigid deck solutions, independent of the type of longitudinal beams.

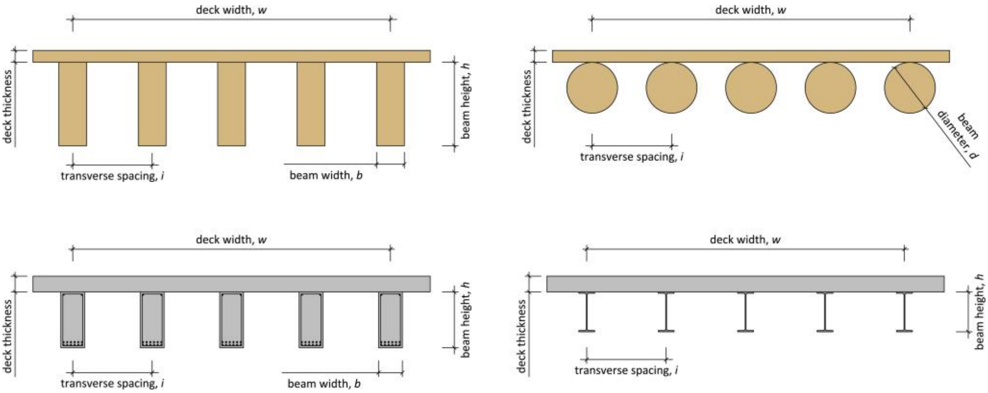

Fig. 2 Cross-sectional views associated with the constituent materials: solid timber with a transversely deformable deck, reinforced concrete with a transversely rigid deck, and steel with a transversely rigid deck

2.3.3 Phase 3: Cross-section calculation

In this phase, the spreadsheet calculates the required cross-section for the main beams, based on the chosen material and beam spacing (ranging from 0.5 to 2.5 m), considering distributed and knife loads equivalent to two commercial vehicle categories (20 t and 44 t). The deck thickness and minimum beam dimensions are determined through calculations that include: i) ultimate limit state (ULS) checks for bending; ii) ultimate limit state (ULS) checks for shear; and iii) serviceability limit state (SLS) checks for flexural deformation under variabile loads [7-10]. For sustainability purposes, the proposed solution is optimized to minimize the material volume used, as the suggested cross-sections for the primary beams are the minimum required to satisfy all three structural verifications. In addition to optimizing the cross-section, the user can also minimize the number of beams, ensuring that the total count is the smallest integer that satisfies the preliminary transverse bending verifications of the deck. The proposed sections are presented both graphically and in tables, allowing the selection of beam shapes - rectangular or circular for timber beams, and HEA or IPE profiles for steel. For reinforced concrete sections, the procedure also provides preliminary sizing of longitudinal reinforcement bars (with diameters ranging from 12 to 30 mm) and stirrup spacing, with the stirrup diameter fixed at 10 mm. As an example, Fig. 3 illustrates the output graph for the recommended solution for a small bridge leading to the Mpangala farm, featuring a 5 m span, a 3 m width, a composite steel-concrete deck, and steel IPE profiles as primary beams, designed to support vehicles weighing up to 20 t.

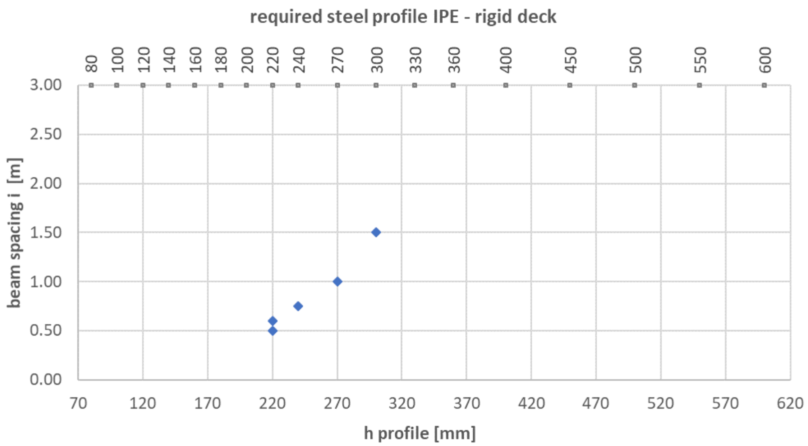

Fig. 3 Example of output graph for the river crossing leading to Mpangala farm, showing the set of optimum solutions (case of steel beams with a transversely rigid deck)

2.3.4 Phase 4: Comparison and optimization of design solutions

The algorithm allows the comparison of various construction solutions for each deck and beam combination. Specifically:

- if a beam spacing is selected, the minimum required dimension for the longitudinal beams is provided;
- if a beam depth constraint is imposed (e.g., to repurpose deconstructed resources available on-site), the algorithm provides the maximum allowable beam spacing.

