A Systematic Framework for Long-Span Timber Structures

Anders BJÖRNFOT, M.Sc.
Div. of Timber Structures
Luleå Univ. of Tech., Sweden
e.mail: Anders.Bjornfot@ltu.se

Anders has a M.Sc. in civil engineering from Luleå University of Technology 2001. Anders is now working as a Ph.D. student at the division of Timber structures.

Lars STEHN, Ass. Prof.
Div. of Timber Structures
Luleå Univ. of Tech., Sweden
e.mail: Lars.Stehn@ltu.se

Ph.D. in Structural Engineering 1993, Head of the division of Timber Structures at LTU. Lars Stehn has 10 years of experience as a designer of Timber structures.

Summary

Modularisation is a key concept in the manufacturing industry and has helped lead the way towards widespread industrialisation. In Sweden, timber has had limited use as a construction material for many years. This is particularly evident for long-span single storey structures used for non-domestic purposes. System Engineering (SE) and modularity principles using the Design Structure Matrix (DSM) and neural networks theory are used to describe a systematic and theoretical framework for construction. The study and analysis are based on a case study at a Swedish design company, together with a survey of 60 long-span timber structures. The potential of DSM to systematise long-span timber structures has been shown in this paper. It is also evident from the analysis of one structural sub-system that industrialisation for the construction industry should be linked with modularisation, incorporating both prefabricated and standardised products.

Keywords: timber structures, modularity, design structure matrix, systematisation, industrialised construction, structural system

1. Introduction

Modularisation is a key concept in the manufacturing industry and has led the way towards widespread industrialisation [1], effectively incorporating concepts like manufacturability and theories of lean and agile production. Incorporating modularisation in construction and shifting the construction industry towards a more industrialised approach has the potential to introduce many positive effects. Research has shown an increase in safety, productivity, and quality using standardisation and pre-assembly [2]. The construction industry has, despite recent improvements, still much to learn from the mechanised industry. A construction renewal needs a holistic, integrated view; not only should the production and structural system be changed, but all levels of design, operation, and improvement of the production system should be changed jointly [3].

The aim of this paper is to describe a systematic theoretical framework utilising modularity,. System Engineering (SE) and modularity principles using the Design Structure Matrix (DSM) are used to form the basis of this framework. This paper will also show the application of neural networks theory in systematization. One type of structural timber roof system, pre-stressed tied rafter, is used to simulate the design and assembly of long-span timber structures. This work is based on a case study performed at a leading Swedish design company, together with a survey of 60 previously built long-span timber structures.

2. A systematic framework

The introduction can be summarised as; *to understand, adapt, and develop industrialised construction, the main theoretical approach must be based on an integrated and holistic systems approach. It is also necessary that these principles be allowed to develop systematically by jointly considering the levels of design, operations, and the production system*. When considering modularisation, the design of buildings and other manufactured products have much in common. In general, a building is constructed of numerous building elements, often standardised and connected to each other, e.g. floor, walls, and roof. Each building element, e.g. a floor [4], is designed from a set of functional requirements. Likewise, the design of a manufactured product, e.g. the modules of a water cooler [5], depends on a set of functional requirements.

2.1 The Design Structure Matrix (DSM)

For artefacts (objects such as buildings), Systems Engineering (SE) provides both problem solving principles and a holistic approach to design so as to avoid sub-optimisation. SE can be extended to the whole lifecycle of a system, providing early-on management of user requirements, systems requirements, architectural design and component development to system verification, validation, and operational capability [6]. The SE method used in this paper is the Design Structure Matrix (DSM). DSM displays the relationship between components of a system, illuminates the structure, and aids in the design of products, processes, and organisations [7].

2.2 Experience Based System (EBS)

The competition between structural systems and materials on the Swedish construction market is rough where timber has had limited use as a construction material for many years. One reason is a general lack of knowledge about timber, both as a construction material and how timber can be used to its full advantage in construction. It is thus important that a framework for timber construction incorporates construction experience. Fig. 1 illustrates the basics of the framework. The feedback obtained from previously constructed structures is stored in an Experience Feedback System (EFS). The EFS, based on neural network theory, is a database providing a constant loop of experience feedback from constructed long-span timber structures. Structural design and production knowledge are systematically stored in another database; Construction Knowledge Database (CKD) based on the DSM, Fig. 1. From the CKD, the whole structure is designed and evaluated. The framework is called an Experience Based System (EBS).

