Saimaa University of Applied Sciences
Faculty of Technology Lappeenranta
Double Degree Bachelor Program in Civil and Construction Engineering

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Preliminary design of wooden road bridge

Thesis 2017

Abstract

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This paper aims to review different constructed wooden bridges hence give a basis for further development. The second purpose of the research is to develop the preliminary timber bridge design for the Pomarkku Bridge.

The information was gathered mostly from literature and the Internet. Also some field researches in Pomarkku were carried out. After the analysis of the existing timber bridges composite SLT and truss options for an old stone bridge replacement was offered. BIM models of variants were done and their fitting to environment assessed by photo montage. The approximate cost estimation was conducted.

Difficulties and tips of timber usage in load bearing bridge structures were discussed in this thesis. Achievements of wooden bridge industry were displayed. The possibility to use timber structures in the case study bridge was showed and assessed.

Keywords: bridge, timber, wood

Contents

1 Introduction

The aim of this work is to consider the design of modern timber road bridges in general and the case of Pomarkku Bridge in particular. The old stone bridge is now closed for traffic and needs significant repair or replacement. The design is based on the analysis of existing wooden bridges and world timber construction experience. Three big parts are considered in this thesis: features of wooden bridges, existing bridges overview and design solutions for the case study. During this study BIM models of different types of timber bridges are made and decisions for the environment are checked and assessed. Approximate cost estimations and comparison are done.

This thesis is a part of the design project for Pomarkku Bridge which WSP makes commissioned by Southwest Centre for Economic Development, Transport and the Environment of Finland.

2 Background

In this part features of timber in bridge structures in general will be considered.

2.1 Timber in bridges

For a long time, timber was the main material for bridges. In the 20th century steel and concrete bridges practically ubiquitously replaced wooden road and railway ones. Most of the timber bridges in the 20th century were footbridges. But in the end of a century a considerable increasing of timber road bridges number is observed. (1)

Timber is a lightweight and easy to handle material. This gives a chance to build solid, monumental and elegant forms. Timber is aesthetically a very pleasant material. Its strength-to-weight ratio is close to steel. Wood with proper treatment is sustainable to deicing agents and weather resistant. Especially in Nordic forest-rich countries it is easy to use this local, renewable material.

Environmental and sustainability questions nowadays encourage the wider use of timber structures in construction industry. As a nature material in comparison with concrete and steel timber structures consume less energy for the fabrication and store carbon dioxide within itself.

There was Nordic Timber Bridge Project in 1994-2001 the objective of which was to increase the competitiveness of timber bridges in comparison with other materials. During the research it was obtained that it is possible to achieve needed durability of wood by careful design against moisture and by using impregnated wood. Wooden bridges as all other bridges need regular inspection and maintenance. Especially in case of timber bridges the lack of care can lead to a shortening of bridge life. (1)

Another project named Durable Timber Bridges (2013-2017) aims at developing durable timber bridges with a given estimated technical lifetime. It is focused on "improving the general applicability of wood as a structural material and contributes to increase the use and market share of environmentally friendly timber bridges" (2). The organizations from Norway, Sweden, Finland and USA are working under coordination of Norwegian University of Science and Technology. They are studying hydro-thermal effects in wooden members and design concepts for the whole bridge and joints, maintenance and repairing techniques.

For 1.1.2016 in Finland 4% of all bridges are wooden bridges (628 from 8864). It is 2% of all bridge area. Also 422 (from 892) steel bridges have timber deck. The peak of timber bridge erection was in the 1970s (276 bridges for 10 years). After that in average 30 timber bridges have been constructed in Finland every 5 years. During the period 2005-2014 6216 m^2 of wooden bridges were erected. Figure 1 shows the distribution of timber bridge types in Finland according to the statistics of Finnish Transport Agency. (3)

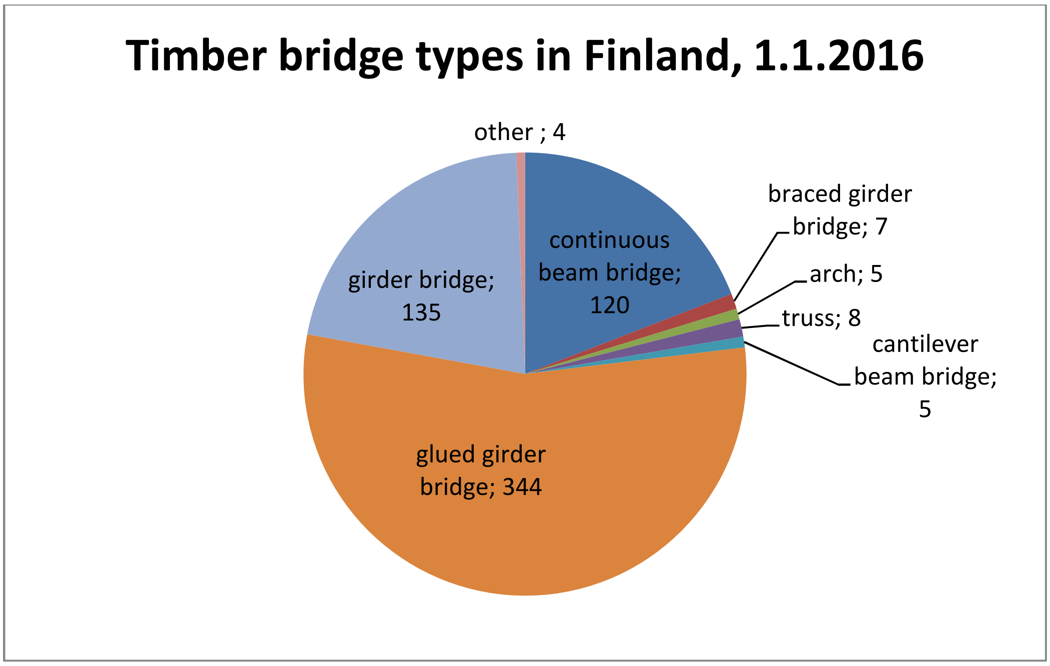

Figure 1. Timber bridge types in Finland for 1.1.2016. According to (3)

We can see that most of the timber bridges in Finland are beam and girder bridges.

2.2 The most important points in wooden bridge design

The basic principles for timber bridge designing according to Michael Flach (4) are:

- Weather protection
- Adequate assembly system
- Bending moments in timber parts should be reduced as possible
- Tension perpendicular to grain should be avoided.

2.2.1 Wood protection

One of the main challenges in timber bridges is moisture. When moisture reaches the untreated part of wood especially in warm time of a year rot and decay became possible. Physical and chemical methods of wood protection exist. Copper flashing plates on every horizontal surface, wooden cashing, overhung deck as well as creosote, CCA (chromate copper arsenate) and heat treatment preserve wood against moisture, insects, fungus and ultraviolet. In Norway practice timber is usually treated firstly with copper salt (Cu) and then, when all holes in wooden part are drilled, with creosote oil. Such procedures together with proper design in details provide the life time of the bridge up to 100 years and cheapen the maintenance. Also very important in design is to avoid moisture traps in any wooden parts and connection. Wood should be well ventilated for avoiding mold. Most problems occur in bearing connections, railing-to-deck joints and in places of tension bars fastening. During construction works it is needed to watch out for deck membrane integrity.

