Knowledge-based bridge design

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Abstract

The increasing industrialization and standardization of construction opens up for the field of design automation, and possibilities to work with several what-if-conditions and several product candidates instead of just one or two during design. Design automation applications for building component and infrastructural part design are starting to appear within construction, but methodologies for developing such applications are few. Knowledge-based engineering (KBE) is a label for automation of routine design and analysis tasks originating from the automotive and aerospace industries. Current KBE methodologies need to be adapted for construction in order to be effective. This paper presents a methodology for producing the logic needed for design automation of bridges and discusses similarities and strengths in comparison with current KBE, configuration and modularisation methods. A case is presented where the bridge was divided into modules and the method was used to develop generic analysis procedures for the main beam of an end frame bridge. The biggest challenge was to define the dimensioning values. The study however indicated that the time for design and review of bridges can be reduced through design automation. This paper also stresses the importance of following and keeping a method updated, when developing design automation applications, to ensure future success. The methodology contributes by combining methods for modularisation and knowledge-based engineering.

Keywords: Knowledge-based engineering; modularisation, end frame bridges, configuration.

1 Introduction

The opportunities of digitalisation have created new possibilities for automation in construction. Configurators can automatically and with precision perform routine design work and save time that can be used for more creative work. Based on an extensive input drawings and other technical documents can be created

automatically. Design change impact on e.g. cost, equipment availability, staff capabilities and buildability can be shown and designers can reuse successful solutions from earlier work instead of reinventing the wheel for every project. Thanks to automation it becomes easier to generate several solutions and trying different what-if-conditions, within a specific design space, than when done manually.

Methods to develop configurators are very much corporate knowledge and open approaches are rare, at least for the construction sector. From manufacturing MOKA, [1], offers a methodology for Knowledge-based engineering, which is a blend of geometry, configuration and engineering knowledge. From the computer science field CommonKADS, [2], describe how knowledge-based systems, which are less geometry focused are developed. In the field of product configuration Hvam et al, [3], present methods stemming from the manufacturing industry. Within construction, methods for developing design automation applications are few [4]. Jensen, , presents approaches for how configurators can be developed for infrastructure and building applications.

This paper presents a method for producing the logic needed for design automation of bridges and discusses similarities and strengths in comparison with current KBE, configuration and modularisation methods. A case is presented where the bridge was divided into modules and the method was used to develop generic analysis procedures for the main beam of an end frame bridge.

2 Theoretical framework

2.1 Configuration

Configurators can be seen as design automation applications specialised toward semi-automatic configuration of modular products. Configuration is based on a generic product structure that can cater each customer's needs and values [5]. According to Hvam et al. [6] there are mainly two types of configuration; engineering and sales. Through the transfer of the customer's requirements, on the basis of a given framework, a detailed product can be created. The company creates the framework by identifying market needs and approach to customer value. Needs and values are then converted into functional and technical specifications for the generic product. The generic product structure itself contains predefined components and modules, as well as rules for how they should be used to generate customer value. Jensen et al. [7] argue that the

products-in-products concept is useful for enabling mass customisation in construction and presents three case studies of configurator for building and infrastructure projects.

Modules are exchangeable product parts with same interface making it possible to create a wide number of product configurations with a small number of product parts. Erixon [8] presented a methodology called Modular Function Deployment (MFD) for module development describing a modularization methodology consisting of five steps: 1) Clarify, customer requirements, 2) Select technical solutions, 3) Generate concepts, 4) Evaluate concepts, and 5) Improve each module,.

Hvam et al. [3] present a seven step procedure for building configurators: 1) Process analysis, 2) Product analysis, 3) Object-oriented analysis, 4) Object-oriented design, 5) Programming, 6) Implementation, 7) Maintenance.

2.2 Knowledge-based engineering

The term knowledge-based engineering (KBE), has become a label for automating routine design work within the manufacturing industry. It is named 'knowledge-based' because knowledge from engineers is captured, formalized and implemented into a computer-based design automation application. Typically design automation applications feature both fully automated tasks as well as semi-automated tasks that require user-interaction and often feature computer aided design and engineering systems. Stokes defines KBE as 'the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way' [1]. Automating chains of engineering activities is not new; this has been used by engineers since the early developments of computer-aided modelling and simulation [9, 10]. Examples of KBE applications from the latest decades are e.g., [11-13].

Li outline success factors for knowledge-based support tools namely: User involvement (e.g. support tool project initiation, user interface design – this is also noted by Hvam [3]), problem difficulty (e.g. availability of expertise for the construction problem), developer's skill (e.g.

ability to extract knowledge from construction experts), shell characteristics (e.g. flexibility, usefulness) and management support (e.g. commitment, encouragement from management to use support tools, appropriate financial resources) [14].