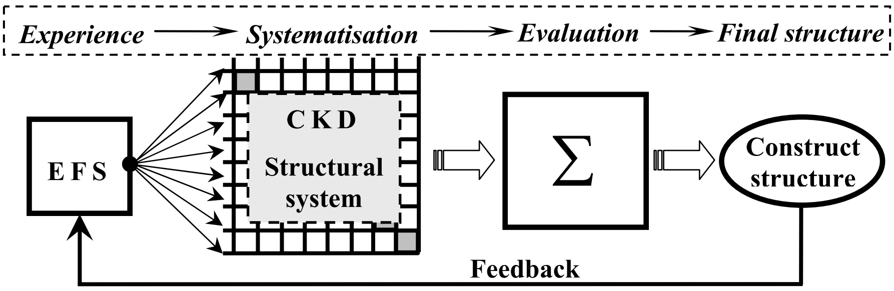


Fig. 1 The EBS structure considered in this paper.

2.3 Scope and limitations

Fig. 2 A long-span timber structure situated in Sweden (only the structural system is shown).

The construction and production of a structural system for non-insulated long-span timber structures will be reviewed and analysed in this paper, Fig. 2. Due to the holistic scope of SE, the design and production phases cannot be separated. In this paper the design phase is limited to the structural design of vertical and horizontal load-carrying capacities, while the production phase is limited to geometric considerations for on site assembly.

3. Research method

The case study in this paper is based on two phases, interviews and a survey. The case company has three employees and has been competing in the Scandinavian construction market since 1986. The aim of the interviews was to collect general experience and knowledge about long-span timber structures, including specific information about the structural system and the design and assembly processes. The survey consisted of 60 long-span timber structures constructed by the case company from 1994 to 2001. This survey amounts to 10% of the total amount of long-span timber structures built during this time frame. The aim of the survey was to collect core quantitative knowledge.

4. Results from the case study

4.1 Design parameters

In general, two types of design parameters influence the design of the structural system, geometrical and geographical, Table 1. There are normally only three design parameters free to a designer: roof pitch, column spacing, and roof-purlin spacing.

Table 1 Geometrical and geographical design parameters.

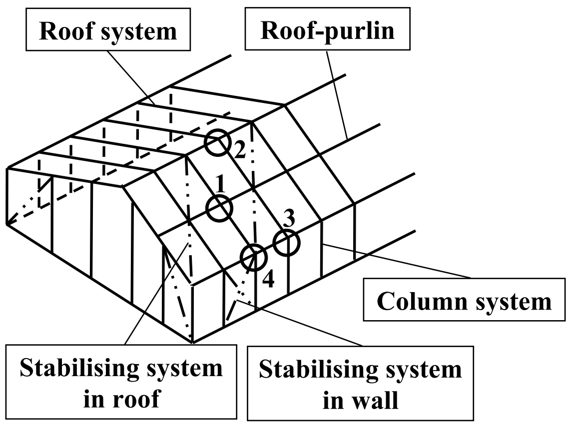
Geometrical parameters	
Parameters	**Definition**
Roof pitch	Pitch of the roof beams
Length	Length if the structure
Width	Width of the structure
Free height	Free indoor height
Column spacing	Column/roof spacing
Roof-purlin spacing	Roof-purlin spacing

Geographical parameters	
Parameters	**Definition**
Snow load	Amount of snow on roof
Wind load	Wind magnitude on roof /facade

Parameters	Can be varied by designer
Parameters	Predetermined by client/geography

4.2 Structural system

The structural system contains four different physical interfaces where the sub-systems join, Fig. 3 and Table 2a. The most important sub-system is by far the roof system, constituting up to 70% of the total cost, including material and assembly (personnel and machinery) of the structural system. Table 2b summarises the costs of the different sub-systems, given as € /m2 (building area). The importance of an optimised system from a material viewpoint is obvious. The design of the roof system is also important from a production viewpoint, as assembly of the roof system requires many sub-assemblies and the use of expensive machinery (mobile cranes) for final assembly.



Joints between sub-systems

1. Roof-purlin ↔ Roof
2. Stab. in roof ↔ Roof
3. Roof ↔ column
4. Stab. in wall ↔ Roof

Fig. 3 Illustration of the structural system

Table 2 a) The average long-span timber structure. b) Overview of the total costs.

a)

Most common sub-systems	
Roof	Tied rafter with three hinges Pre-stressed tied rafter
Roof-purlin	Crossed purlins on support
Column	Rectangular
Stab. in roof	Steel bracers over two roof beams
Stab. in wall	Single steel bracer or a cross of bracers

b)

Sub system	Total Cost [€/m^2]	Ratio [%]
Roof	26	70
Roof-purlin Column Stab. in roof Stab. in wall	9	30
Total	35	100

5. Experience Based System (EBS)

5.1 Experience Feedback System (EFS)

The generalised regression neural network (GRNN), used for function approximation [8], is used as the basis of the EFS. From Table 1, the geometrical design parameters length and width are used together with the geographical design parameter snow load as input to the neural network. The result, when simulating the network, should be proposals for the five sub-systems together with spacing and roof pitch, Fig. 4. When using the GRNN, the three inputs; length, width, and characteristic snowload are asked for. The GRNN then simulates the network with the given inputs and gives the outputs a1 to a8, Fig. 4. Using the EFS may give a designer valuable early aid in design of long-span timber structures.