2.2.2 Joints

One of the weakest places in timber bridges are joints. Durability of the whole bridge largely depends on connection design. The main task in detail design is to keep wood dry and exclude the possibility of moisture traps in the structure.

As water is absorbed most quickly through wood end grain, part ends should be protected very carefully. Where it is possible ventilation gaps around wooden parts should be left. Of course insulation is needed between wood and absorbent materials like concrete or masonry. In some types of connection it is necessary to watch for weep holes to allow moisture to drain.

A separate important task is to provide proper railing-to-deck connection. In case of wooden deck it cannot be just bolted to deck from above because of easy moisture acess. Common practice for stress laminated wooden deck bridges is to fasten railings from the edge, and cover the bridge butt with planks for hiding tension rods ends and better bridge appearance (see (5)). Recently it was discovered that tendons inside the deck start to rust and this fact needs more research. Experts advice to keep distance between the railing post and the deck and to prevent water running down the railing post. Otherwise water is collected near the pillar footing and this moisture trap can cause decay of wooden parts of the bridge as shown in (6).

In case of truss and arch bridges with slotted-in plates joint notches for plates should not extend to the upper surface or should be closed by metal cladding. It is important to pay attention to dowels fastening. Due to dynamic traffic load they can move out of joint. Features of fatigue strength of wood are not fully understood (7), but it should be taken into account according to Eurocode 5.

2.2.3 Sideway stability

In high bridge structures such as arches and trusses one of the important tasks is to provide a sideway stability. Long compressed elements in the upper part of the bridge are slender and need sideway support. Wind bracings and rigid portal frames from below act as transverse stabilizers as some other structures like for example in Lehmilahti Bridge (Fig. 16).

3 Existing bridges

In this part examples of existing wooden road bridges in the world are collected. Generally, three groups of timber bridges are considered: girder bridges, truss brides and arch bridges. Of course it is not a strict classification and mixed types exist. Also suspended, cable and frame timber bridges exist, but they are usually used for pedestrian traffic. Beam structures are commonly used for small spans (5-20 m). Wooden arch bridges and trusses can have a span of more than 80 m. There is a lot of literature about timber bridges in Scandinavian countries before 2003. This chapter will also show the latest achievements in wood bridges industry.

3.1 Girder bridges

In this work the term girder bridge applies to all bridge structures in which the bearing structure of the bridge is beams or a slab. It usually has a relatively low constructional depth. Usually beam bridges are used for short spans, but they can overlay up to 42 meters, for example, multiple-span glulam bridge over Dangerous River in Alaska. The height of beams is about 2.5 m. So the length of such bridges is restricted mostly with transportation limit for glulam beams. (8)

Nowadays some technologies for girder bridges are commonly used:

- Longitudinal glulam deck

Glued lamellas plates are mounted along traffic direction on the crossbars and bonded one to another with additional beam from below with bolts. Sizes of plate are limited by production capacity. Reasonably this type of structure is used for span up to 10 metres. (8)

- Stress-laminated timber deck

The main bearing structure of the bridge is wooden deck, which consists of planks or glulam beams connected and stressed one to another by metal rods approximately 600 mm one by another. This pre-stressing increases friction between planks. Point load is distributed due to interaction between lamellas to the nearest lamellas. So the deck behaves as an orthotropic plate (Figure 2). Butt laminations joints are acceptable, that is why a continuous deck for the whole length of the bridge is feasible. Waterproof layer and asphalt covering provide durable pavement. The first time stress laminated bridge was constructed in Canada in 1981.

SLT deck requires some special maintenance. Throughout its lifetime tendons should be tensioned few times due to creep.

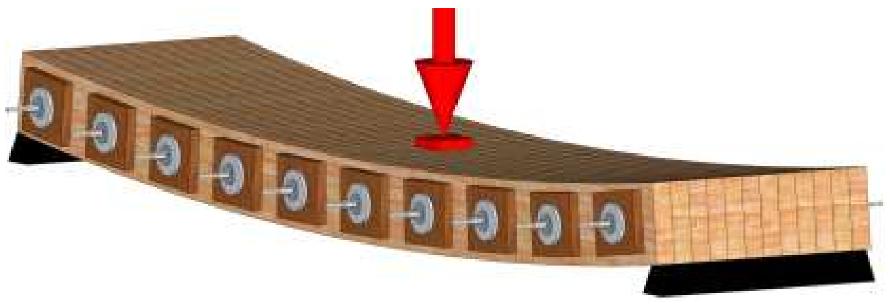

Figure 2. Stress laminated timber deck. (9)

- Stress laminated composite cross section

It consists of glulam beams and stress laminated deck connected as T-beam or as a Box-beam section. The cross-section in that case is used more effectively.

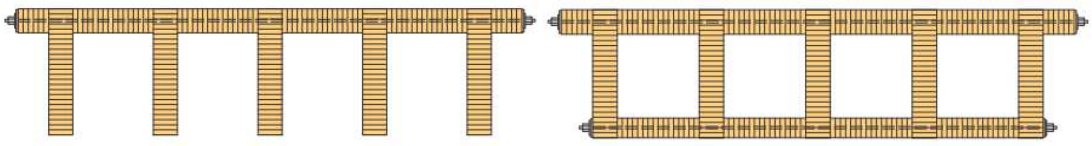

Figure 3. Stress laminated T-beam and box-beam bridge. (10)

- Timber-concrete composite (TCC) structures

Wooden beams are covered with a cast-in-place reinforced concrete deck. These two parts are working like a composite structure thanks to glued-in and cast-in rods, which provide sufficient shear force between wood and concrete (Figure 4).

"The three major benefits achieved by using wooden beams and a concrete deck as a composite structure in road bridges are:

- the strength and stiffness properties of the two materials can be utilized better,
- the concrete deck makes it possible to use similar wearing surfaces as in bridges made from other materials and
- the durability of the timber beams is increased when they are protected against harsh weather conditions under the concrete deck." (11)

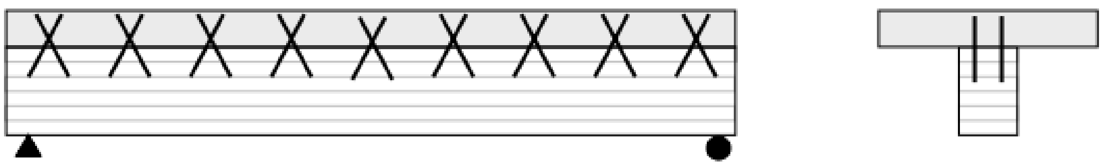

Figure 4. The principle of joining a timber beam and a concrete deck by using glued-in steel bars. (11)

Dabbsjö Bridge

Location	Year	Span, m	Width, m
Dabbsjö, Sweden	1998	15	4
Structure			
Stress-laminated deck bridge from European whitewood with wooden railings is covered with rubber foil, oil impregnated hardboard and gravel on top of it.			

