Knowledge-based geometric modeling in construction

Bonev, Martin; Hvam, Lars

Published in:
Proceedings of NordDesign Conference 2012

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

Knowledge-based geometric modeling in construction

Martin Bonev
PhD student, Technical University of Denmark
mbon@dtu.dk
Lars Hvam
Professor, Technical University of Denmark
lahv@dtu.dk

Abstract

A wider application of IT-based solutions, such as configuration systems and the implementation of modeling standards, has facilitated the trend to produce mass customized products to support inter alia the specification process of the increasing product variety. However, not all industries have realized the full potential of using product and process modelling tools as well as the implementation of configuration systems to support their business processes. Especially in the building industry, where Engineer-to-Order (ETO) manufacturers provide complex custom tailored products, up to now, often a considerably high amount of their recourses is required for designing and specifying the majority of their product assortment. As design decisions are hereby based on knowledge and experience about behaviour and applicability of construction techniques and materials for a predefined design situation, smart tools need to be developed, to support these activities. In order to achieve a higher degree of design automation, this study proposes a framework for using configuration systems within the CAD environment together with suitable geometric modeling techniques on the example of a Danish manufacturer for precast concrete elements.

Keywords: Knowledge based engineering, geometric modeling, product configuration, construction industry.

Introduction

Background

Unlike most other industries, over the last decades the architectural, engineering and construction (AEC) industry has struggled with achieving any significant productivity improvement [3]. Both, researches and professionals, have therefore been studying ways to gain better performance within this area. Two major approaches have thereby been mainly pursued:

By introducing and adopting lean methodologies to construction, professionals and standardizing associations have initially tried to push forward standardization of products and practices and thereby to reduce waste throughout the construction activities performed by various stakeholders [5, 7]. However, being in a strongly project-oriented business, where each projects is regarded as being unique in terms of design, specifications, context and construction processes [5], the application of formal tools and methods requires comprehensive experience and deep understanding of project specific information [6].

Implementing such a holistic top-down approach turned out to be rather difficult, especially when firms are using separate applications, which are specific for their area of business [7].

More recently, with a wider use of information technologies in the building environment, the industry has then started realising the benefits from transferring the use of IT tools from being dedicated to specific applications, where little or no compatibility was provided, towards more comprehensive solutions [7]. To this end, even though still in its early stage of transformation into a widely accepted practice, building information modelling (BIM) and the creation of common data exchange standards, like Industry Foundation Classes (IFC), have demonstrated a promising potential for an improved way to manage construction projects [8].

Research objectives

Despite all the research effort that has been done especially with regard to the BIM approach, creating tools to support the construction work is still challenging [4]. Tizani and Mawdesley (2011) thus state that in order to facilitate the progress towards higher productivity throughout the building lifecycle, more aspects have to be considered. For instance, apart from the BIM approach, information modeling should also address operational practices of construction. Furthermore, the authors illustrate that with the detailed digital representation of products and processes will help to improve the accuracy and productivity in construction toward a higher degree of automation. Product and processes should thereby follow standardized modeling technologies [2].

Inspired by the industrialization in the plant and machinery industry, with this research we therefore attempt to bring forward the idea of using IT tools and standardized modeling techniques to facilitate a higher degree of automation of the performed construction activities. The focus in particular set on evaluating the current applications of knowledge-based IT support to improve the efficiency of ETO manufacturers in designing geometry-oriented models. A major objective is hereby to automate recurring and non-creative design tasks and to establish generic product models that enable the representation of complex geometry-oriented product architecture.

Research methodology

Based on a literature study, the paper first examines the existing design processes within the building industry and how current procedures of using knowledge-based IT support have thereby been implemented. New methodologies are then introduced that better meet the predefined objectives. To apply the developed methods and techniques, a single case study has been conducted on the example of a Danish prefabricating plant for concrete elements. Being a major producer of precast concrete elements on the Danish market, the studied company has well-established business and production processes and can therefore be seen as a representative example for the precast construction industry. By generalizing the achieved results, the developed methods and techniques can be suggested as a suitable approach for the whole industry.

