A master model approach for design and analysis of roof trusses

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Abstract

Apartment housebuilding takes too long time and optimal solutions are seldom found. In housebuilding projects, there is an increased popularity of using virtual models for analyses of structural integrity and floor layout. However, these analyses are seldom coordinated since the models rarely are linked and the designers are not working close enough. As such, optimal designs are hard to find and time flies since even small changes turn into many iterations between design and structural analysis. General building information modeling and virtual design and construction methodologies suggest the use of interoperability and automation to bridge these gaps. There are examples of design tools that link different models using off-the-shelf tools or programming. However, most of the housebuilding companies seldom have these advanced tools or have the competence to do advanced programming. In this paper, we suggest an approach of using visual programming in a common BIM-software to explore the linking of different models. As an example, we study design of roof trusses since for many different roof shapes the same rules usually apply to the design of the truss. This project connects a BIM-software and a FEM-program with a master model. The model automatically generates a roof with the designed truss, draws the representation in a BIM-software and analyze it in a FEM-program. The early evaluations of this visual programming based approach are promising as there are possibilities to connect other domain models and create an even richer evaluation bases for early apartment housebuilding design.

Keywords –

Roof trusses; Design automation; Finite element model

1 Introduction

The housebuilding industry strives to cut lead times, increase quality and reduce cost. In early design, many important decisions are taken which will impact the rest of the building life cycle, why the use of virtual models are increasing in popularity to predict life cycle effects, e.g. structural integrity, energy consumption, constructability changes due to design changes. Although more and more models are being used during design there is still a challenge to coordinate design and analysis in a way that promotes evaluation of more design alternatives than just a few, why solutions tend to be good enough instead of optimal. Making changes in models tend to take time since not all models are linked with each other and not always have parametric capabilities. Building information modelling (BIM) sets the framework for how to create parametric and information rich models [1], and virtual design and construction (VDC) likewise sets the framework for visualization, interoperability and automation [2]. Thus, BIM and VDC targets this challenge on an overarching level.

Looking in to more specific applications several researchers exemplify applications of how to link models, e.g. [3], or automating design tasks, e.g. [9], using off-the-shelf tools or text-based programming, such as C++ or Python. These types of applications are suitable for larger housebuilding companies or very specialized consultant companies with competences and resources to handle such advanced technology. But, many small and medium sized construction companies do not have these opportunities.

Therefore, the aim of the paper is to suggest an approach that creates a master model using visual programming languages (VPL), since VPL with its graphical interface enables a lower threshold to climb than most text-based programming languages.

There are examples of architects using VPL to automated generation of more shape-based buildings or artefacts [4]. Other examples of VPL use includes leveraging it to enable BIM-based assessment of environmental performance [5]. The use of VPL for model coordination within construction design and analysis is yet to be detailed by the research community. The approach suggested in this paper is exemplified with a design tool for roof trusses.

2 Background

This paper deals with virtual construction and particularly how to use models to enable flexible and efficient design and analysis during early design of buildings. As mentioned above the fields of BIM and VDC are framing the theory for this paper and below we introduce the areas of design automation and master models which are key topics for the presented approach. Research regarding roof truss design tools are also described.

2.1 Design automation

Design automation stems from the area of parametric mechanical CAD (computer aided design) and can, according to Cederfeldt and Elgh [6] within the manufacturing industry, be a way of developing tools that enable re-use of engineering solutions. According to Sandberg et al. [7] design automation in construction relates to several different techniques of which we here briefly introduce knowledge-based engineering, configuration and modularization.

Knowledge-based engineering (KBE) is essentially rule-based CAD where rules are implemented using for example object oriented programming. These rules are used to generate geometry models, finite element models, reports, bill-of-materials etc. [8]. The term knowledge-based comes from the act of acquiring knowledge from engineers to allow for automating some of their routine tasks to free time for more challenging engineering tasks. This act of automating engineering tasks has been used by experienced engineers since the dawn of the computer, as one of the important roles of the computer is to automate tasks.