The deck consists of 213 x 495 mm laminations, with pre-tensioning force 395 kN in Dywidag stressing bars. The lower side of the deck, railings and side cashing are coated with a semi-transparent coating in 3 layers. The substructure is also made of wood.

Figure 5. Dabbsjö Bridge. (12)

Husån Bridge

Location	Year	Span, m	Width, m
Sweden	2000	15	4.5
Structure			
Deck is stress-laminated box-beam.			

The overall deck height is 1 m. The upper plate of the deck is 215 mm glulam, the lower one is 165 mm. Wood is untreated. The lower side of the deck is coated by 3 layers semi-transparent coating, protective cladding – by 2 layers. Breaking forces from the deck are transferred to the ground through end-screens of 300 mm concrete, fastened to deck with running through the whole box Dywidag rods. The whole deck has a slope to one side for drainage.

Figure 6. Husån Bridge. (12)

Pikisilta Bridge

Location	Year	Spans, m / Length, m	Width, m
Oulu, Finland	2001	13+16+13 / 50.5	9.5
Structure			
Three girders from four glued laminated beams each hold continuous concrete deck slab. Girders are creosote impregnated. Road has an asphalt pavement.			

Figure 7. Pikisilta Bridge. (Wikimedia commons)

“The new bridge respects the tradition of the wooden house neighborhood of the Pikisaari Island adapting at the same time the newest technology of wooden bridges.” (12)

Kruununmylly Bridge

Location	Year	Spans, m	Width, m
Hämeenlinna, Finland	1993	8	12
Structure			
Wood-concrete composite bridge with wooden railings			

20 years after construction there was a research about its condition. There were no cracks or damage in loading structures. Only renewing of wooden railings and surfacing the edge beams were needed. The moisture content was between 14 and 18% (13)

Figure 8. Kruununmylly Bridge. General view and deck detail. (13)

Tirva Bridge

Location	Year	Spans, m	Width, m
Kouvola, Finland	1997	17.9	
Structure			
Wood-concrete composite bridge with wooden railings			

Girders of Tirva Bridge are slightly curved from below. It makes a good influence to bridge image in general. It is reached by gluing additional wooden parts near beams ends. If the bridge has some bulge it does not give the impression of sagged, but light and airy, although it can create some difficulties in timber parts manufacture and increasing of costs.

Figure 9. Tirva Bridge. (13)

Birkbergbrücke

Location	Year	Span, m	Width, m
Germany	2008	16.4	4.5
Structure			
Composite structure of block laminated glulam beams and concrete deck. Railings are made of timber.			

This bridge is designed for heavy forestry traffic. It is a pioneer TCC road bridge in Germany. German wooden industry is developing, but mostly in direction of timber pedestrian bridges.

Figure 10. Birkbergbrücke, general view. (14)

Figure 11. Birkbergbrücke, bottom view. (14)

Ruhpolding Biathlon bridge

Location	Year	Spans, m	Width, m
Ruhpolding, Germany	2010	17	13
Structure			
Wood-concrete composite bridge			

It is calculated for a 15 t snow track load. All details are made very accurately, so only few bolts are visible.

Figure 12. Ruhpolding Biathlon bridge. (14)

3.2 Truss bridges

Truss timber structures are usually used for middle and long span bridges. Typically, bridge consists of two trusses, a floor system and bracings. The bridge deck can be situated on the level of lower chord, top chord or between them. King post truss, truss with parallel chords and bowstring truss are the most popular geometrical configurations of bridge trusses.

A reducing of bending moments and shear forces in truss members is the main feature of truss structures. Due to hinge connections there are mainly axial forces in truss segments. That is why timber with its high strength in longitude grain direction and light weight is very suitable material. Extra attention should be paid to junction design because stress perpendicular to grain is common in hinge connections.

Advantages of a truss structure are relatively small timber members and light weight. On the other side they need more careful maintenance owing to large number of joints and are more difficult in installation.

In the next examples it is worth to pay attention to the bracing system and providing a global stability of the whole structure. The upper struts of trusses are usually compressed and need to be fixed against transversal displacement and buckling of the whole construction.

Vihantasalmi Bridge

Location	Year	Spans, m / Total length, m	Width, m
Finland	1999	21+ 3 x 42 + 21 / 182	11 + 3
Structure			
Wooden trusses support wood-concrete deck structure.			

It is one of the most famous timber bridges in Finland. Its height is 31 m above water level. Stability of the superstructure is achieved by wooden bracings and steel X-bracings in the upper part. For Vihantasalmi superstructure 1050 m^3 of timber and 270 tons of structural steel were used.

Figure 13. Vihantasalmi Bridge. (Photo K.Bell)

Great Karikobozu Bridge

Location	Year	Spans, m / Total length, m	Width, m
Japan	2002	25 + 2 x 50 + 15 / 140	7
Structure			
Reinforced cedar wood king-post trusses.			

It is the longest timber bridge in Japan. Cedar laminated timber was used because it is situated in Miyasaki prefecture, which is the biggest provider of cedar timber in Japan. For it 5435 m^3 of timber and 305 tons of steel were used.

Cedar's features are low density (0.38 t/m^3) and at the same time strength 20% lower than Oregon pine (15). Lower chords of trusses are reinforced with steel bars, because otherwise the cross-section of it will be too big. So reinforcement bears the axial force of the truss, wooden parts carry the floor system load.

Timber for the bridge was treated with an antiseptic and ant extermination, protective coating was placed and drainer was installed to protect the wood surface. (16) As no test with cedar wood was performed before, behavior observations and static and dynamic tests of bridge parts periodically take place.

Figure 14. Great Karikobozu Bridge. (16)

Bouchu bridge

Location	Year	Spans, m	Width, m
Japan	2001	2 x 27	7
Structure			
It is continuous hybrid wood-steel kingpost truss bridge with steel deck. All its wooden parts are reinforced with steel rods or plates.			

Free height for traffic is 4,5 m.

Figure 15. Bouchu Bridge. (17)

Lehmilahti Bridge

Location	Year	Span, m / Length, m	Width, m
Sonkajärvi, Finland	2000	19 / 20.8	5
Structure			
Bearing structure is king post truss of round logs with concrete filling. Sawn timber bridge deck rests on glulam beams located on steel transversal beams.			

One of the most interesting features of this bridge is the absence of any bracings between two king post trusses. It is achieved by unique technology when logs in the main diagonals have different distance between them in different parts – from 1,2 m near foundation to 0,4 m on the top. The space between logs is filled with concrete. Hang ropes are inclined in both sides. This way transverse stiffness of the whole structure is provided. For taking a horizontal force in the lower part of the truss four steel rods are established.

Figure 16. Lehmilahti Bridge. (12)

Spydeberg Bridge

Location	Year	Span, m	Width, m
Sweden	2009	30	3
Structure			
Hanging truss with SLT-deck			

These hanging trusses allow extending the span of the bridge without increasing SLT deck thickness. The central suspended beam works like one more support for the deck. Traffic load is transferred through the truss framework to abutments. It suits very well in case when it is needed to leave as much space underneath as possible, for example for road crossings, because the deck structure in that case is relatively thin.