Related work

Design activities in the precast industry

Even though building design activities have been performed for hundreds of years, it wasn't until 1960s when the design process was initially formalized [10]. Further descriptions of processes and practices have followed since, aiming to define the activities of the involved stakeholders in detail. The main activities were structured according to the lifecycle of a building, where five major phases were identified: feasibility study, design, construction, operation and support, and demolition [11]. Going into detail, the design phase thereby contains a conceptual, preliminary and detailed design, clearly separating the design processes from the construction operations [12]. Similar to the design approach in other industries, a preferred design approach in construction is the top-down design [14], where first the overall product, i.e. the building, is defined, followed by breaking it down into subsystems, assemblies and physical components [9]. Based on the initial design intent of the architect, engineers are transferring a design concept into a structural model with the objective to create feasible structural solutions while referring to given architectural patterns and constrains. Such decisions are mostly based on the engineer's knowledge and experience of the realization of the design intents on a given situation [9]. In the detailed design phase further specifications determining the precast elements need to be done to define the structure and assembly layout, the assembly design and analysis and the piece and connection detailing [13]. As most of the building parameters have already been decided, now, concrete calculations of the costs for production can be made. With the focus on specifying the reinforcement, the dimensions and surfaces, and the exact placement of recesses for doors, windows and other instillations for each precast element, the design procedure is recurring in nature.

Managing knowledge in the design process

Knowledge-based engineering for repetitive design tasks

A number or research has been done to investigate how to reduce the resources spent for routine design. Knowledge-Based Engineering (KBE) has thereby been identified as a major approach to study the reuse of product and process knowledge with the aim to reduce the time and cost spent on product development thorough automation of repetitive design tasks [15]. Depending on the application, various definitions on KBE can be found in literature. Stokes (2001) refers to KBE as "the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way" [16]. According to Chapman and Pinfold (2001), KBE is an "engineering method that represents a merging of object oriented programming (OOP), artificial intelligence (AI) techniques and computer-aided design technologies, giving benefit to customized or variant design automation solutions" [18]. To realize the required integrity, the knowledge to be modeled should therefore be provided within the CAD systems that are used by engineers and architects. Geometrical constrains and heuristic knowledge on the product design can thereby be stored in the so called knowledge base [14]. Sandberg et al. (2011) further state that by using rule-based applications, geometrical models can be represented in a way which is beyond the traditional parametric models. For routine engineering tasks such applications are found being useful [17]. The authors explain how object-oriented KBE software makes use of predefined classes for major geometry objects, such as blocks and cylinders, and predefined functions for modeling parameters, like *min* or *max* functions. Application Programming Interfaces (API) and Macros help to create design and analysis loops, which after a number of iterations can eventually lead to the optimal overall design. As the authors focus on supporting an early stage of the design process, the detailed design is suggested to be carried out in the CAD models, once a suitable product design containing the desired overall parameters has be achieved.

Knowledge-based engineering in construction

One of the first attempts to implement rule-based design in construction was done by Gross (1996). The author refers to a constraint-based program for developing suitable construction kits. Similar to building up a house out of LEGO blocks, the program defines rules for the dimensions and the positioning of building components, which eventually leads to nearly unlimited possibilities of approved combinations [19]. A similar approach is suggested by

Sandberg et al. (2008), where a configuration system is used to define the dimensions and placement of stairs within a building. The program provides support to the sales and design process by implementing if-then-else rules for choosing the right stair geometry for a given layout and calculating the production costs. To achieve better product documentation and to obtain information on geometry configuration and engineering knowledge, the authors suggest the use of a product data management together with the stair configuration. Even though not further specified, the integration to various CAD systems should be solved through a connection with the API of the systems [20]. A recent study on KBE in the precast industry by Jensen et al. (2012) refers to a rule-based support through the use of a configuration system which is directly integrated into a CAD system. SolidWorks [27] is chosen as a main CAD system for both, making parametric product models and for realizing the communication with product data management (PDM) systems. A standard integration with the configuration system TactonWorks [28] creates the desired design configuration of the dimensions and exports an xml-based parametric file to widely applied architectural CAD software, such as Autodesk Revit [29]. The engineer using this software can then import all precast components and continue the design process manually. Depending on the application area, the communication of the product to the different stakeholders, such as production, engineering and sales, is provided though CAD drawings and lists of rules for dimensioning [21].