Configuration is usually enabled by developing a product platform which consists of a limited number of modules that can be combined into many products and can be used during detailed design [9]. So, compared to KBE, configuration usually is connected to modular product architectures while KBE also is used for more integral product architectures. KBE can be used for both early, system and detailed design while configuration is more common to apply in detail design. Of course, there is overlap here and one could say that a KBE tool is used to configure a product. A difference is that KBE tools also can include generation of analysis models. In short configuration can be seen as a subset of KBE.

Some architects do design automation by building up parametric models using VPL such as Grasshopper, Dynamo, GenerativeComponents etc., [4]. This is a more shape-based type of parameterization that uses more advanced mathematical expressions, compared to KBE and configuration, and is suitable for calculating the form of more advanced shaped architectures. In a more similar fashion to KBE, the use of VPL has been seen in the realm of environmental concern. For example, Asl et al. [5] presented a framework for BIM-based performance optimization where VPL was used to generate design options, assess environmental performance, and search for the optimal design solutions. Other applications of VPL include Khaja et al. [10] that investigated using VPL to automatically populate non-geometric data into BIM models for operations.

2.2 Master models

The idea with master models is to reduce the need for manual updates of virtual models and instead create a governing product definition that is linked to other domain models of interest, e.g. finite element models, energy calculations, micro climate estimations. So, when the product definition is changed in the master model, this change automatically propagates to all other linked models. This idea has featured some modelling computer systems since the 1970s, [11].

The main idea of having information stored in one place connects to the idea of the BIM-hub [1] and some off-the-shelf CAD and BIM software also feature master model capabilities. Some examples are the connection between the BIM-tool Revit and Vico Office for model-based cost estimation and planning, or Revit and Robot for structural integrity evaluation, although these links require many manual interventions as well.

Negendahl [4] describe three ways of coupling tool models: 1) *combined model method*, where the design and analysis functionalities essentially are integrated but the user is restricted to the options and features offered by a particular software, 2) *central model method*, which is close to BIM where the data is centralized in a shared data schema usually using IFC (industry foundation classes) or other neutral formats such as gbXML (Green Building Extensible Markup Language) and is argued to be time consuming to use in team based design exploration, and 3) *distributed model method*, is compared to the central model method not hierarchal, instead the connections are more distributed into a more flat model organization.

The field of multidisciplinary design optimization (MDO) also connects to the master model idea by embracing the importance of linking models to each other allowing for automated design and analysis loops. According to Díaz et al. there is still research work to do to overcome parametrical issues and challenges to create interoperability between models, [3].

2.3 Roof truss design tools

Shea et al. [12] present a performance-driven generative design tool for cantilever roof truss design. GenerativeComponents (Microstation) is used together with an optimization process called structural topology and shape annealing within the generative structural design system called eifForm. By applying XML models, it is possible to link these softwares together.

Flager et al. [13] present a method for fully constrained design applying gradient-based optimization that also is exemplified for steel roof trusses for a sports arena. The process integration and design optimization software ModelCenter was used together with the Digital Project CAD software and a finite element analysis software. The implementation was evaluated with conventional design and the results showed that the implementation took 30 man-hours longer but evaluated almost 500 times more solutions.

Villar et al. [14] describe how to use genetic algorithms to optimize the design of heavy timber trusses. This research is centered around an analysis model where the design optimization is done. It was found that genetic algorithms are effective for optimization of glulam roof truss structures.

2.4 Research motivation

Since off-the-shelf MDO tools as well as automating BIM activities usually involves advanced programming in this paper explores how the possibility of using VPL to mitigate the parametrical and interoperability issues by creating a master model. Also, automatic design tools connecting design and analysis models seem to focus steel structures why it is a need to investigate automatic design tools for timber roof trusses.

3 Research process

This research was conducted by studying earlier research to motivate the research gap and serve as input to the development of the proposed approach. Developing the master modelling approach was an iteration between studying literature, generating ideas and developing the example tool.

Discussion were held with designers from a company that was interested in the field of making design and analysis more efficient using virtual models. The company conducts design and production of prefabricated modular multi-family timber buildings. Roof truss design was identified as an interesting topic, since they are featured in all projects, and an implemented design tool has the possibility to be used continuously in future projects. The company supplied drawings from a recent building project as input to the tool development. The drawings showed a surprising number of different configurations and the possibility to standardize the design of roof trusses was identified as an opportunity for saving design costs. As a way of limiting the design space the company articulated that it is most economic to use trusses with same length for the top beam.

