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Conceptual Design of Bridges Suitable for Rurally Isolated Areas

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Abstract

Construction of bridges in rurally isolated areas differs a lot from building bridges in industrialised parts of the world: the sites are remote, the availability of materials is limited, and the access to heavy machinery is non-existent. To develop a concept that can manage these challenging conditions, an alternative design process has been developed. This design process has then been applied to develop a bridge concept suitable for spans ranging from 15 to 30 meters in rural areas of Rwanda. The result is a modular steel truss bridge that can be assembled entirely by hand and adapted to various spans. To ensure that all necessary parts can be transported to the most remote sites, none of the individual elements are longer or heavier than what can be transported by foot through rugged terrain. The bridge concept is presented alongside the alternative design process developed to address the critical design challenges of rurally isolated areas.

Keywords: Conceptual design; Rural isolation; Bridge design; Steel truss bridge.

1 Introduction

All over the world, rural communities are isolated from vital resources such as healthcare, education, and employment opportunities due to dangerous river crossings or steep ravines [1]. One way to create access to these vital resources and significantly increase the quality of life for the local communities [1] would be to build footbridges over the obstacles. However, the demands placed on footbridges in rurally isolated areas are significantly different from those typically relevant when designing bridges for industrialised parts of the world [2]. Therefore, bridges designed specifically for rurally isolated areas are needed.

One of the main challenges of designing bridges for rurally isolated areas is to ensure that all the demands critical to the bridge's viability are fulfilled to a sufficient degree. In this paper, an alternative design process is proposed, aiming to handle the demands relevant to these areas more intuitively. The proposed design process is assessed and further detailed through a case study of a footbridge in an isolated rural area of Rwanda.

The work presented in this paper was initially performed as part of the master's thesis *Conceptual design of bridges suitable for rurally isolated areas: Development of a conceptual design process for bridges in rural Rwanda* by Ryrstedt and Stanek Sörner [2].

2 Alternative design process

The development of the alternative design process started with gathering information about the context of rurally isolated areas. This information was then used to gain an understanding of the relevant demands in rural areas, including their characteristics and the main differences from the demands that engineers working in industrialised areas usually encounter. The results from this comparison were then used to define an outline for the alternative design process.

2.1 Context of rurally isolated areas

Areas that are disconnected from the main infrastructure due to rugged terrain and have limited access to raw materials, logistics facilities, as well as necessities such as water, healthcare, or education, are considered rurally isolated areas in this study.

2.2 Difference in demands

The demands applicable to the circumstances in rurally isolated areas are, in some ways, similar to those used in Europe, but with a different order of priority. Here, the focus is on providing a cost-effective and easy-to-build bridge that enables people living in isolated areas to access vital resources. Additionally, due to limited resources, logistical challenges, and a shortage of skilled workers, some demands that are non-essential in developed countries, as they can be fulfilled in numerous ways, are here critical and have only a few possible solutions [2]. In developed countries, on the other hand, regulatory requirements are stricter due to market homogenisation and societal values, as well as climate-driven regulations.

2.3 Outline of the design process

The alternative design process has three main parts: a filtration process, a modification phase, and a final detailing step. A flow chart illustrating the different parts of the alternative design process is presented in Figure 1.

To ensure that the demands critical for the viability of the bridge are all fulfilled to a sufficient degree, the alternative design process starts by dividing the demands into filters and criteria. The demands critical for the viability of the design are turned into filters that can be either completely fulfilled or not fulfilled. The less important demands are instead turned into criteria, which can be fulfilled to different degrees.