The studies described above demonstrate the potential the approach of using KBE in construction has. However, various factors seem to hinder the transformation towards a higher degree of design automation. The first aspect refers to the limited integration and reuse of the product and process knowledge within the CAD system. While in the approaches done by Gross and Sandberg no dynamic integration with the CAD models is proposed, Jensen's study suggests a dynamic integration to only basic parameters of the CAD model, such as the length and width. The suggested consideration of only few main parameters leads to another obvious limitation of the studies. To continue the design process, the obtained product parameters need to be transferred to other CAD systems, where the design detailing of the building components and the corresponding production specifications is performed manually. And finally, even though well defined product information is seen as a key aspect in increasing the productivity in construction [23], none of the studies proposes a suitable technique for making visual the product and process knowledge. Without a clear definition of the product geometry the implementation of variant design automation is done in an unstructured way and thus becomes rather challenging [22].

Geometric modeling for knowledge-based engineering

As described previously, in order to achieve significant efficiency improvements, more comprehensive configuration solutions that contain detailed design information and which define the parametric boundaries of the product variants need to be developed. Since a higher level of design detail increases the complexity of the product geometry, suitable techniques have to be used to communicate the spatial structure and the corresponding geometric rules of the elements under study. Such a detailed product documentation is in particular needed, when rules, constrains and dependencies have to be defined to be incorporated in the configuration system [22]. The literature dealing with capturing, storing and representing geometrical design knowledge suggests different modeling techniques for describing a product model. Research done within the CAD domain typically tries to use models that are close to the environment of a CAD system. The described modeling methods are therefore mainly based on sketches and on 2D drawings which use predefined notation for symbols, lines, arrows and dots. Together with simple if-then-else expressions, the drawings are used to express the geometrical constrains and the object behavior of the parametric models [23]. The main purpose of the so called Building Object Behavior (BOB) description is to provide constructability guidance to architects and to reduce the communication cycles with the structural engineers [24]. Therefore, incorporating knowledge of the geometrical constrains directly in a drawing helps to make visual the spatial design intent to architects and technical drawers in an intuitive way. But at the same time it also hampers describing the parametric relations needed for defining the configuration constrains in a formal mathematical way.

A more accepted method for representing geometry-oriented product models, that are to be incorporated in the knowledge base, is the use of class diagrams and generic product trees or Product Variant Masters (PVM) [1, 16, 19, 22, 24, 27-32]. Such a formalized description not only better provides an overview of the product variants and the dependencies of the parameters, but also serves as the basis for the subsequent mathematical formulation of geometric constrains within the API. The examples found in the literature are generally based on established modeling standards for products and processes, such as the Unified Modeling Language (UML) and the Integrated Definition (IDEFx) methods. Despite the formalized structure, the used product models reveal some restrictions in providing sufficient information on the design intent and the topology of the product that is to be developed in the CAD system. Even if a defined product model captures all geometric dependencies of an object, it still does not provide any information on how to construct it in the CAD system, what the determining parameters are and accordingly how to define parametric constrains in a structured way. In order achieve a wider acceptance in the construction industry for using KBE and automating the (detailed) design process, a well defined framework and easy to use tools are needed.

When summarizing the results found in literature dealing with applying KBE and geometric modeling in construction, the following hypotheses on how to achieve higher level of design automation can be proposed:

1. The design knowledge of a product should be dynamically integrated within the CAD system
2. Suitable modeling techniques have to be used for making visual the design intent and the topology of the product
3. The use of KBE should aim to cover a wide range of the design process
4. The design knowledge to be incorporated should obtain a sufficient level of design detail

The following sections deal with the question of how redesign the current way of using KBE within the building industry, while keeping the newly developed hypothesis in mind.