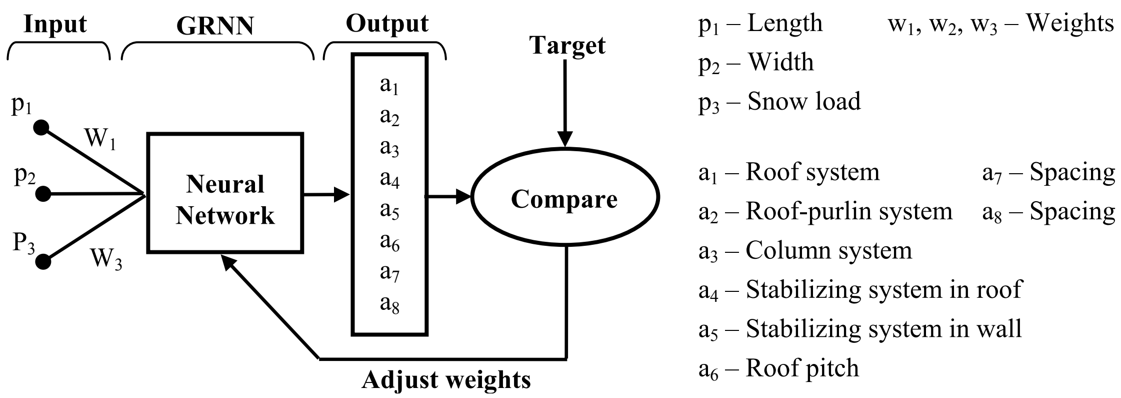


Fig. 4 The basic functionality of a neural network and the inputs/outputs used for the EFS.

5.2 Construction Knowledge Database (CKD)

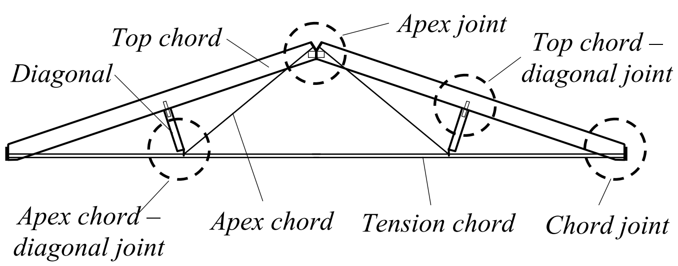


Fig. 5 The components of a pre-stressed tied rafter.

The structural system, composed of its sub-systems and joints, can be seen as a modular system where technical sub-systems can be altered while preserving the function of the final structure. How can a holistic SE view be maintained during such a complicated design? The DSM is a tool with the power to combine a holistic view with detailed interactions. According to the results in Table 2a the pre-stressed tied rafter is one of the most common systems in Sweden and it is used for a more detailed study of modularised systematisation.

The DSM result in Fig. 6 is a systematisation of Fig. 5 and should be interpreted as follows: letters along a line signify a physical connection between the studied element and another element within the sub-system, letters up and down a column means that this element is influenced by another element. Empty cells in the matrix imply no physical relationship and letters along the diagonal contain information about the respective element or joint. In Fig. 6, an **F** denotes the load transfer between elements and joints, and a **G** denotes the geometric constraints for assembly.

According to the sums ($\sum$) in Fig 6, the most important element of the pre-stressed tied rafter is the top chord influencing, and influenced by, both the design and assembly of four other elements or joints. What this means is that, during the design of the pre-stressed tied rafter special attention should be given to the top chord. It is possible to structure the complete design of a sub-system, and even the whole structural system, in this way.

		A1	A2	A3	A4	A5	A6	A7	A8	Σ
Top chord	A1	A1	F G			F G	F G		F G	4F 4G
Diagonal	A2	F G	A2					F G	F G	3F 3G
Apex chord	A3			A3		F G	F G	F G		3F 3G
Tension chord	A4				A4		F G			1F 1G
Apex joint	A5	F G		F G		A5				2F 2G
Chord joint	A6	F G		F G	F G		A6			3F 3G
Apex chord - diagonal	A7		F G	F G				A7		2F 2G
Top chord - diagonal	A8	F G	F G						A8	2F 2G
	Σ	4F 4G	3F 3G	3F 3G	1F 1G	2F 2G	3F 3G	2F 2G	2F 2G	

Fig. 6 Detailed DSM interpretation of a pre-stressed tied rafter.