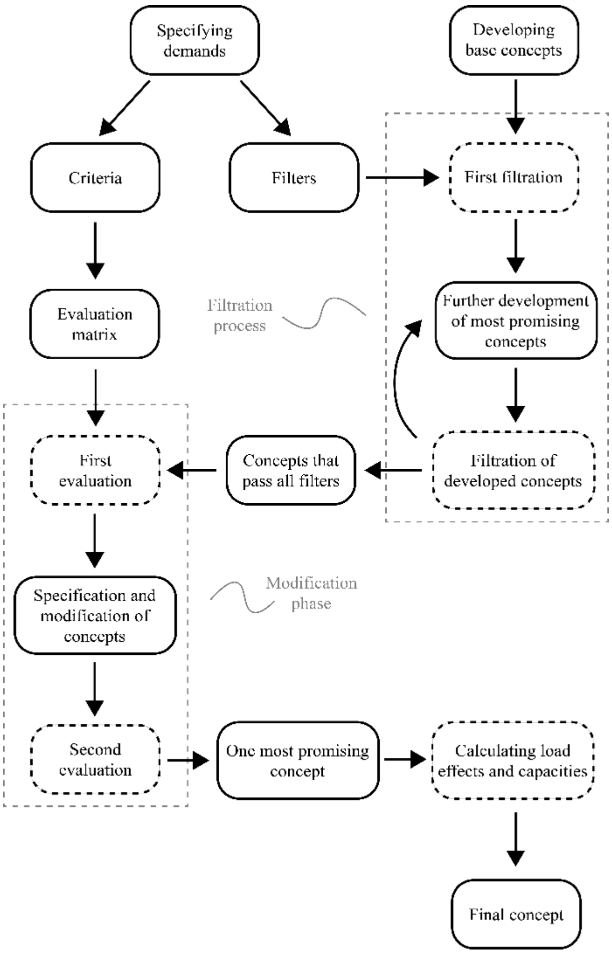

Figure 1. Flow chart of the alternative design process.

In parallel to this, base concepts are developed. These base concepts serve as potential starting points for the design and should therefore be in a very early stage of development. The base concepts are evaluated against the filters in the filtration process to find at least one concept that can pass all filters.

The filtration process begins with a first filtration, during which all the base concepts are evaluated against the filters. If no concept passes through all filters, the concepts with the most potential to pass all filters are further developed specifically to pass the filters they did not pass in the first filtration. A second filtration is then performed to see if any concept passes all filters. If no concepts pass through all filters, the most promising concepts from the second filtration are further developed before being filtered again. This process is repeated until at least one concept passes all the filters.

When one or more concepts pass all the filters, they move on to the modification phase.

In the modification phase, the concepts are evaluated against the criteria gathered in an evaluation matrix to identify the most promising concept. The modification phase begins with an initial evaluation, where each concept receives a score based on how well it fulfils the criteria. The concepts are then modified and further specified to increase this score as much as possible. After that, a second evaluation is performed. Based on the scoring in the second evaluation, one concept is chosen as the most promising.

This most promising concept then proceeds to the final step of the design process, where the dimensions of all remaining elements are determined and the structural integrity of the design is verified. To achieve this, calculations are performed in accordance with the relevant regulations and standards. The concept passes when it meets the regulatory requirements, and the design process is complete.

3 Implementing the alternative design process

In Rwanda, many rural communities reside in areas without sufficient infrastructure [3] and thus face rural isolation. Several organisations are working to minimise this rural isolation, one of them being Bridges to Prosperity.

Today, Bridges to Prosperity primarily utilises two bridge concepts: a suspension bridge and a hybrid between a suspension bridge and a stressed ribbon bridge. Both of these bridge designs have been developed to suit spans of 30 meters or longer; however, Bridges to Prosperity now has a need for a bridge design suited for shorter spans. Therefore, the alternative design process presented in this paper has been applied to develop a design concept for a footbridge suitable for construction in rural Rwanda on sites with a span of 15 to 30 meters.

3.1 Specifying and prioritising the demands

The demands applied for the bridge design were discussed and specified in collaboration with professionals at Chalmers University of Technology and Bridges to Prosperity. The prioritisation of demands, and therefore the division of these into filters and criteria, was conducted through the process described in Chapter 2.3 and illustrated in Chapter 3.1.1 and Chapter 3.1.2.

3.1.1 Filters

The filters used, i.e. the most critical demands for the viability of the design, with minor modifications, are listed and described below.

Reliability: Can users trust that the bridge will always be available for use?

Transportability: Is it possible to transport the construction materials and incoming elements to a rural site with very limited infrastructure? Can the parts be carried by hand or transported using small vehicles or cattle?