The precast industry example

Introducing a procedure for the development of configuration systems

The use of knowledge-based systems for industrial applications has excessively been discussed in literature [25]. A growing number of cases, where in particular expert systems have been applied successfully, has helped to implement best practices and common concepts. Hvam et al. (2008) present a comprehensive procedure for the development, implementation and maintenance of configuration systems, which are a typical example of expert systems. With this regard, a seven step approach is suggested as a guiding framework for organizations that are dealing with ways on how to implement mass customization, reorganize their way of working and make use of supportive IT tools to streamline their business processes [26]. The industry cases described in this context are typically operating within the electrical, automobile and machine industry, like APC, Dell, Scania, Danfoss and others. As in the mentioned examples product configuration has predominantly been used for making calculations and defining optimal combinations of parts and features, in the building industry, a higher focus has to be set on designing and visualizing the products and its components, i.e. buildings and walls, windows etc., respectively. Therefore, in the following paragraph the well established framework for using knowledge based systems have been adopted to the context of the precast construction business

Applying the framework to the precast industry

The presented industry case produces in average around 7000 precast elements per year, where for each of the elements detailed design drawings for production have to be made. According to the company, it would usually take up to three hours for the drawers to make these drawings. In case of a partial or full automation of this part of the design process, the manufacturer could free up a high amount of the resources spent on the repetitive design tasks and reallocate them towards the foregoing creative work. Both, the literature and our own investigations therefore show that the highest potential for implementing KBE is for the detailed design, where the design decisions are done on a routine basis and configuration systems can easier be implemented, as the integration to only one CAD system needs to be realized. The resulting system architecture of the expert system, the CAD and the PDM system, and the knowledge base is displayed in Figure 1 below.