Figure 17. Spydeberg Bridge. (http://www.martinsons.se)

Evenstad Bridge, Norway, 1996

Location	Year	Spans, m / Length, m	Width, m
Norway	1996	5 x 36 / 180	6.5
Structure			
Structure of the bridge is hybrid of parallel-chord truss and bowstring type truss.			

Truss members are creosote impregnated. Timber parts are connected with four slotted-in steel plates.

Figure 18. Evenstad Bridge. (Flickr)

Flisa Bridge

Location	Year	Spans, m / Length, m	Width, m
Norway	2003	55 + 70.3 + 55 / 196	6.5 + 2.5
Structure			
Trusses and railings are made from glue laminated timber and bridge deck is stress laminated sawn timber.			

Foundations for the bridge were reused. The one-lane bridge was replaced by this wooden two-lane with pedestrian walk bridge. Side spans are covered with an arched upper chord truss, which is supported by abutments and by 17-metres cantilevers of middle span truss. The maximum bridge structure height is 9.5 m. Rigid steel frames are installed outside the truss above the piers and provide a lateral stability. Also wooden wind truss between the upper chords of the bridge takes lateral loads. The maximum length of timber members was 28 m and was restricted by the size of creosote impregnation tanks. Deck is made from 48 x 223 mm planks. For joints about 200 t of steel were used. Assembling of all the timber structures takes 2 months. (18)

Figure 19. Flisa Bridge. (19)

Kjøllsæter Bridge (Rena Bridge)

Location	Year	Biggest span, m / Length, m	Width, m
Norway	2005	45 / 158	6
Structure			
Wooden truss with slotted-in plate connections with concrete deck.			

This bridge was designed for supporting a heavy military vehicle convoy (20). It is designed to withstand even if one of the supports will be lost. The designed service life of the bridge is 100 years. The concrete deck and wooden truss have slide bearings for free longitudinal translation due to temperature deformations. The total cost of the project in 2005 was about 2.65 million euros.

Figure 20. Kjøllsæter Bridge. (bridgeinfo.net)

Tretten Bridge, Norway, 2013

Location	Year	Spans, m / Length, m	Width, m
Norway	2012	41 + 70 + 37 / 148	10.5
Structure			
Continuous asymmetrical wooden truss with steel struts. Stress laminated deck.			

In construction the middle river pillar was reused. Truss bridge in this case was chosen because the concrete option did not fit according to span requirements, the combined steel-concrete one did not match aesthetical requirements. The bridge deck is lifted up and placed inside the truss for lowering the height of the bridge.

Connections of truss members were implemented by embedded steel plates in sawn slots and dowels in it. Railings were done according to the most common system for SLT decks in Norway.

Figure 21. Tretten Bridge. (19)

3.3 Arch bridges

Arches are very efficient structures for big span covering. Thanks to their shape bending moments are decreased through increasing compressive force in arch cross section. That is why bracings in arch are very important due to buckling of the structure. Also for releasing of bending moment and compensation of influence of temperature and settlement deformation arches are usually two or three-hinged.

A very effective solution for bridges is underneath supporting arch (see appendix). Timber parts are hidden under the deck from weathering and the most compressed parts are stiffly fixed with the deck and bracing ties. But in that work we will not dwell on arch and truss deck bridges, where the bearing structure situated under roadbed, because of high-rise limit between water level and road in this case study.

Tynset Bridge

Location	Year	Spans, m / Length, m	Width, m
Norway	2001	70 + 2 x 27 / 124	7 + 3
Structure			
The big span of the bridge is covered by 2-hinged glulam arch. Small spans are 3-hinged arches with stabilization from underside. SLT deck is supported by steel beams.			

For the construction of Tynset Bridge superstructure 400 m^3 of glulam, 200 m^3 of plank and 95 tons of steel were used. Glulam members in arches are connected with slotted-in steel plates.

Small spans of Tynset Bridge are very interesting by stabilisation solution. They have no chords which fixed top parts of arch in transverse direction. Instead of wind truss stiff metal hangers were used because of lack of free car space (h=5.8 m). Arches have a copper cladding and are treated with creosote which coloured them in that deep brown.

Figure 22. Tynset Bridge. (Photo: K.Bell)

Fretheim Bridge

Location	Year	Span, m	Width, m
Norway	2006	38	
Structure			
3-hinged wooden arch with steel ties			

Glued laminated arches are tied by a double steel rod on each side of the bridge. The bridge is designed for one lane road. The pedestrian way takes one half of the bridge. Because of wide arch cross section and slight incline inward the bridge does not require big lateral wind truss. Preservation of arches can be a good example. It is covered with copper plates on top and with so called "Venetian blinds" made from creosote impregnated planks from sides. Thus it provides protection against sun and rain and at the same time let air go through and ventilate the timber structure. It prevents moisture and fugal decay. That is why in that situation arches themselves are only pressure salt impregnated.

Figure 23. Fretheim Bridge. (SWECO)

Steien Bridge, Norway, 2016

Location	Year	Span, m	Width, m
Norway	2016	82	9+3
Structure			
Arch cross section consists of two wooden arches connected one to another by steel truss with slot-in plates.			

For 2016 it is the longest timber road bridge in the world with span. The feature of this structure is network cables, which reduce a lot bending moments in arch in the case of unsymmetrical loads.

Figure 24. Steinen Bridge. (Photo: Kai Røen)

Hanareum Bridge

Location	Year	Span, m	Width, m
Korea	2012	30	6.6
Structure			
Glue laminated arched truss with steel and timber braces.			

The arch bridge was constructed near Yangyang city according to AASHTO standards for vehicular traffic. The overall width of the bridge is 8.4 m. It was the first wooden road bridge in Korea. Authors of (21) expected that this first experience will lead to development other vehicular bridges in Korea. At first it was tested in a laboratory, after that disassembled and installed on the construction site. The maximum load capacity of the bridge is 110 t.

Figure 25. Hanareum Bridge. (21)

Hopland Casino Bridge

Location	Year	Span, m	Width, m
California, USA	2003	55	5.5
Structure			
Glulam 3-hinch arches have cross section 273x1143 mm. Each arch consists of four 15-m pieces, connected with side and shear plates with dowels.			

Timber arches, beams and deck panels are treated with Pentachlorophenol in heavy oil carrier, which gives this chocolate brown colour for timber. Such protection provides for a minimum 50-year service life for the bridge.

The cost and schedule of the construction was very modest. There were US$254,720 (€240,000) material and transportation costs and US$68,000 (€64000) erection costs not including concrete abutments. The whole construction project took 7.5 months from contract to completion. (22)

Figure 26. Hopland Casino Bridge. (22)

3.4 Other schemes

Nowadays timber construction industry develops and tries to find new technologies for durable, aesthetic and economic structures. Composites of glulam, LVL, Cross Laminated Timber (CLT), veneer and non-wooden materials are tested and implemented in constructions.

Macaisagi bridge

Location	Year	Span, m	Width, m
Quebec	2011	68	
Structure			
Box beam structure with cross-laminated timber webs screwed to structural glued-laminated timber beams			

This bridge was designed to be capable of withstanding 180 t truck.