Only solutions compatible with geometric constraints are displayed, accompanied by tables reporting the volume and weight of structural elements. Regarding the river crossing for the Mpangala farm and the solution with steel beams, the possible configurations include a number of beams ranging from 3 to 7, with profiles varying between IPE 300 and IPE 220, a deck weight of 56.25 kN, and a beam weight ranging from 6.33 kN (3 IPE 300 beams) to 9.17 kN (7 IPE 220 beams).

After obtaining these preliminary results, a structural engineer can proceed with detailed design, considering mandatory standards and site-specific requirements. Additionally, the volume estimates facilitate the preparation of a preliminary bill of quantities, useful for assessing material procurement costs and environmental impact, which is crucial in resource-limited contexts.

2.4 Preliminary design tools

As previously stated, the Excel tool allows users to select an optimized solution based on specific input parameters, such as geometry, materials, and load conditions. To further simplify the process, the tool can also generate sizing charts in both tabular and graphical formats.

Fig. 4 presents an output table illustrating the minimum required cross-sections as a function of beam spacing for nine different spans (ranging from 4 m to 12 m). The data is based on the following assumptions: a width of 3 m, a timber deck, rectangular timber cross-sections for the primary beams, and load combinations for vehicles up to 20 t.

	L =	4	m	5	m	6	m	7	m	8	m	9	m	10	m	11	m	12	m
n. beams	i	h	b	h	b	h	b	h	b	h	b	h	b	h	b	h	b	h	b
-	m	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
-	-																		
-	-																		
-	-																		
7	0.500	600	200	630	210	630	210	630	210	630	210	660	220	660	220	660	220	660	220
6	0.600	630	210	630	210	630	210	630	210	660	220	660	220	660	220	660	220	690	230
5	0.750	630	210	630	210	630	210	660	220	660	220	660	220	690	230	690	230	690	230
4	1.000	630	210	630	210	660	220	660	220	690	230	690	230	690	230	720	240	720	240
3	1.500	660	220	660	220	690	230	690	230	720	240	720	240	750	250	750	250	780	260
-	-																		

Fig. 4 Minimum required rectangular timber cross-section for various spans

As another example, Fig. 5 graphically illustrates the minimum required steel IPE profile as a function of beam spacing for the same nine spans, ranging from 4 to 12 m. The assumptions considered include a width of 3 m, a composite steel-concrete deck, steel IPE profiles for the primary beams, and load conditions for vehicles up to 20 t.

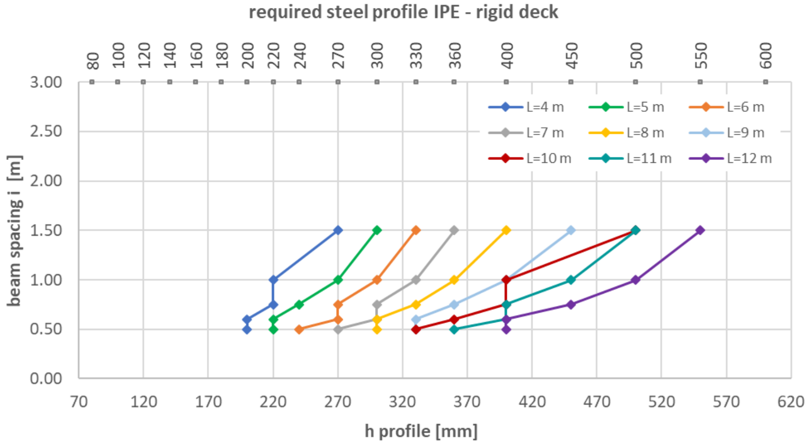

Fig. 5 Output graph with minimum required steel IPE profile for different spans

As a guide for selecting sustainable solutions in terms of material and economic costs, each sizing chart can be accompanied by corresponding tables detailing the safety factors derived from structural checks, along with the volume or weight of the structural elements.