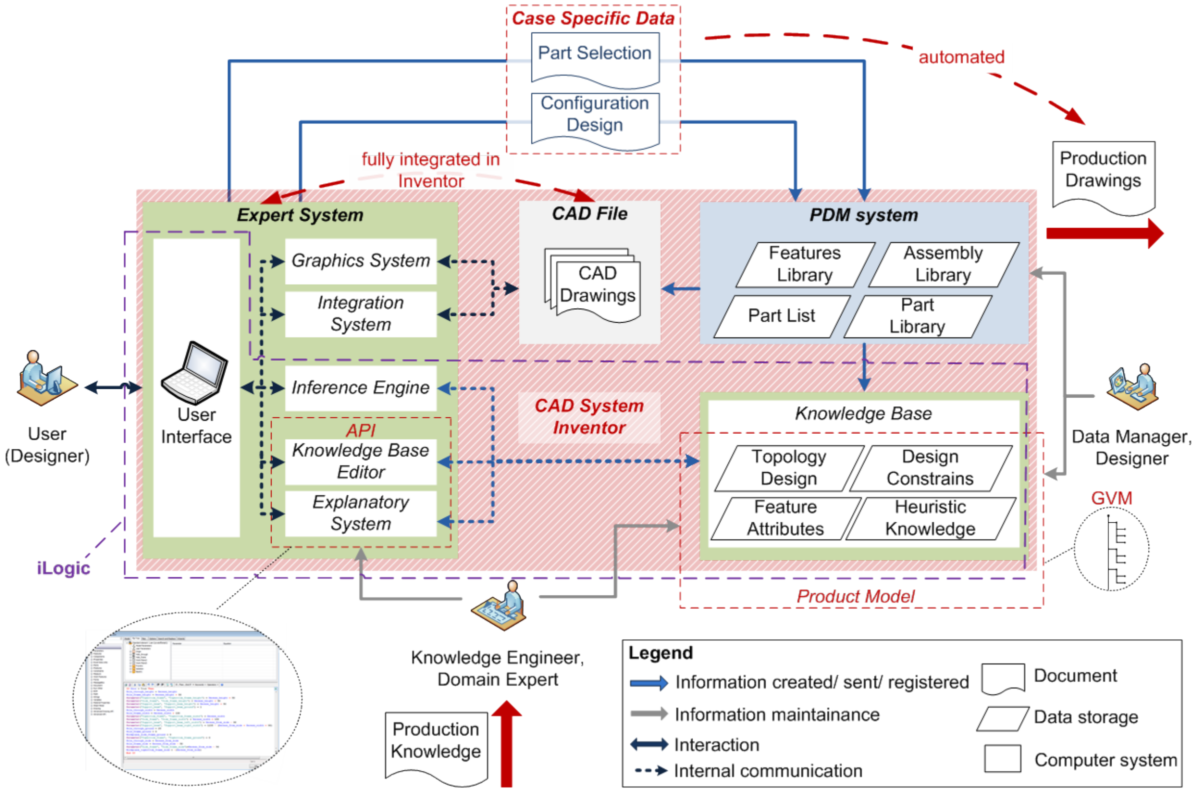

Figure 1 Integrated system architecture for automated precast design

Depending on the type of CAD system, different abilities of integrating it to the expert system exist [22]. The displayed system architecture used in this case suggests a configuration system with a dynamic visual interaction to the CAD system. The graph corresponds to the specific CAD system that is used by the studied precast manufacturer. It outlines how in case the commercial CAD program Inventor 2012 together with the built-in configuration system iLogic [29] is used, the CAD system and the expert system can be realized in a fully integrated way. In case another commercial CAD program and configuration system are chosen, such as SolidWorks and Tacton Works Engineer, the integration between those two systems would be realized slightly different, while the rest of the system architecture would remain the same.

Compared to manually performed design processes, by using the build-in configuration system the work of the designer, i.e. user of the CAD system, could be changed drastically. The designer would be able to use suitable templates, containing information from the knowledge base of a precast element, directly within the already familiar environment of the CAD system. The built-in configuration system iLogic would guide the user through the control parameters via a user interface. Based on his input, the design of the element could be done in an automated way, while a production drawing would be produced of the configured element design and selected parts. This information would then be stored in the Product Data Management (PDM) system and could then be sent further to production. A data manager and a knowledge engineer would maintain the system, as they interpret the design information from PDM system and the restrictions and preferences derived from the production. The created parametric constrains would directly be implemented in the system, by using iLogic's API.