Examples of KBE-like design automation applications have started to emerge within construction e.g. [7, 15], but a comprehensive methodology for design automation application development is absent within construction. Such methodology should be hands-on and describe how to choose tasks to automate, how to capture knowledge, formalize knowledge and implement the knowledge in a computer software. This makes it hard for companies to know what tool to develop and how to develop it, especially for companies with little or no experience in design automation, apart from the usual hinder for change which is that most companies are too busy with their everyday tasks. Additionally for researchers it is hard to reproduce research and build on ideas due to lack of details in the papers regarding how the design automation application was created.

2.2.1 MOKA

MOKA is the most comprehensive methodology for KBE application development although other less detailed methodologies exist, e.g. [16]. The focus of MOKA is to describe how to capture engineering knowledge and implement it into a KBE application [1]. It was developed to aid Europe to catch up with the USA and the Far East regarding KBE applications for mechanical design. MOKA contains six phases which are shown in Figure 1. CAPTURE and FORMALIZE are the most elaborated phases although the other phases also are explained.

Figure 1. The MOKA phases, adapted from Stokes [1]

IDENTIFY determines objectives, scope and a concept level technical specification for the design automation application. JUSTIFY examines commercial, cultural and technical risks. CAPTURE collects the raw knowledge and structures it into the Informal Model. FORMALIZE translates the Informal Model into the Formal Model. PACKAGE involves translating the MOKA Formal Model into code for a KBE application. ACTIVATE involves distribution, installation and use.

In the CAPTURE part ICARE (Illustration, Constraint, Activity, Rule, Entity) forms are used to document engineering knowledge. A special developed modeling language, the MOKA Modelling Language is used to FORMALIZE the captured knowledge.

3 Case study

The project was conducted as a Master thesis project, [17], but was part of a bigger multimillion (SEK) that intend to develop a configurator for the final documentation and drawings for a unique project. The case company has chosen to develop a modular end frame bridge. The basis for this product choice lies in analysis of the market and economic potential, and design suitability.

According to an analysis of data from the Swedish Transport Administration's database Batman (Bridge and Tunnel Management) The Swedish Transport Administration is responsible for about 17,000 road bridges in Sweden. Data shows that there are about 6,500 slab frame bridges which make it the most common. A tube bridge is the second most common type of bridge with a number of about 3400 bridges. The third most

common type of bridge is the end frame bridge with a number of about 2800 bridges which corresponds to 16% of the total number of bridges in Sweden.

The difference of an end frame bridge compare to a slab frame bridge is that the super structure is simply supported unlike the slab frame bridge where the super structure is clamped in the frame legs. Therefore, the reinforcement solution is less complicated for end frame bridges and this bridge type is a good candidate for modularization.

Every year about 20 end frame bridges are built for the Swedish road network by the Transport Administration and indications are at least as many within the local road network. These bridges have an average cost per square meter at 26 000 SEK in accordance with the Swedish Transport Administration, which corresponds to

approximately 5 million per bridge based on bridges constructed in 2009-2010.

The case company chose to do a top-down analysis by modularization this bridge type and therefore collected documents of end frame bridge drawings. The documents have been produced from the Swedish Transport Administration database Batman and are from bridges designed over the past 20 years.

In order to reuse the different parts of the end frame bridge in other products the case company divided the bridge into modules that are completely or partly independent of each other, see Figure 2.

Figure 2. The modules of the end frame bridge.

4 Method

The final method is depicted in Figure 3 and contains 10 steps.

Figure 3. Proposed methodology for knowledge-based bridge design

4.1 Choice of design

This step is based on the 1) commonality of the design type, 2) the variation in geometry and 3) the complexity of the dimensioning. By analysing these three parts the profitability of a possible configurator can be assessed. This is also dependent on the size of the automation project and should be balanced with the return of investment.

4.2 Data collection

A data collection is conducted to enable a top-down analysis of the design to enable efficient modularization. From the top-down analysis the design requirements are found by analysing existing designs combined with the respondent's answers and books regarding design, production and aesthetics. A data collection should produce the following: 1) drawings and documents of existing designs, 2) possible construction methods, 3) aesthetic requirements, 4) experience feedback

from the production and 5) experience feedback from the operation.

4.3 Design break down into modules

To be able to break down or divide the design into different modules it is important to have some knowledge about design, production and aesthetics but also how the drawings are designed and delivered to the customer. This is important because the result should be a parameterized geometry that should fulfil all requirements. The design break down starts with an analysis of the collected data. The analysis considers: What generates customer value? What requirements are realistic? What functions are associated with the design? What modules can the design be divided into? How do the module interfaces look like? What geometries can fulfil the requirements? How do the geometries affect the building process? How do the geometries affect the operation? What limitations can the reinforcement solutions have on the geometry?

By using the collected previous designs it is possible in a reverse engineering manner to identify starting requirements.

The analysis of how the reinforcement solutions can affect the operation of the bridge need to be done in four steps: 1) Connect requirements to the design, 2) Divide the design in modules that each fulfil the requirements, 3) Analyse the geometric variation within a module and connect the geometry to the requirements and 4) Analyse that the reinforcement solutions match the geometry.