Constructability: Is the bridge possible to construct on a rural site with limited access to tools and knowledge?

Erectability (Erection method): Is the bridge possible to erect on a steep site, with limited access to both sides and underneath the bridge, without any cranes or similar equipment?

Adaptability: Can the bridge concept be adapted to fit a variety of sites, with different span lengths and ground conditions?

Cost efficiency: Are the incoming parts and the erection method economically sustainable?

If the answer to these questions were yes, then the bridge concept was considered to pass the filter. The concept or concepts that passed all filters were deemed suitable for this context.

3.1.2 Criteria in the evaluation matrix

The demands that did not need to be fulfilled to make the concept possible to use were used as criteria in a weighted evaluation matrix. The criteria are listed and briefly described below.

Simplicity: A bridge that does not require, or requires fewer, tools receives a higher score.

Service life: A longer service life results in a higher score.

Safety: A lower risk for injuries, both during construction and use, results in a higher score regarding safety.

Maintenance: Less need for maintenance of the bridge results in a higher score.

Usage: A bridge that is easy and comfortable to use receives a higher score.

Durability: A bridge that is durable and can be used at all times, i.e. after an earthquake or storm, receives a higher score.

3.2 Developing the base concepts

In this project, six base concepts were developed in the initial stage. To keep the concepts open enough for this early stage of development, but still distinctly different, the concepts were inspired by different types of load-carrying systems. The six base concepts were: a suspension bridge, a self-anchored suspension bridge, a stressed ribbon bridge, a steel truss bridge, a masonry arch bridge, and a reciprocal frame bridge. Illustrations of each one of these base concepts are presented in Figures 2-7.

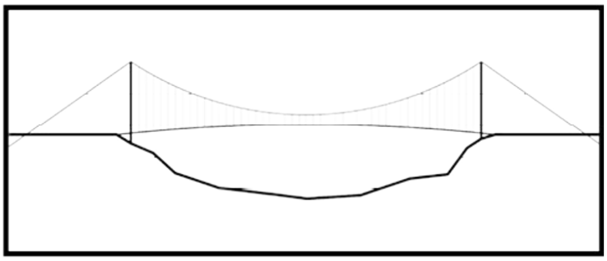

Figure 2. Illustration of a suspension bridge.

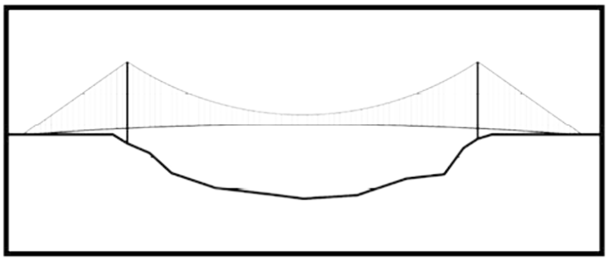

Figure 3. Illustration of a self-anchored suspension bridge.

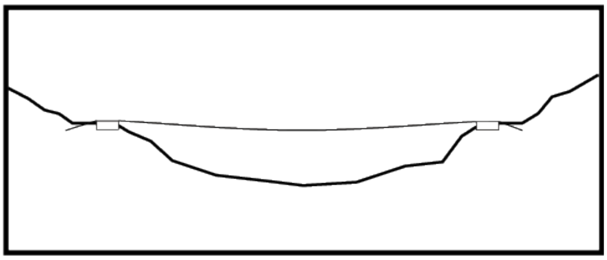

Figure 4. Illustration of a stressed ribbon bridge.

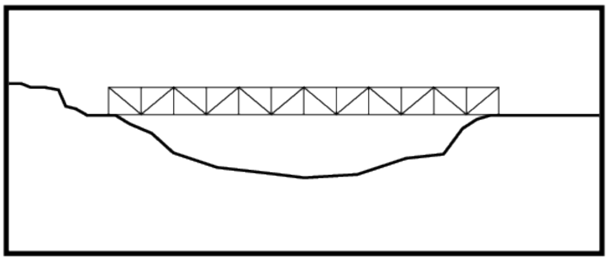

Figure 5. Illustration of a steel truss bridge.