3 SIMPLIFIED CALCULATIONS VS. RIGOROUS ANALYSES

To provide a user-friendly computational tool accessible to non-specialists, several simplifications have been incorporated into the calculations, along with fixed design choices (such as the width-to-depth ratio for rectangular timber or reinforced concrete cross-sections). The next paragraph outlines the key differences between this simplified approach and more comprehensive, rigorous analyses.

3.1 Limitations of the approach

The main limitations of the proposed approach arise from the simplifications adopted in the design assumptions and the scope of the algorithm's applicability. While the objective is to provide a tool accessible to non-specialists, significant approximations have been introduced to reduce computational complexity. The methodology applies to spans of up to 12 m, considering only simply supported structures and excluding more complex configurations. Moreover, the contribution of the deck slab to longitudinal bending is assumed negligible, accounting for the likely absence of shear connections between the beams and the deck. A more accurate evaluation of potential connections would require advanced analyses, which should be carried out by specialists. Additionally, the individual contribution of the deck to the bending resistance mechanism, which can still be quantified even in the absence of shear connections between the beams and the deck, is neglected, assigning to the deck a negligible flexural stiffness. However, this assumption may not be valid for short spans with a high number of relatively small beams.

The algorithm considers only two extreme cases of deck torsional stiffness. In the first case, assuming a transversely flexible deck, the concentrated load is conservatively assigned to two adjacent longitudinal beams. In the second case, assuming a transversely rigid deck, vertical live loads are distributed among the longitudinal beams according to their influence lengths, while torsional effects are neglected. This assumption, along with the absence of cross-bracing design, is considered conservative yet acceptable, given the narrow deck widths and the presence of a single lane, which limits torsional actions. Future studies will further investigate the validity of these assumptions, particularly assessing the influence of torsional effects on the preliminary cross-sectional design.

Furthermore, the methodology does not address more complex aspects such as foundation and hydraulic design, as these stages require specialized studies. In practical applications, these factors are essential for ensuring the overall safety of the infrastructure, representing a significant limitation of the current approach. These constraints highlight the preliminary nature of the algorithm and the necessity of more in-depth analyses and expert involvement for full-scale implementation.

3.2 Validation

To preliminarily validate the proposed tool, comparisons have been carried out with more refined numerical models. As an example, the previously mentioned case of the river crossing to Mpangala farm is presented in Fig. 6, considering the same geometry and load conditions (5 m span, 3 m width, and load capacity up to 20 t).

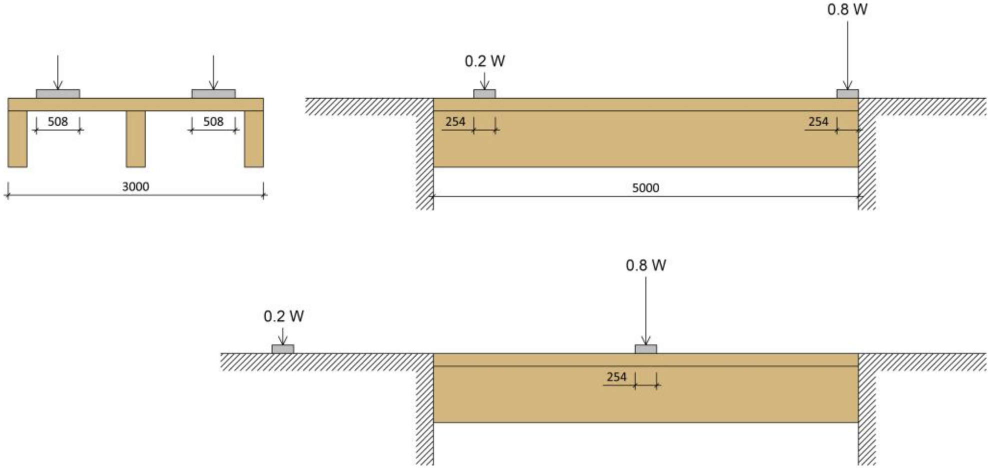

Fig. 6 Details of the validation model, including load configurations recommended in [4] for a conventional vehicle (H truck) with a total weight (W) of 18 t. Dimensions are provided in mm.

To validate the effectiveness of the equivalent distributed and knife load approach implemented in the procedure for small-span structures, the exact load footprint of the 18 t conventional vehicle, for which the equivalence is stated in [4], was incorporated into the numerical model developed in Abaqus 6.14-5.