Figure 27. Macaisagi Bridge. (http://nordic.ca)

Talkirchner Bridge

Location	Year	Span, m	Width, m
Munich, Germany	1991	13 x 13.4	13
Structure			
It consists of glulam timber elements connected with specially-developed cast steel joints. Steel plate deck.			

This amazing bridge crosses the river Isar and is calculated for car and pedestrian traffic.

Figure 28. Talkirchner Bridge. (23)

A separate category of truss bridges is covered bridges. This old technology is still common in America, Germany and Switzerland. The bridge with the lattice truss from planks, bulks or glued members is covered with roof and walls so that all bearing structures are protected from environmental influences. The lifetime of such constructions provided with careful maintenance is outstanding. A lot of covered bridges exist more than 150 years. It suits more for pedestrian and one line routes and has a height limit. They are only mentioned in this work.

4 Case study

In the case study a preliminary design of a new bridge instead of the old stone bridge in Pomarkku is considered. Pomarkku is a town with 2,500 citizens. The old bridge (see Fig. 29) was built in 1913 with the technology of arch stone bridge. It has 3 spans (7, 7.2 and 7.6 m), 2 existing supports are situated in a riverbed. Nowadays the middle span has a visible deflection, one of the supports has a settlement and inclination. This led to cracking of the road cover and may cause the bridge to collapse. According to Finnish Transport Agency it is now a bridge in poor condition and with greatest need in repair (3).

The owner of Pomarkku Bridge is Southwest Centre for Economic Development, Transport and the Environment of Finland (ELY-keskus). It is responsible also for the transport and infrastructure of that region. Usually bridges are owned by a municipality, but such an old and historical bridge is another case.

Nevertheless, the city and museum administration are also involved in the renovation project.

It is estimated that a rehabilitation of the bridge will be more expensive than the construction of the new bridge. That is why Southwest Centre for Economic Development, Transport and the Environment of Finland hired WSP to develop a preliminary design for different options of a new bridge. The company made the design of old stone surfaced concrete, new concrete, composite steel-concrete, and timber bridge alternatives. Thus this thesis is a part of WSP's project.

Figure 29. Pomarkku Bridge, October 2016. (WSP)

4.1 Pomarkku features

One of the main things to consider is the historical environment of this region. All buildings around are old, Finnish-looking. And the new bridge should fit into the landscape.

Pomarkku Bridge has very strict frames in dimensional variations. At first, floodings on Pomarkku river sometimes occur. That is why timber bridge structures should not be too close to the water. Topography is such that the road is 4,15 m above the usual water level. The highest point of the existing bridge road is 4,5 m above water.

The open space of the bridge now is 6.25 m. For 2-lane road №13039 it is too narrow. So the new bridge should have 7 m road width. A pedestrian path passes through the pedestrian bridge 30 meters nearby upstream.

One of the variants is to leave the existing supports, make needed soil strengthening to be sure in their reliability for the next 100 years. After that we can place a 3-span structure on it. Thus each span will be near 9 meters long.

In the process of design development these main points should be considered:

1. *Number of spans*

It may be unacceptable to use the existing supports in their present condition. But they make all other constructions easier in weight and technology. Saving supports leads to necessity of river soil survey and expensive middle-river works.

According to the soil map there are mostly gravels exactly in the bridge site, and around it is clay. As supports had a settlement, most likely they will need at least strengthening with injection. This expensive procedure will make them more reliable and reduce a risk of new settlements. Anyway, trying to save supports is associated with risk of heavy expenses.

Making one span bridge requires 29 m span structure. “For road bridges with a span over 20-25 m, arches and trusses dominate.” (1) Using a one span girder bridge is not justified because the cross section of beams will be too bulky. Such thick bridge outline will not fit to the surrounding landscape.

2. *Type of bridge*

There is 28,5 m span (or 9,5+9,5+9,5 in case of saving supports). There are the most common options of bridge type:

- Beam bridge
- Arch bridge
- Truss bridge

Suspended and cable bridges are not taken into account with such short span.

Timber supply in Finland is not a significant problem. Glulam Metsä Wood factory is situated in Hartola, 400 km from Pomarkku. Versowood factories are near Heinola (280 km). Pölkky has impregnation facilities in Oulu (500 km).

As it is a preliminary design of structures and calculations it will take a lot of time, in this thesis the dimensions of all structures are obtained from appropriate similar existing bridges and world experience. For determining the exact cross-sectional dimension calculations are needed to be conducted, but it is beyond frames of this bachelor thesis.

4.2 Option 1 – composite SLT deck

In this thesis two options are considered: saving historical supports like a building heritage of that region and a whole new timber bridge.

The first option includes saving old supports in riverbed and use three-span structure. The simplest way to span two shores in that case is stress laminated deck. With about 400 mm height it will fit to 9-meters spans. Then there is a problem that the existing supports are too low for such thin structure. It is needed to make it higher with concrete and new stones and this will be too observably. Also proportions of the supports will be unpleasantly changed. That is why a higher structure is needed. More of option 1 is shown in the figure 32 and visualisation is in the figure 35.

A composite timber-concrete structure is very nice from many points of view, but concrete butt of the bridge will not suit to this landscape. Using of composite stress-laminated timber structure will be more appropriate. It will allow to use cross section more economically although mounting process will be more complicated.

The structure of the deck is based on experience of different bridges. Firstly SLT deck is covered by a primer, then by waterproof membrane and a waterproofing layer. On top of it an asphalt is applied. For correct drainage the road should have an inclination in transversal direction. According to Nording Timber Bridge Project research, in case of proper waterproof covering and accurate detail design SLT deck does not require any other treatment (24). But beams which are exposed to weather effects shoud be treated. It will prolong the life time of wood structures, protect timber from moisture destruction and fungal decay.

From 2010 all bridges in Finland should be designed according to EN Eurocodes. For designers the so called NCCI – “Non-Contradictory Complementary Information” was written to adopt a new design and calculation system.

4.3 Option 2 - truss bridge

The second option for the study case is truss bridge. Actually, arch structure can also be discussed, but more likely 30 m is too small a span for arch and the cost of it will be disproportionate to the result. Also high circle structure will not fit to the landscape with only triangle roofs around. On the other side it looks perspective to use king truss structure for Pomarkku case because of the middle span. It will repeat the tune of buildings around. Model of option 2 is shown in the figure 33 and visualization is in the figure 36.

Glulam trusses are situated laterally alongside the roadway. Connection between truss members is made with slot-in steel plates and dowels. Steel beams on hangers support stress laminated timber deck with asphalt pavement. Wind truss and brace beam at the truss ridge provide transversal stability of the whole structure and leave 5.2 m height gap. Between two supports steel rod ties are tensioned for taking pushing apart forces due to truss inclined structure. Road structures are implemented the same as in beam bridge. Railings are fastened to steel transversal beams and to the deck in between.