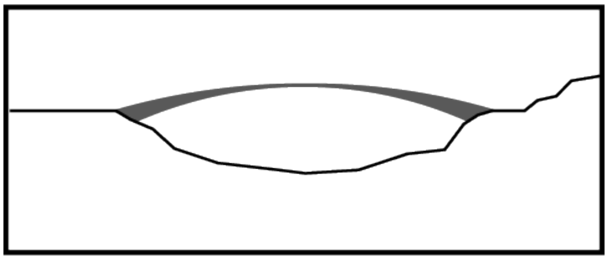

Figure 6. Illustration of a masonry arch bridge.

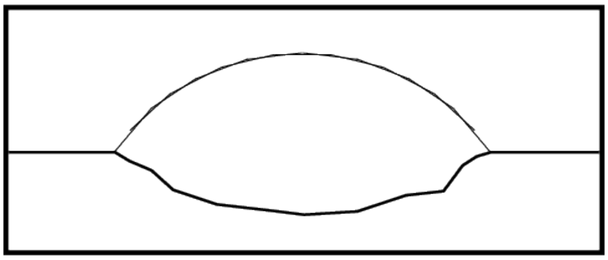

Figure 7. Illustration of a reciprocal frame bridge.

3.3 Filtration process

The filtration process required two rounds of filtration before a concept was found that could pass all filters. In the first filtration, two concepts performed better than the others: the stressed ribbon bridge and the steel truss bridge. In Table 1, which shows the results from the first filtration, it can be seen that the stressed ribbon bridge did not pass the cost-efficiency filter, and the steel truss bridge did not pass the erection method filter.

Table 1. Results from the first filtration.

Filter \ Concept	Suspension bridge	Stressed ribbon bridge	Masonry arch bridge	Steel truss bridge	Reciprocal frame bridge	Self anchored suspension bridge
Reliability					×	×
Transportability	×					×
Constructibility						×
Erection method			×	×	×	×
Adaptability			×		×	
Cost-efficiency	×	×			×	×
SUM	2	1	2	1	4	5

These two concepts were then further developed specifically to pass the filters that they did not pass in the first filtration. For the stressed ribbon bridge, that meant redesigning how the cables were anchored in the ground, while for the steel truss bridge, a new erection method had to be developed.

The redesign of the anchorage for the stressed ribbon bridge primarily involved removing as much concrete as possible from the anchors and replacing it with locally sourced rocks or sand. To ensure that this was possible, the capacity of the anchorage was calculated. These calculations showed that even without removing any concrete, the volume of material needed for the anchorage to reach the required capacity meant that it was not as adaptable as had previously been assumed.

For the erection method of the steel truss bridge, inspiration was taken from the construction of the top part of tower cranes. As in a tower crane, the construction would consist of a counterweight, a tower with a cable running over it, and a horizontal cantilever. The horizontal cantilever, which here would eventually become the bridge, is balanced by the counterweight. To increase the length of the cantilever, new truss modules would be rotated into position at the end of the cantilever. This rotation would be controlled by the cable running from the new module, over the tower, down to the counterweight. In Figure 8, an illustration of this erection method is shown.

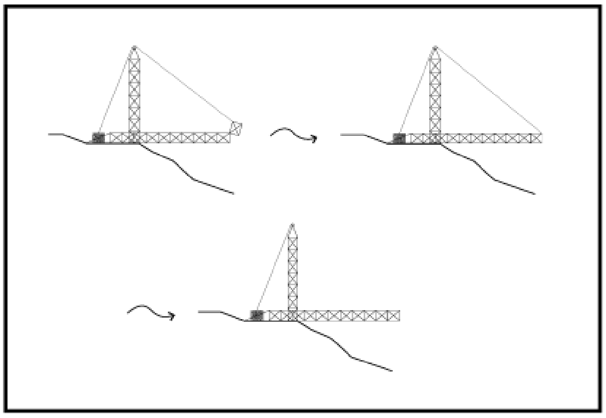

Figure 8. Illustration of the erection method for the steel truss bridge.