The beams were modeled using 2-node linear beam elements (B31), while the deck was modeled with linear quadrilateral shell elements (S4R) with 5 integration points through the thickness. Maintaining the assumption of no shear connection between the beams and the deck, the shell's plane was positioned at the neutral axis of the beams. A surface-to-surface contact was then introduced between the beams and the deck, characterized by frictional behavior in the tangential direction (with a wet wood-to-wet wood friction coefficient of 0.2) and a unilateral "hard contact" normal behavior.

As shown in Fig. 6, eccentric placements of the load footprint in the transverse direction were omitted due to the limited width of the deck. In the longitudinal direction, two possible load positions were explored: i) the vehicle fully placed on the bridge, thereby maximizing the shear in the beams; ii) the vehicle exiting, with the rear axle positioned at the midspan of the beams (resulting in the maximum bending moment and maximum deflection).

3.3 Preliminary results

From the comparison between the internal actions at the ultimate limit state identified in the simplified approach (used for the preliminary design of the beams) and those obtained from the linear static numerical model, a good correspondence between the simplified results and the numerical outputs can be confirmed. As shown in Table 1, the value of the maximum bending moment in the beams is overestimated by 10.1%, and the value of the maximum shear force is overestimated by 33.6% (it should be noted that, in the simplified approach, the flexural and shear stiffness of the deck are neglected). The maximum deflection at the serviceability limit state is slightly underestimated (-1.8%), likely due to a different load distribution and the neglect of shear deformability in the simplified solution.

Table 1 Comparison between the maximum bending moment M_{Ed} at ULS, the maximum shear V_{Ed} at ULS, and the maximum deflection f_{max} (associated with variable loads only) in the beams identified in the simplified approach and the linear-elastic numerical model. The last column shows the percentage variations of the simplified approach compared to the numerical result

Parameter	Simplified approach	Numerical model	% variation
$M_{Ed,max}$ (ULS) [kNm]	107.5	97.6	+10.1%
$V_{Ed,max}$ (ULS) [kN]	113.0	84.6	+33.6%
f_{max} (SLS) [mm]	1.62	1.65	-1.8%

4 SOCIAL AND ENVIRONMENTAL IMPACT

This project responds to a critical need identified by local authorities, specifically the Catholic University of Congo (UCC), and has been developed collaboratively to enhance the sustainability and self-sufficiency of a local farm. The project aims to improve the existing infrastructure of the Mpangala farm, which currently provides intermittent food for around 200 people living nearby. With the implementation of new infrastructure, the farm's potential could be fully realized, allowing it to support a significantly larger population with a more consistent food supply throughout the year.

The results of the project have also been incorporated into a dedicated MOOC titled "*Sustainable Farm Design in Developing Countries*", which provides accessible training for a global audience and can be accessed for free through the link provided in the references [2]. In particular, Week 1 of the MOOC is dedicated to the preliminary design of road infrastructure, with a specific emphasis on river crossings in developing contexts. The week introduces materials and structural systems suitable for small bridges and outlines the key phases of conceptual design. The course also guides students through the use of a user-friendly software tool developed for the project, applying these concepts to a case study based on the Mpangala farm. The MOOC ensures that the project's outcomes are widely disseminated, increasing the reach of the knowledge generated and further enhancing the local capacity to implement sustainable infrastructure solutions.

From an environmental perspective, the project emphasizes the use of locally sourced materials and sustainable design principles, which will not only minimize the environmental impact but also contribute to the resilience of the infrastructure in the long term.

5 CONCLUSIONS

This study offers new perspectives on the preliminary design of small river crossings in developing contexts, with a particular focus on the Mpangala farm in the Democratic Republic of the Congo. The main goal was to create an accessible and simplified design approach for local practitioners, enabling them to design and implement road infrastructures, particularly small river crossings, in rural areas with limited resources. The results demonstrate the effectiveness of the developed algorithm, which combines basic design tools, such as tables and spreadsheets, with material and structural solutions tailored to the local context. Furthermore, the integration of these findings into a dedicated MOOC has provided a platform for broader dissemination, allowing students and professionals to apply the developed methods to similar projects in other regions.

A preliminary comparison between the simplified approach and a numerical model, using the load footprint of a conventional vehicle, confirmed that the approach is conservative. However, detailed design by a structural engineer is still recommended, and further research is needed to validate the methodology across different geometries and materials. This project has contributed to the broader objective of enhancing the autonomy and sustainable development of rural communities, providing them with the tools and knowledge needed to improve their living conditions and create long-term, self-sufficient solutions.

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