One of the ideas for the truss bridge was to make it from Laminated Veneer Timber (LVL). There is an example in Spain, Vitoria, when 19,2 m cantilever was made with layers of Kerto Q and plywood and steel gusset plates in between. The main advantage of this type of structure is cross veneers in joints, working as transversal reinforcement and preventing splitting of joint. Also the strength of LVL is quite big. On the other hand, research about the durability of LVL in outdoor conditions had not been conducted yet. Resistance to moisture and temperature changes of veneers is not investigated enough.

4.3.1 Support

Managing with supports joints should be very careful. Usually it is a place where rot and mold can appear first of all. Bridge bearings should take vertical downwards and upwards (dead weight, vehicles), longitudinal (breaking forces) and transversal (wind) loads. One support should be immovable in longitudinal direction, others to movable because of thermal and moisture length changes. Authors (5) offer to use a steel plate cast in bearings and slotted in deck for transversal deck moving restriction. For creating immovable support a cross bar should be inserted perpendicular to the plate. Generally, bearing and expansion connections in timber bridges are simpler than in steel or concrete. A rubber mat and a hardwood plank on it between the beam or the deck and concrete foundation are usually enough.

For SLT decks a typical support joint according to (5) is shown on Fig. 30.

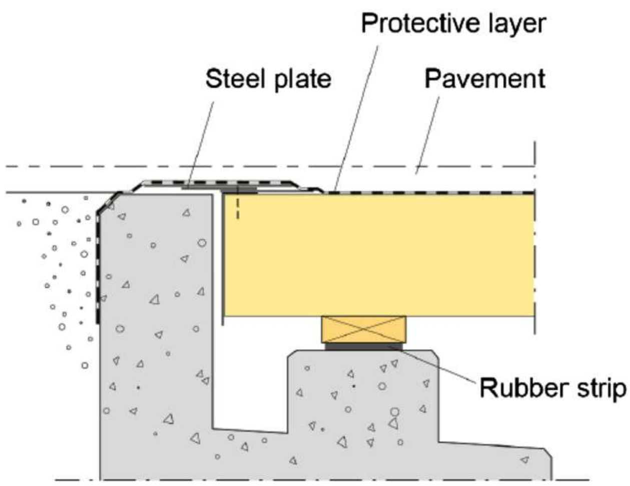

Figure 30. End support for timber deck. (5)

The bearing joints of truss require special attention. It should provide hinge connection of members and take significant loads. Moisture removal from the connection of timber strut with steel saddle should be carefully provided. For example, in Vihantasalmi Bridge now timber soaking in that part is one of the maintenance problems.

4.4 Modelling

In frame of this thesis preliminary planning phase modelling was done. It can be used to compare alternative solutions graphically. According to BIM modelling instructions (25) at the preliminary phase parts should be modelled with sketching accuracy. There should be open surfaces of parts shown. Useful width and gap requirements are modelled as support lines. Pre-planning model is not for calculating volumes and material properties, but for explaining different solutions and transport infrastructure options in bridge construction and their effect on environment. Also a virtual model, perspective pictures and rendering accession can be received.

The phase of general planning requires a bridge modelled with visible structures and accessories and related structures. Technical transport dimensions, gap requirements, lane lines and dimensions, support lines and cardinal points should be shown. Reinforcement and hidden parts of non-structural elements are not modelled. (25)

The 3D model of existing Pomarkku Bridge was done by Destia Oy 10.10.2016 with point cloud and then modified to IFC and dwg formats (Fig. 31).

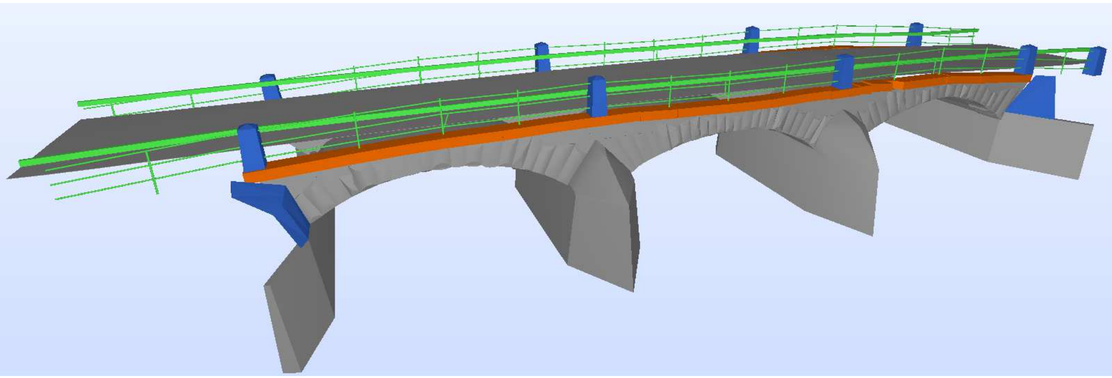

Figure 31. IFC model of existing Pomarkku bridge. (WSP)

The new bridge was modelled in Tekla Structures 21.1 in single user module (Fig. 32, 33, 34). It allows obtaining data about the weight, volume and surface area of structures for cost estimation. The model can be easily converted from Tekla to IFC and DWG format if needed.

Firstly, grid lines were set. They were placed according to support points for beams on shore and on supports in transversal direction and align the bridge center and center of side beams in longitudinal direction.

For beam bridge old supports were imported from DWG model as solid objects. All other parts are made in Tekla. A very useful tool is Polybeam, which allows to create the curved shape of bridge deck, covering, edge beams and railings. It is like polyline with certain cross-section shape. It was performed with step 1 m, so the model has such a smooth shape.

An advantage of Tekla software on the first stages of design is ability to change the cross section and other properties of beams very easily. In this way, for example, it was possible to try and choose the most suitable railing type. Inward steel tubes have specified cross-section according to licenced railing system, but outward décor is without such strict limitations.

As this model was made for preliminary design, the level of detail is very low. Tension bars, any fasteners and insulation were not modelled. In truss bridge model detailing is also moderate. No slotted-in plates were made. As exact dimensions of ropes and other steel parts are not calculated they were only outlined. If this option will be chosen by the client as the main one, the outlines of these parts will be modified to calculated cross-sections.

Concrete structures were implemented with beam and plate tools and cuttings. Foundations were modelled exactly only in truss model. Abutments and wings were made. The material quantity from this model can be used also for another option.

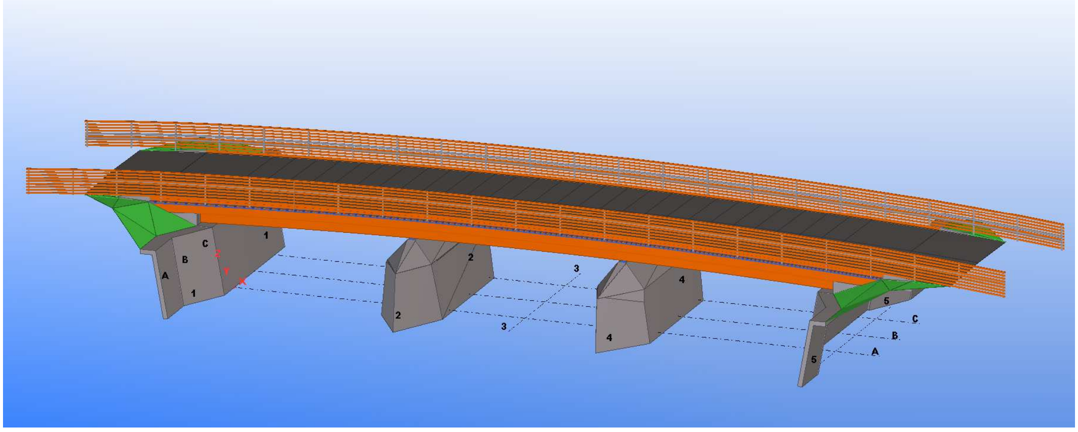

Figure 32. Tekla model of composite SLT bridge.