A second filtration was then performed with only the developed versions of the stressed ribbon bridge and the steel truss bridge. As shown in Table 2, the steel truss bridge passed all filters in this second filtration, whereas the stressed ribbon bridge no longer passed the adaptability filter.

Table 2. Results from the second filtration.

Filter \ Concept	Stressed ribbon bridge	Steel truss bridge
Reliability		
Transportability		
Constructibility		
Erection method		
Adaptability	×	
Cost-efficiency		
SUM	1	0

Since only the steel truss bridge passed all filters in the second filtration, it was the only concept that moved on to the modification phase.

3.4 Modification phase

Since only the principle behind the load-carrying system and the erection method had been decided in the previous steps of the design process, the modification phase in this project mainly focused on specifying the geometry and detailing of the concept. The only aspect that was modified was the erection method. Additionally, since only one concept reached the modification phase, the scores given in the two evaluations were here used as indicators for how well the concept fulfilled the criteria instead of being used to evaluate different concepts against each other.

3.4.1 First evaluation

During the first evaluation, the concept was still in such an early stage of development that it could only be evaluated against the simplicity criteria, see Table 3. To evaluate the degree to which the concept fulfilled all other criteria, it needed to be further developed.

Table 3. Results from the first evaluation.

		Steel truss	
Demand	**weight factor**	**score**	**score × factor**
Simplicity	7	3	21
Service life	7		
Safety	8		
Maintenance	7		
Usage	5		
Durability	8		
SUM	42		

3.4.2 Modifications and specifications

The focus of the modifications and specifications step was to specify the geometry and detailing of the concept, making it possible to evaluate it against all the criteria in the evaluation matrix. The erection process was also modified to make it less reliant on temporary structures and easier to perform.

One of the most critical aspects that needed to be specified was the properties of the cross-section used for all bar elements in the truss. To ensure that the cross-section used would be available in rural Rwanda, Bridges to Prosperity was asked about what kind of cross-sections they usually have access to. Based on the information they provided, it was determined that a U-shaped profile already in use in their bridges would be suitable. An illustration of this cross-section is shown in Figure 9.

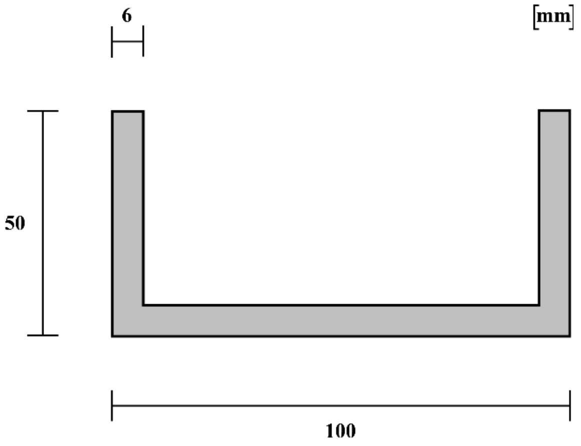

Figure 9. Cross-section of all bar elements in the truss.