The development of the example tool was done mainly by the first author and discussed among the authors. First, a simple version was developed to investigate if Revit, Dynamo and Robot worked as expected. Then the tool was further refined to incorporate more details and parametric capabilities. When the second version was developed the tool was evaluated against relevant literature.

4 Results

4.1 Proposed approach

The proposed master modelling (MM) approach is shown in Figure 1. A design and analysis loop can be conducted and contains 1) giving product definition input to the master model, 2) generating analysis models, 3) evaluating objective function (design goals) and 4) if not satisfied repeat.

The MM contains the logic done in VPL that represents the building geometry and its properties as well as other parameters needed for linking to the other domain models. If the VPL part is not enough in terms of built-in functionality to automate the generation of the domain models, scripts and software-specific macros might be needed. A database with additional information regarding e.g. materials, environmental product declarations can be either part of the MM or provided as a linked resource. If a fully automatic design and analysis loop is reached, then optimization is possible to conduct. This could be done either through the VPL part or by a separate managing unit using e.g. MATLAB or text-based programming.

Using the MM starts with giving input. If it is a fully automated MM then the input concerns the optimization, e.g. objective function, possible parameter values, maximum number of iterations. Then the MM is executed and models are generated and evaluated until the optimization unit is satisfied or maximum number of iterations are done. If the MM is used in a semi-automatic fashion, then the input is values for the design parameters and then the model generation is executed. When the models have produced their results, the user or users within the design team must evaluate the results and decide if another design and analysis loop should be initiated.

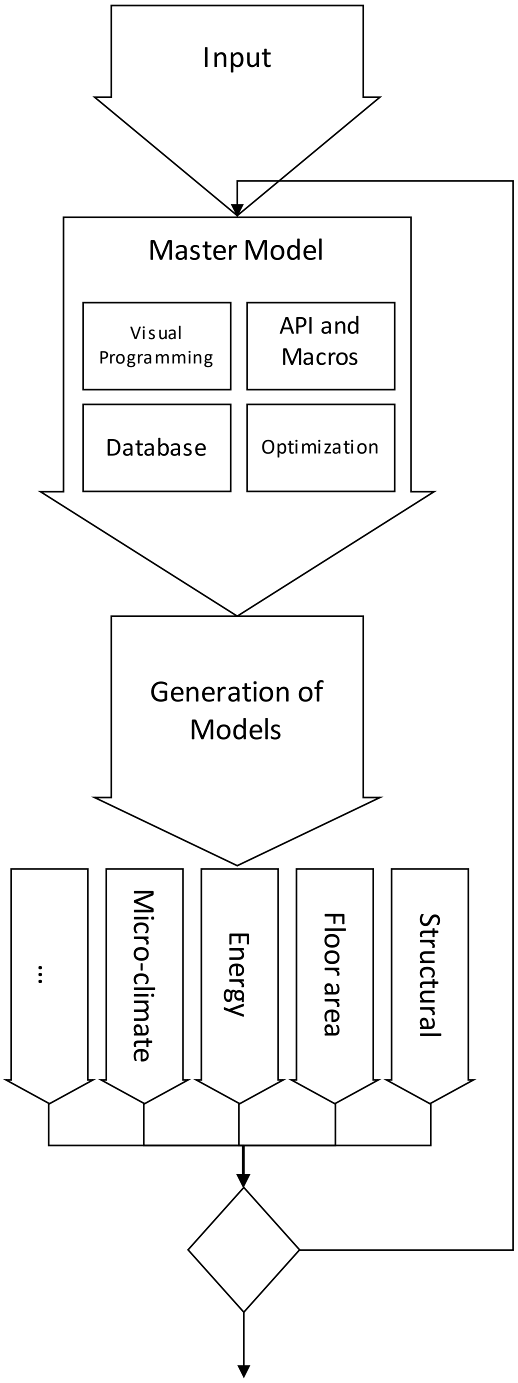

Figure 1. The proposed master modelling approach.