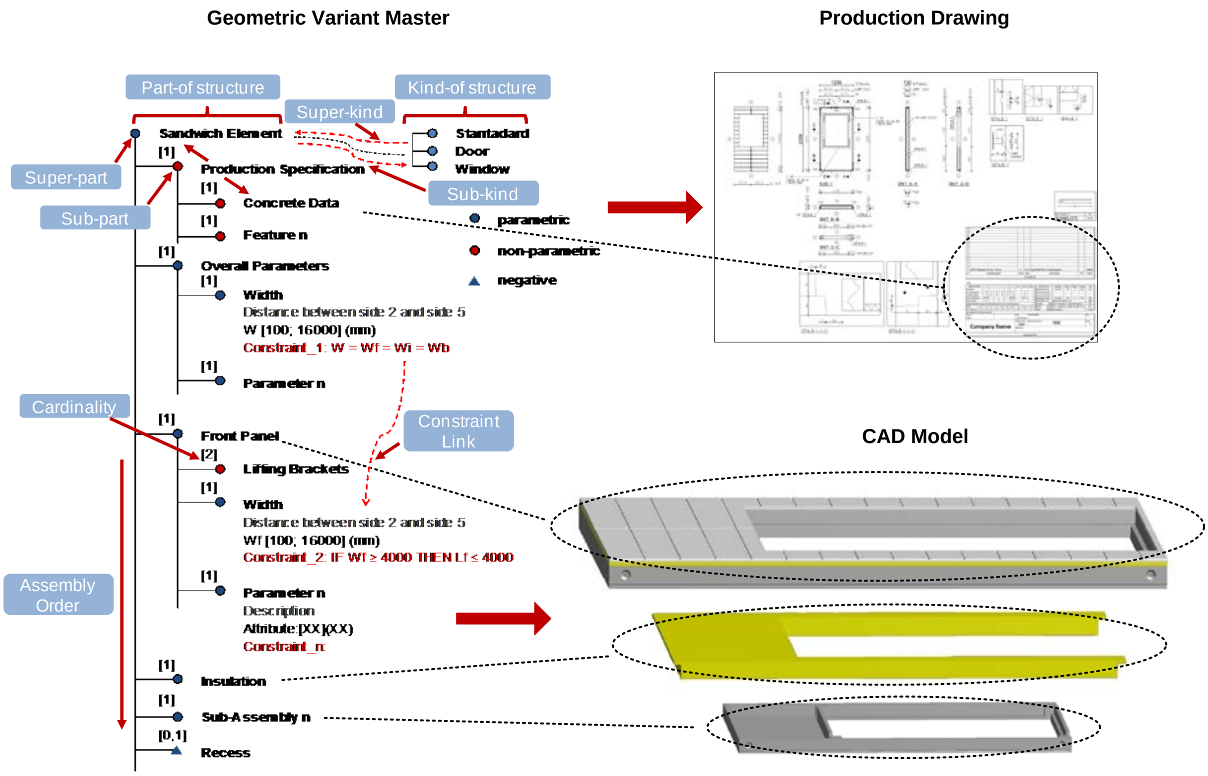

Figure 2 Geometric Variant Master as a Template for the Knowledge Base

In order to record the design information for the knowledge base appropriately, a new way of product documentation is suggested. A so called Geometric Variant Master (GVM) should be used to capture the relevant geometrical knowledge of the product, as well as to communicate the product architecture and the design intent across the organization. The method is based on the well-established product modeling techniques of the PVM [1], where additional notations were defined to better obtain the topology of a CAD model, as well as to include specifications for production. As illustrated in Figure 2, the first part of the GVM specifies the information, which is needed for producing a concrete element, such as the concrete recipe, the surface quality or the transportation weight. Further down, the assembly order and the topology of the product model is described. The developed notation helps highlighting the occurring parameters that need to be incorporated in the configuration system, including the design restrictions, the parametric constrains and the "negative" parts that are being used to suppress material.

Conclusion

Even though the use of KBE to support and automate the design process has widely been discussed in academia, analyses show that the current applications of KBE in construction reveal some major limitations, in terms of degree of design automation and design detailing. To overcome these limitations, a framework for using configuration systems, as a widespread example for knowledge bases systems, has been introduced and adopted to the construction business. The introduced methods and techniques have exemplary been applied on an industry case, an ETO manufacturer of precast concrete elements. The achieved results demonstrate the promising potential of using KBE for geometry oriented models, as the majority of the routine design tasks could be automated and engineering and design recourses could instead be reallocated to the more creative phase of the design activities. However, in order to cover a wider range of the design process, besides focusing on routine design tasks, design automation could be supported by a higher degree of modularization of the building components and their interfaces and by better working data exchange standards.

References

[1] Mortensen, N. H., Pedersen, R., Kvist, M.; Hvam, L., "Modelling and visualising modular product architectures for mass customization", *International Journal of Mass Customisation*, Vol.3, no. 3-4, pp 216-239, 2008

[2] Tizani, W., Mawdesley, M. J., "Advances and challenges in computing in civil and building engineering", *Advanced Engineering Informatics*, Vol.25, no. 4, pp 569-572, 2011

[3] Zhang, J., Eastham, D. L., and Bernold, E. B., "Waste-based management in residential construction.", *Journal of Construction Engineering and Management*, Vol.131, no. 4, pp 423-430, 2005

[4] Hartman, T., van Meerveld, H., Vossebeld, N., Adriaanse, A., "Aligning building information model tools and construction management methods", *Automation in Construction*, Vol.22, pp 605-612, 2012

[5] Yu, H., Tweed, T., Al-Hussein, M., Nasseri, R., "Development of Lean Model for House Construction Using Value Stream Mapping", *Journal of Construction Engineering and Management*, Vol.135, no. 8, pp 782-790, 2009