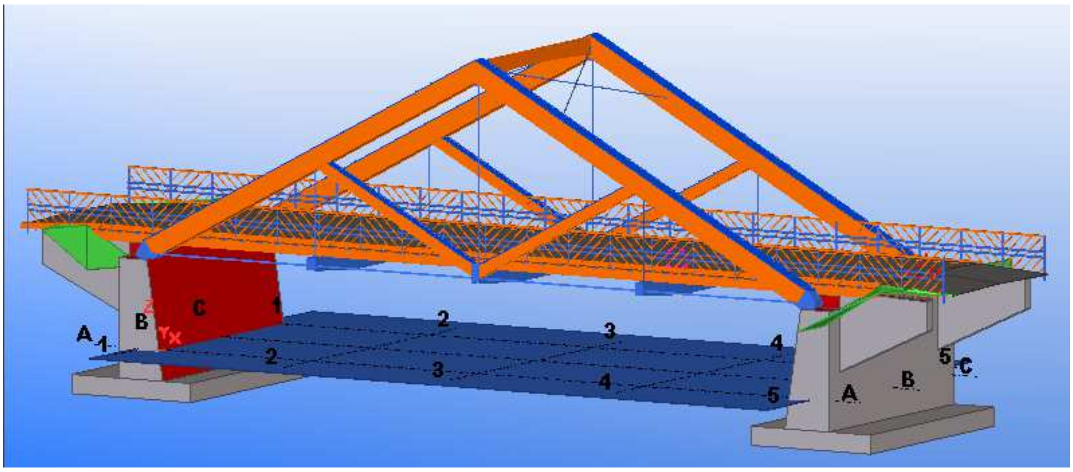

Figure 33. Tekla model of timber truss bridge.

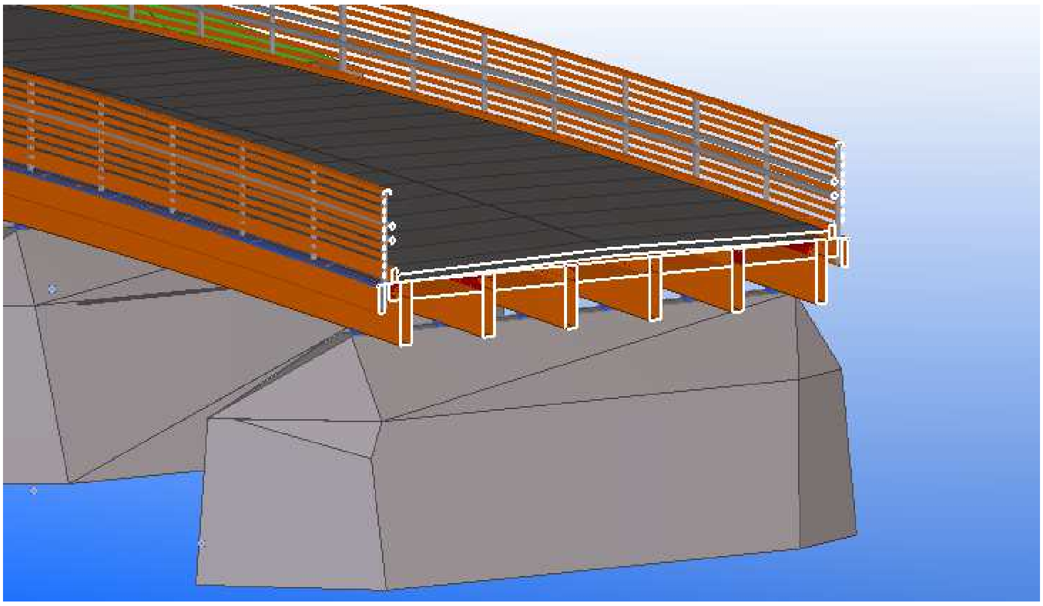

Figure 34. Option 1. Section of the deck.

On figures 35 and 36 the visualization of two bridge options is shown.

Figure 35. Visualisation of composite SLT bridge. (WSP)

Figure 36. Visualisation of truss bridge. (WSP)

The design of girder bridge is calm. It continues peaceful atmosphere around. Supports without former arches look not so graceful as before. Triangle truss shape supports and underlines the dynamics of buildings and nature around and provide vista for sight. Due to low constructional depth the river is wide open.

4.5 Timber bridge costs

Timber is a building material which has some unbearable advantages. In right place it can be cheaper than other bridge materials. Prefabricated wooden pieces require least time to mount and are easy to install so construction time is usually shortened. It has a relatively light weight that let to use less heavy mounting machinery and makes transportation expenses lower.

Table 1 shows the unit costs of timber bridge superstructure according to its type. The database includes only American load-rated bridges constructed after 1980.

Table 1. Bridge cost by construction type. (26)

Construction type	Observa-tions (no.)	Cost ($/ft^2) Median	Cost ($/ft^2) Mean
Slab	138	24.83	28.58
Stringer/multi-beam	56	31.12	31.59
Girder and floorbeam system	1	45.25	45.25
T-Beam	2	64.10	64.10
Box beam or girder			
Multiple	7	56.00	57.80
Single or spread	1	51.69	51.69
Frame	1	149.50	149.50
Truss, through	2	60.18	60.18
Arch, deck	1	39.09	39.09
Total	209		

From that table due to inflation only the price ratio between different timber structures is clear. The slab structure is the most common and the cheapest one. Beam structures is more expensive. All composite structures are twice more expensive than slab structure due to more complicated technology.

In planning not only construction costs should be estimated, but also lifetime and maintenance expenses. The experience from almost 100 timber bridges built in Norway since 1993 indeed proves that chemically treated bridges have a very low maintenance cost. (27)

Cost estimation in this work is very preliminary and approximate. There are two reasons. Firstly, soil conditions on site and the exact characteristics of structures are not determined yet. Secondly, norms and rates for calculation of timber structures is not so precise as for concrete and steel bridges, where prices are based on wide construction experience.

In case of Pomarkku Bridge not only bridge superstructure should be considered to compare variants' price. Continuous beam bridge needs support repairing but is cheaper itself. Truss does not need bulls, but has more complicated joints and protection. For concrete bridge due to its weight expensive pile foundation is needed. Additional costs not included in table 2 in all these variants are for the old stone bridge demolition (about €50-100 thousands).