4.4 Choice of boundary geometry

The choice of geometry is based on the analysis of the existing designs and earlier experience of the design. Aspects to consider are: 1) Customer value, 2) aesthetic requirements, 3) other functional requirements, 4) identification of relationships between parameters to decrease the number of parameters, 5) how to make for reinforcement solutions, 6) how to make production easier, and 7) connecting design parts.

4.5 Choice of reinforcement solutions

Reinforcement solutions should be chosen so: 1) there is a possibility to fulfil the geometric variation, 2) programming of the dimensioning solutions is simplified, 3) production is possible and 4) material volume is reduced.

4.6 Validation of geometry and reinforcement solutions

The geometry choices and reinforcement solutions need to be validated by a group of people with expertise within dimensioning, production and operation of the specific design. This validation can cause iterations where the geometry and the solutions need to be changed and evaluated again. The evaluation has two main purposes: 1) make sure that all functional requirements are fulfilled and 2) make sure that the solutions are done in the best possible way to facilitate design, production and operation.

4.7 Development of generic analysis procedures

The analysis procedure should be developed so the input data parameters can be changed to fulfil the functional requirements. It is important to find a balance between the number of input parameters and the variability of the module. By studying existing analysis procedures for different design it is possible to identify common part and reuse them. The different parts can also be identified.

It is important to choose a software that facilitates reuse. The analysis parts should be able to be presented in a way that is easy to evaluate. It should also be easy to extract parts of the analysis to enable reuse in other projects.

4.8 Validation of analysis procedures

To make sure that the analysis procedures are correct they need to be tested with different examples and then evaluated. This can be done by creating obligatory check boxes that in a clear way show if specific dimensions are approved and letting someone outside the project evaluate the analysis procedure.

4.9 Configuration

Configuration enabled generation of unique variants of the product in an efficient way. Some important aspects to consider: 1) Clear boundaries for the product parameters should be defined, 2) the GUI for inputting values for the parameters should be user-friendly, 3) the configurator should fit in the current work process and 4) maintenance should be simple. This process is described in [18].

4.10 Updating

To make sure that the configurator will be used in as many projects as possible it is important that the configurator is continuously updated and developed. Updates need to be done simultaneously with every use of the configurator and collection of feedback need to be done after every major stage: design, production and operation

The method was followed to develop a knowledge-based bridge design tool. MathCad and Brigade were used for the calculations.

5 Comparison

On an overarching level the methodology presented in Section 4 share similarities with MFD methodology for modularisation of Erixon, [8], the procedure for developing configurators suggested by Hvam et al., [3], and the methodology for KBE-application development presented by Stokes, [1].

Choice of design includes finding the customer needs and requirements as Step 1 of MDF, even though MDF features use of Quality function deployment matrices. The profitability evaluation resembles part of the Justify step of MOKA.

Data collection resembles the Capture step of MOKA although MOKA provides detailed ICARE forms for this purpose.

Design break down into modules, Choice of boundary geometry and *Choice of reinforcement solutions* have similarities with Step 2 and 3 of MFD although Step 2 also features functional decomposition using a functions means tree and Step 3 contains the use of the Module Indication Matrix. MOKA focus classes containing attributes instead of modules during the Formalisation step using a Unified Modelling Language-based approach and Hvam et al.'s procedure focus both classes and modules during phase 3 and 4.

Validation of geometry and reinforcement solutions has the same goal as Step 3 and 4 of MFD although MFD employs a systematic way of evaluating e.g. the module interfaces using interface matrices. Step 5 includes evaluating producibility as well.

Development of generic analysis procedures and *Validation of analysis procedures* deals with identification of rules that should govern the variability of the design. This resembles the use of the informal and formal models of MOKA.

Configuration has commonalities with the Package step of MOKA and Programming phase of Hvam et al.'s procedure. The Updating step share goals with MOKA's Indentify step and Hvam et al.'s Maintenance step.

6 Discussion and conclusions

A methodology for developing design automation applications for knowledge-based bridge design has been presented. The methodology shares similarities with methodologies within modularisation, [8], configuration, [3], and knowledge-based engineering [1]. The contributions of this methodology are presenting a way of combining all this three fields and showing the potential for use in bridge applications. The proposed methodology needs to be detailed further on and tested on other construction applications to increase its value.

Reinforcement solutions need to be chosen according to the geometrical boundary of the object (e.g. bridge platform) to be able to develop a configurable product. This is done by identifying the technical requirements and what components that fulfil these requirements. Then components are chosen with aspect to producibility and how they fit together.

Workers from bridge production units could have added more experience to the choice of detail solutions. Also feedback from operation on the output from the configurator would create valuable feedback for improvement.

The biggest challenge for the development of the generic analysis procedures was to define the dimensioning values. In some parts of the Eurocode the dimensioning values are found by plotting torque curves or the shear force curve and using empirical values. This can pose programming challenges to do this automatically.

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