In design, the holistic approach of the DSM provides a means to avoid sub-optimisation by applying functional requirements and geometric constraints on design. Also, the best use of systematic R&D findings regarding, e.g. connection and reliability-based timber engineering research, can be linked to DSM. In Fig. 7, examples of R&D findings are linked to the pre-stressed tied rafter DSM. All references given in the figure is from the latest CIB - W18 proceeding [9], supplying the latest advancements in timber research.

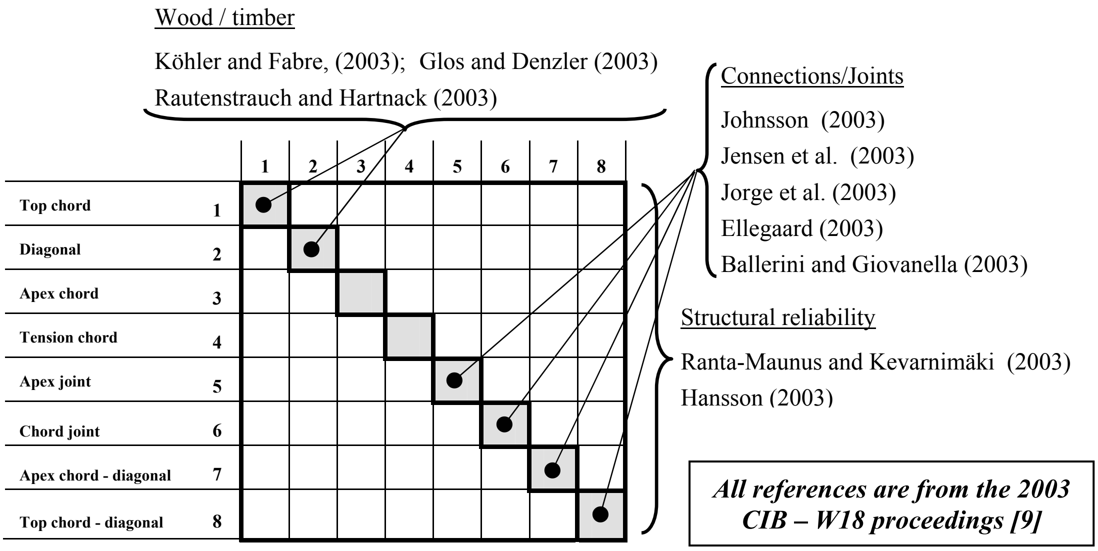


Fig. 7 Examples of R&D finding and their link to DSM detailed design.

6. Discussion & Conclusions

The main theoretical approach to understand, adapt, and develop industrialised construction must be based on an integrated and holistic systems approach. Further, it is necessary that these principles be systematically developed by jointly considering the levels of design, operations, and the production system [3]. By taking an integrated view of the appropriate construction requirements, in this case the structural and production system, this study shows that the benefits of modularity in construction can be realised.

Based on the case study and the theoretical DSM systematisation, the pre-stressed tied rafter is but one example of an industrialised product. This sub-system is one of the most common roof systems in Sweden because it is optimised as a module from a material and structural viewpoint, thereby being a viable economic choice. Since only one geometric design parameter, roof pitch, can be varied during its design, Table 1, optimisation is done within the sub-system, i.e. the roof system is designed by considering all of the functional requirements and geometric constraints in Figure 6.

The pre-stressed tied rafter is not prefabricated as a whole; instead assembly of prefabricated and standardised elements and joints is done on site before final assembly. The effectiveness of the roof-system is thus governed by a material and structural optimised design in combination with a modularised assembly, utilising standardisation and prefabrication. Using the DSM (Fig. 6) presented in this paper yields an optimised pre-stressed tied rafter can be obtained where the top chord cross section governs the rest of its components. This can be observed from the geometric constraints (**G**) in Fig. 6 which imply that, for example, the diagonal must have the same width as the top chord. If the widths are not equal, standardised joints cannot be used (**A8** in Fig. 6) resulting in the need of extra work on site or the development of a new type of joint for this application. And maybe even more interesting is that the available standardised glulam cross sections (**A1** and **A2** in Fig. 6) may be unusable implying requirements on the supply of customised standardised glulam cross sections. In the same way, other design oriented question and implications of design choices may be simulated with the provided DSM.

In design, the holistic approach of the DSM provides a means to avoid sub-optimisation by applying functional requirements and geometric constraints on design. Only considering one part of a system, i.e. the examples given in Fig 7, is a form of sub-optimisation that violates the principles of SE. This does not mean that such research should be avoided; rather this research should be placed into an SE perspective. The usefulness of a component-based DSM from a production viewpoint is the assembly stage. By advancing the component based DSM and by using an activity based DSM the production system as a whole may be incorporated and developed. To get the most out of the modularity approach a lean construction process should be considered, thereby supporting [3].

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