4.2 Example

Here, the inner workings of a MM approach for a framework of a double pitched roof is explained. Dynamo is used as the VPL of choice as it provides links to both a BIM tool, namely Revit, and a tool for structural analysis, Robot. A two-stage approach is adopted. First the whole geometry for the framework is created in Dynamo using points and lines. Then, depending on the situation, the geometry is either used to generate the BIM representation within Revit, or sent for structural analysis in Robot.

4.2.1 Dynamo model

The framework of a roof contains several trusses that are set in given spacing. To generate the framework, Dynamo uses points that in pairs create lines. Only the coordinates of the three corners of each truss are necessary to specify in an Excel sheet, see Figure 2. Each point contains x-, y-, and z-coordinates in the Cartesian coordinate system to describe it and users must type in the coordinates in a specific order. It should be noted, that the x-coordinates must be typed in column A, y-coordinates in column B and z-coordinates in column C.

	A	B	C
1	0	0	0
2	8	0	0
3	4	0	3
4	0	1,2	0
5	8	1,2	0
6	4	1,2	3

Figure 2. Input coordinates in Excel.

Each row describes one point and every three rows describe one triangle. The first point of each triangle is the bottom left corner, the second point the bottom right corner and the last point is the top point. With that method, it is possible to create as many triangles as needed for the framework. The Excel sheet is linked in the Dynamo model so that Dynamo can read the data and generate the specified points. Then, Dynamo generates lines between each of the three points and the lines of these triangles will later be defined as top or bottom chords.

The second input is for the “box”, a room to fit within the framework, which can be used as e.g. a utilities room. These input parameters, for the box, control the length, width, and height and its bottom left position. Dynamo creates a box from the bottom left point to the upper right point of the box. In the next step, lines (diagonals) between the chords are generated to support the triangles. There are two different ways how they are built that depend on if the box intersects a roof truss or if it does not.

1) The box does not intersect a roof truss: All triangles that does not intersect the box are generated like a W-beam. At first an uneven number of sections must be selected. It is possible to choose between 3 up to 9 sections. More than 9 sections are not necessary for a roof truss. The sections are the subdivision of the bottom

chords. The top and bottom chords are subdivided in equal lengths with points. Lines connect the points to build diagonals.

2) The box intersects a roof truss: First the framework for the box is built. Dynamo generates vertical lines on each side of the box. They reach from the bottom chords to the top chords. A horizontal line between the vertical lines is generated to mark the height of the box. Diagonals are created to support the top chords next to the box. Two separate cases of the intersection between the box and roof truss are managed:

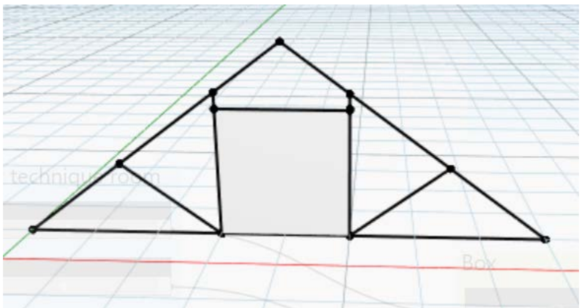

Figure 3. Case a) Box in the middle.

Case a) the box is placed in the middle under the left and the right top chords, see Figure 3. In this case Dynamo generates a diagonal line on the left side and a diagonal line on the right side of the box. Each line starts on the bottom side of the box and ends at a specific point of the top chords. That point is in the middle of the distance between the start of the top chords and the end of the vertical line of each side.

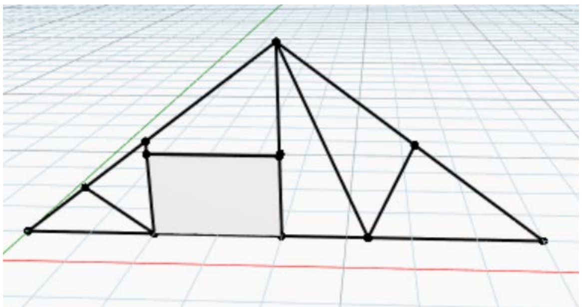

Figure 4. Case b) Box is on one side.