[6] Peterson, F., Hartmann, T., Fruchter, R., Fischer, M., "Teaching construction project management with BIM support: Experience and lessons learned", *Automation in Construction*, Vol.20, pp 115-125, 2011

[7] Howard, B., Björk, B., "Building information modelling – Experts' views on standardisation and industry deployment", *Advanced Engineering Informatics*, Vol. 22, pp 271-280, 2008

[8] Salman, A., "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry", Leadership and Management in Engineering, Vol. 11, no. 3, pp 241-252, 2011

[9] Mora, R., Bédard, C., Rivard, H., "A geometric modelling framework for conceptual structural design from early digital architectural models", *Advanced Engineering Informatics*, Vol. 22, no. 2, pp 254-270, 2008

[10] Archer, B., „The structure of the design process“, *Emerging methods in environmental design and planning*, MIT Press, pp 285-307, 1968
[11] Eastman, C. M., „*Building Product Models: Computer Environments Supporting Design and Construction*“, CRC Press, 1999
[12] AI-Masalha, S., Wakefield, R., „Design for Construction Utilizing A Virtual Environment“, *Computing in Civil and Building Engineering*, Proceedings of the Eighth International Conference on Computing in Civil and Building Engineering, pp 23-30, 2000
[13] Sacks, R., Eastman, C. M., Lee, G., "Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry", *Journal of Construction Engineering and Management*, Vol. 130, no 2, 2004
[14] Myung, S., Han, S., "Knowledge-based parametric design of mechanical products based on configuration design method", *Expert Systems with Applications*, Vol. 21, no 2, pp. 99-107, 2001
[15] Verhagen, W. J. C., Bermell-Garcia, P., van Dijk, R. E. C., Curran, R., "A critical review of Knowledge-Based Engineering: An identification of research challenges", *Advanced Engineering Informatics*, Vol. 26, no. 1, pp. 5-15, 2012
[16] Stokes, M., "*Managing Engineering Knowledge - MOKA: Methodology for Knowledge Based Engineering*", ASME Press, 2001
[17] Sandberg, M., Tyapin, I., Kokkolaras, M., Isaksson, O.,"A knowledge-based master modelling approach to system analysis and design", *Proceedings of the 18th International Conference on Engineering Design (ICED11)*, Vol. 4, pp. 347-356, 2011
[18] Chapman, C. B., Pinfold, M., "The application of knowledge based engineering approach to the rapid design and analysis of an automotive structure", *Journal of Advances in Engineering Software*, Vol. 32, no. 12, pp 903-912, 2001
[19] Gross, M. D., "Why can't CAD be more like Lego? CKB, a program for building construction kits", *Automation in construction*, Vol. 5, no. 4, pp 285-300, 1996
[20] Sandberg, M.; Larsson, T.; Johnsson, H., "Knowledge-based engineering in construction: The prefabricated timber housing case", *Electronic Journal of Information Technology in Construction*, Vol. 13, pp 408-420, 2008
[21] Jensen, P., Olofsson, T., Johnsson, H., "Configuration through the parameterization of building components", *Automation in Construction*, Vol.23, pp 1-8, 2012
[22] Hvam, L., Ladeby, K., "An approach for the development of visual configuration systems", *Computers & Industrial Engineering*, Vol. 53, pp 401-419, 2007
[23] Lee, G., Sacks, R., Eastman, C. M., "Specifying parametric building object behavior (BOB) for a building information modeling system", *Automation in Construction*, Vol. 15, no 6, pp 758-776, 2006
[24] Cavieres, A., Gentry, R., Al-Haddad, T., "Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis", *Automation in Construction*, Vol. 20, no 6, pp 716-728, 2011
[25] Hopgood, A., *Intelligent Systems for Engineers and Scientists*, CRC Press, 2012
[26] Hvam, L., Mortensen,N. H., Riis, J., *Product Customization*, Springer, 2008
[27] Dassault Systèmes SolidWorks Corp., http://www.solidworks.com
[28] Tacton Systems AB, http://www.tacton.com/
[29] Autodesk, Inc., http://usa.autodesk.com/