The cost estimation was done using Silava 2009 software. At first the costs for year 2000 (100%) were calculated and then cost index i = 175.4 was used. That means that prices in 2016 amount to 175.4% of 2000.

The following table contains preliminary cost estimation for wooden bridges and for concrete bridge options for the same site.

Table 2. Preliminary cost estimation for bridge options

Part	Timber 1		Timber 2 - truss		Concrete	
	Costs	%	Costs	%	Costs	%
Soil strengthening (injection)	34830	10,8				
Piling					19300	6,3
Excavation works	10000	3,1	10000	2,7	10000	3,3
Sheet piling	27200	8,4	13600	3,6	13600	4,5
Embankment	4600	1,4	4600	1,2	4600	1,5
Trench backfill	12100	3,7	11000	2,9	11000	3,6
Bridge end supports						
Cast and scaffolding	10545	3,3	10545	2,8	13395	4,4
Reinforcement	19800	6,1	19800	5,3	21372	7,0
Concrete	19050	5,9	19050	5,1	17105	5,6
Middle supports						
Cast and scaffolding	570	0,2				
Reinforcement	880	0,3				
Concrete	635	0,2				
Stone covering	36960	11,4	36960	9,8	36960	12,1
Retaining wall	20000	6,2	20000	5,3	20000	6,6
Equipment and supplies	32750	10,1	32750	8,7	36870	12,1
Superstructure	93025	28,8	198126	52,6	100538	33,0
Glued timber	69225	21,4	119556	31,8		
Steel parts	6000	1,9	55720	14,8		
Copper covering			5050	1,3		
Mold					13395	4,4
Reinforcement					32058	10,5
Concrete					17105	5,6
Stone covering					18480	6,1
Concrete impregnation					460	0,2
Insulation	11720	3,6	11720	3,1	12960	4,3
Asphalt pavement	6080	1,9	6080	1,6	6080	2,0
Total	322945	100	376431	100	304740	100,0
Construction site cost (25%)	80700		94100		76200	
Bridge cost 2000	403600		470500		380900	
Bridge cost 2016 (i = 175,4), €	**707900**		**825300**		**668100**	
VAT 22%	**155700**		**181600**		**147000**	
Costs per square meter	3323		3875		3137	

As it can be seen, there is no big difference in costs for concrete and simple timber superstructure. Truss bridge and truss superstructure in particular are

noticeably more expensive than other variants. It is because of greater volume of wood due to longer span, more steel details, more consuming of wood treatment and installation in comparison with composite SLT structure.
Quite a big part of costs is stone covering for abutments and supports due to high level of manual labor in surfacing work with old stones.

4.6 Discussion

For the final choice of option for further designing these factors had to be taken into account: bridge appearance and suiting to environment, clients budget, cost of the bridge including demolishing works, production and construction capacities, site conditions, availability and competence of the labour and risks during the project.

Truss variant is objectively more expensive, but has some big advantage that there is no need to do anything with old stones after demolition. It is more safe in terms of substructure costs. On the other side, mounting works with truss are more complicated than in the other option.

5 Summary

In general, it should be noted that timber in bridges wins in such aspects as aesthetics and erection time and simplicity and in some cases are on a par in terms of cost with other materials. Wooden structures in their nature are more resource consuming in maintenance and it is needed to be taken into account. Nowadays timber construction industry expands and becomes more demanding.
During the thesis examples of timber structures application in bridges were presented and a preliminary BIM model of two timber options for Pomarkku bridge was implemented and visualised. During cost estimation it was revealed that SLT composite structure can be a competitive alternative to a concrete bridge here if the foundation research shows very weak ground underneath. Truss structure is more expensive but has its own advantages.

In conclusion one can say that the timber bridge in this case study is a possible alternative to design, but needs further development.

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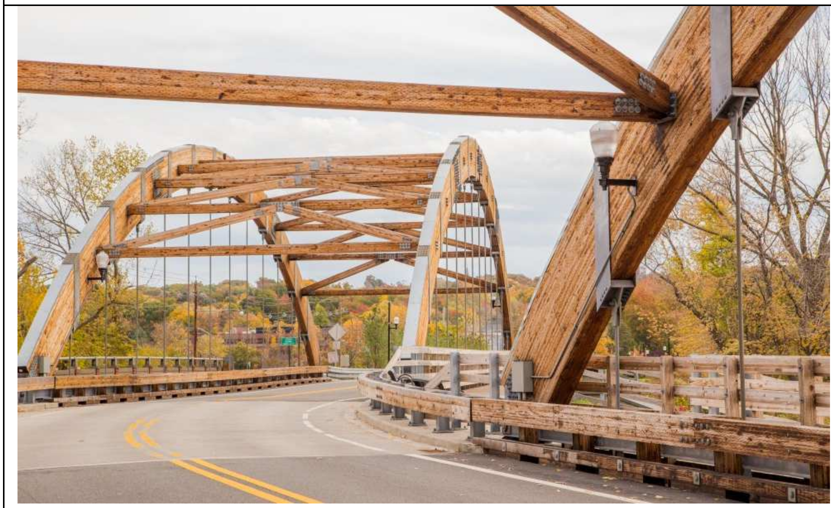
In the Appendix more wooden bridges which exist in the world are listed.

	**Uusisalmi bridge** Forssa, Finland, 1995 18 m span, 7.5 m width, 7 glu-lam beams, wood-concrete composite structure
	**Mistussini Bridge** Quebec, 2014 Spans 37 + 2 x 43 + 37 m, $9.5 million CAD
	**King post bridge in Umeå** Sweden, 2010
	**Moumbekken Bridge** Norway, 2014 This underlying timber truss with stress laminated glulam deck has a 25,4 m span and width 9 m.

	**Norsenga bridge** Norway, 2017 Main span 55 m, width 9 + 3 m. Glulam truss bridge with steel crossbeams and glulam stress-laminated deck.
	**Glulam Timber Arch Bridge** Allegany County, New-York, USA, 2003 Cost $2,853,800.
	**Temiscamie River Bridge** Quebec, 2009 Span 32 m
	**Daleråsen Bridge** Norway, 2001 It has spans 33 and 27 m, three-hinged arches and SLT deck.

	**Skogsrud Bridge** Norway, 2009 37 m span, 7,5 m width, arch with intermediate stress-laminated glulam deck plate.
	**Ner-Hole Bridge** Norway, 2007
	**Stampen Bridge** Norway, 2008
	**Ulnes bridge** Norway, 2003 Longest span 35 m, length overall 105 m. Width 8.5 m. Stress laminated timber deck on 3-hinged arch with tie rods.

	**Fønhus Bridge** Norway, 1998 Span 28 m, carriageway width 7,5 m. Stress laminated deck. Double impregnation.
	**Overpeck Park Bridges** New Jersey, USA 42.7 m span, 9 + 3 m width.
	**Keystone Wye** USA, 1966 Crossing of two glued-laminated timber bridges.
	**Timber arch bridge** Lohmar, Germany, 2014 Spans 10 + 45 + 10, bridge is for one-line road. Arch members cladded with larch laterally and covered with titanium zinc sheets.