Case b) describes a position of the box, where it is on one side of a truss, see Figure 4. Two diagonal lines will be generated at the side without box. They start at the half distance between the one side of the box and the corner of a truss. The top point of a truss is an endpoint and the middle of the top chords is the other endpoint. The program generates a diagonal line like in case a) at the side with the box. The program generates four lines that are used for wind bracings. They start at each bottom corner of the framework. The endpoint is at the top of the second truss or rather the next before the last truss. All lines are joined in a list at the end of the Dynamo model. The list will be used for the Revit model and the Robot model.

4.2.2 Revit model

The Revit model uses a node within Dynamo that contains a collection of all the lines generated for the trusses. It distinguishes the lines in the different structural elements of the framework, e.g. top chords, and assigns the appropriate structural framing type to them. This information is then relayed to Revit where a representation of the truss is generated. Through the change of parameter values, different aspects of the elements in the trusses can be altered, e.g. rotation and dimensions.

4.2.3 Robot model

The Robot model uses the same collection of lines as the Revit model. However, due to differences in object types, Dynamo does not send the lines automatically to Robot. As such, they must first be changed into analytical bars before they can be transferred. See Figure 5 for an excerpt of how coding in Dynamo looked.

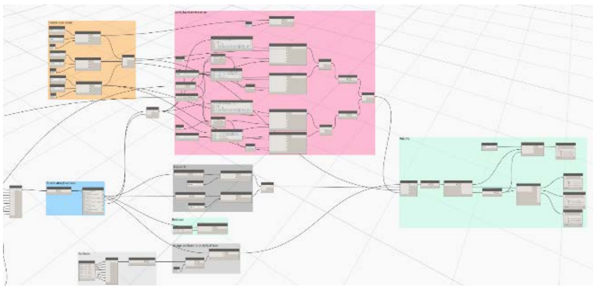

Figure 5. Code in Dynamo for generation of the Robot model.

For the whole and larger programming layout see the Appendix on the last page of this paper.

5 Discussions and conclusion

A master modelling (MM) approach based on visual programming languages (VPL) has been presented and exemplified with a roof truss design tool. MMs could increase the chance of finding optimal solutions instead of just good enough solutions since the design and analysis loop enables multiple solutions to be evaluated. Compared to configuration, [9], MMs could be used for developing building systems since the optimized solution could be reused and therefore could become a member of a company’s product platforms. Compared to the tool model coupling methods that Negendahl [4] presents the

MM, and especially the presented example, is closer to the distributed model since the models are created in a process flow, i.e. first the Dynamo geometry model is created, then the Revit model is created and lastly the Robot model is created. Also, Asl et al. [5], with their case study showed an application of VPL in closer resemblance to configuration where parametric changes are made to existing objects. Although, the authors also acknowledge that their framework could be used in a far broader extent than exemplified.

VPL is more graphical and possibly more intuitive compared to text-based programming languages. VPLs makes it possible to link models and the master model in our example is a Dynamo model that is linked to Revit and Robot. The example show that several roof truss solutions can be found faster than manually generating the different geometrical representations in Revit and Robot.

The design teams that could use a tool like this should preferable have members from each of the included domain models, in our example architect and structural engineer. With the design team having basic programming skills it would be possible for them to develop tools like this and keep them maintained with latest data.

As Negendahl [4] argues, the presence of VPL does not solve all interoperability issues why the inclusion of scripting (potentially using text-based programming) and macros in the MM is important to increase the possibilities for full automation capabilities. For fully automated master models, the early design stages are suitable since then the building design is still overarching and therefore less effort is needed for automation.

Compared to other truss design tools, e.g. [12] and [13], the presented tool was developed within a BIM environment which is important to increase the possibilities for model coupling between architects and structural engineers. Also, the presented tool is for timber truss design and analysis where earlier similar tools have a majority within steel trusses. There are examples of timber truss design tools, e.g. [14], but most of them are design tools for structural engineers and not for both architects and structural engineers.

Future work involves connecting more models and implantation of full automation to enable more efficient optimization. Conducting design studies is also of interest.

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APPENDIX – The full layout of the Dynamo programming blocks used in the example