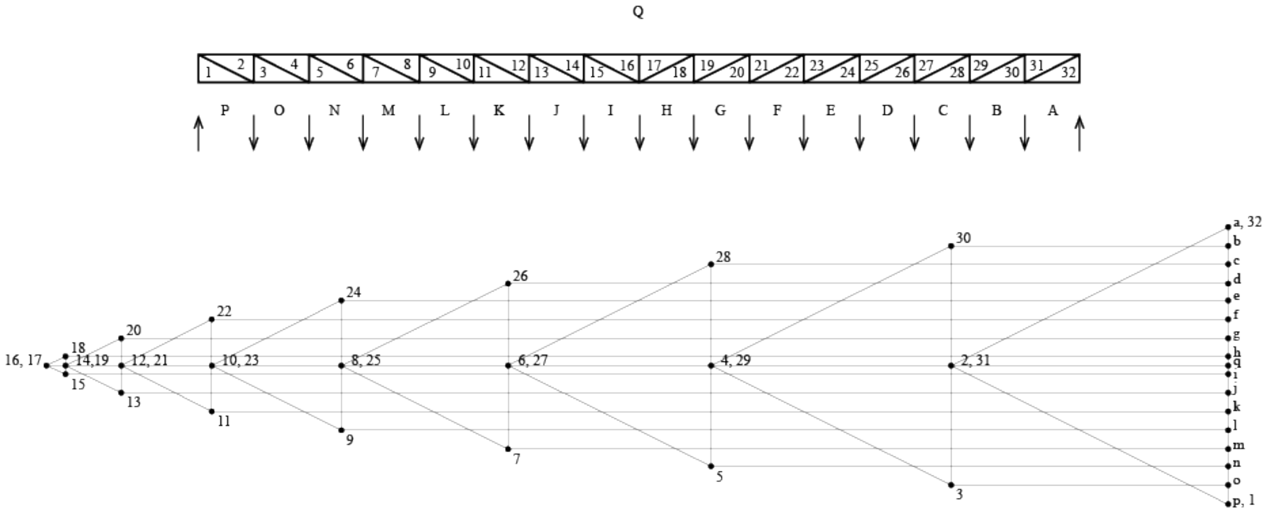

Figure 10. Example of Cremona diagram used in the design process.

To find both a suitable relationship between the height and length of each module in the truss and an appropriate topology, Cremona diagrams [4] were used. One of these Cremona diagrams is shown in Figure 10. From the Cremona diagrams, it was decided that a 1:1 relationship between the height and length of each module would be appropriate for this project. Based on the properties of the chosen cross-section and the need for all elements to be possible to transport through rugged terrain on foot, it was also proposed that the length of each module should be 2 meters. Since the Cremona diagrams indicated that the direction of the diagonals would not affect the maximum force in the truss, it was decided to place the diagonals as crosses in each module to increase the redundancy of the structure.

The stabilising structure connecting the two trusses to each other went through several iterations before an appropriate solution was found. For example, solutions with diagonals placed on the outside of the trusses and various types of frame structures were examined; however, they all had properties that made them inappropriate for the context relevant to this project. Instead, a solution with diagonals connecting the two trusses placed underneath the walkway was deemed most appropriate. In Figure 11, an illustration of this final version of the stabilising structure is presented.

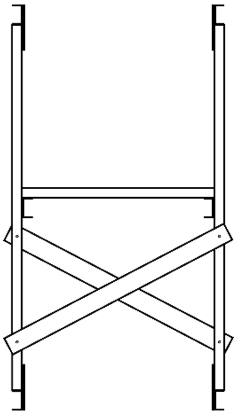

Figure 11. Cross-section of the bridge showing the stabilising structure connecting the two trusses.

To make the erection process less reliant on temporary structures and easier to perform, the erection process was modified. An illustration of the final iteration in this modification process is shown in Figure 12. In this version, the bridge is still supported by a counterweight, but the tower has been removed. Instead, the new modules are assembled directly onto the end of the cantilever by hanging the lower horizontal elements of the truss from temporary cables back-anchored to the previous module. This final iteration was deemed more appropriate than the earlier versions, as it requires almost no temporary structures, only the counterweight, and no custom-made parts other than the two cables.

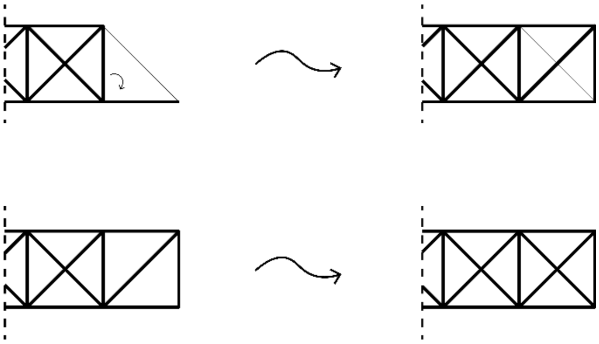

Figure 12. Illustration of the new erection method.

3.4.3 Second evaluation

When the concept had been further developed through modifications and specifications, it was evaluated a second time. The results from this second evaluation are presented in Table 4.

Table 4. Results from the second evaluation.

		Steel truss	
Demand	**weight factor**	**score**	**score × factor**
Simplicity	7	5	35
Service life	7	5	35
Safety	8	5	40
Maintenance	7	5	35
Usage	5	4	20
Durability	8	4	32
SUM	42	28	197

3.5 Validation of structural integrity

To be able to validate the structural integrity of the concept, Bridges to Prosperity's policies were used. Since these policies were developed specifically for the types of bridges Bridges to Prosperity already build and do not cover aspects critical when designing a truss bridge, Eurocode was used as a complement. In some cases, Eurocode was considered to be too strict, and then some assumptions or reliefs were applied.

At an early stage of the design process, critical structural requirements were verified. Both the structural reliability of the whole structure and that of the individual truss elements were calculated in accordance with Eurocode. The bolted plate connections were designed in accordance with Eurocode, but with the modification that the design load was the maximum normal force in the truss elements, rather than assuming them as the weakest link. Additionally, the global behaviour was examined dynamically and statically. To examine the dynamic performance, the in-plane eigenfrequencies of the trusses were calculated to ensure that vibrations during operation (such as people walking) were not too large. The static performance was checked by calculating the deflection of the bridge, even if this was assumed to be of less importance in this case. These global analyses were performed with a finite element model of the bridge.

3.6 Final concept

The final concept was a modular steel truss bridge where all elements are possible to transport by foot, and which can be assembled using only hand tools. Drawings of the final concept are shown in Figures 13-14.

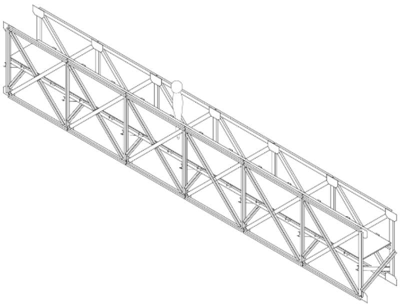

Figure 13. Isometric drawing of the final concept.

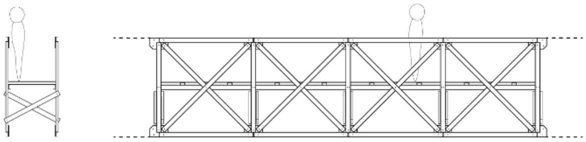

Figure 14. Section and elevation of the final concept.

4 Discussion

When designing a bridge concept that should be suitable for harsh conditions, a complex context, and limited resources, there are several possible approaches. The demands adopted in this design process largely correspond to those in Eurocode, although they are prioritised differently and are more stringent. This led to the development of the proposed and implemented alternative design approach.

The filtration and evaluation process did not clearly point to one concept; therefore, a slight change in approach could potentially yield another result. If, for example, the context of the bridge sites was limited to only steep sides with solid rock, the stressed ribbon concept might have been a better solution. Additionally, certain assumptions were made during the process that may have influenced the design in a particular direction.

The final concept is optimised for a wide variety of sites, and a project-specific solution may exist that is more optimal. However, the benefits of having a bridge concept for shorter spans that is appropriate for a wide variety of sites are of higher importance. The benefits are numerous, including a well-established supply chain of materials and components, extensive logistical and erection experience built up over time, and a more streamlined design process, among others.

5 Conclusions

Building bridges in rural, isolated areas differs a lot from building bridges in industrialised parts of the world. The remote sites and limited resources create a need for a design process that focuses on fulfilling a few critical demands rather than balancing multiple demands against each other. A design process that places more weight on the most critical demands has therefore been developed.

The alternative design process has then been applied in the context of rural Rwanda to develop a bridge concept suitable for spans of up to 30 meters. The process resulted in a modular steel truss bridge that can be assembled entirely by hand and that is adaptable to a variety of spans.

The need for bridges in rurally isolated areas is immense, but the conditions there are complex. The bridge concept presented in this paper is a possible solution, but it is far from the only one. By changing the context only slightly, the final design might look completely different.

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