Design automation in construction – an overview

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Abstract
As the construction industry continues its digital journey the applications within design automation is growing, making development processes less time-demanding and more organized. Design automation applications can show design impact on e.g. cost, equipment availability, staff capabilities and buildability. It can also facilitate reuse of successful solutions instead of reinventing the wheel for every project. Thanks to automation it becomes easier to generate several solutions and trying different what-if-conditions. The field has many different approaches but an overview for construction where the connections between the different approaches are indicated is needed. The purpose of this paper is to describe our view of how the design automation fields of building information modelling, master models, knowledge-based engineering, configuration, modularization, platforms and simulation are connected and to provide input to the design automation discussion in construction. Each of these areas are introduced and then they are analyzed in relation to each other and presented as an overview. These results will serve as a base for future studies.

Keywords: Configuration, modularization, knowledge-based engineering, product and process platforms, discrete-event simulation, master models

1 Introduction
The construction industry is being more and more digitalized as building information modelling (BIM) (Eastman et al. 2011), internet technologies and other information technologies are being adopted. More and more organizations start to see the benefits of IT (Samuelsson 2012) which opens up for possibilities to evaluate the life cycle impact of early design decisions. This can be done using rules that evaluate the design or by using simulation such as discrete event simulation (DES) (Larsson et al. 2016). Taking the use of virtual product models a step further is possible, by using one master model where changes automatically propagate to connected models (Hoffman and Joan-Arinyo 1998). Trying what-if scenarios virtually is more cost efficient than in real life and make it possible to have several design candidates to choose from than only a few. Configuration (Jensen et al. 2015) and knowledge-based engineering (KBE) (Stokes 2001) let the computer do time demanding routine work and frees up time for more creative development work. The computer never gets bored, does the work quicker than us and does everything in the same way every time which implies a quality control since the process of designing can be standardized to a certain degree using approaches such as platforms (Simpson 2004) and modularization (Holmqvist et at. 2003). Each of the mentioned concepts are related to design automation and have been described and studied (although to different degree) within construction but there is a need for an overview that connect them to

each other as a first step to get a more holistic picture of design automation in construction. The purpose of this paper is to describe our view of how the design automation fields of building information modelling, master models, knowledge-based engineering, configuration, modularization, platforms and simulation are connected and to provide input to the design automation discussion in construction.

2 Design automation approaches

Automating chains of engineering activities is not new; this has been used by engineers since the early developments of computer-aided modelling and simulation (Dixon 1995). The term of design automation stems from automated design of electronical circuits and chips (Macmillen et al 2000).

2.1 Building information modelling

Today's CAD systems can be applied for much more than 3D modelling and the generation of drawings. Building information modelling (BIM) is described as a modeling technology and associated set of processes to produce, communicate, and analyze building models (Eastman et al. 2011). BIM can reduce information losses since the models and information ideally should follow the whole building process and only be created once. A standardized BIM platform for information contains description of: terminology and related terms, processes and shared information and how generated data are structured and stored. With BIM objects the computer also understand that a piece of geometry for example is a window, and treat it thereafter and not just like arbitrary geometry. From this the computer also knows how many windows, what type, on which floor, inserted into what type of wall, having which fire rating etc. The neutral format IFC (Industry Foundation Classes) goes hand in hand with BIM since it enables the linking of different software systems to let the information travel through the process.

Although offering many opportunities, the potential of BIM systems is often not fully utilized and application is still quite limited to generating and exchanging traditional documents, such as 2D drawings, in a digital format. The traditional way of exchanging information in the construction industry is document centered. Examples are 2D drawings, written specifications, manually calculated bills of quantities, etc. Although computers offer substantial help today in the production of these documents, the data exchange and management procedures are still focused on documents, which have an important legal status. The use of tools that can handle 3D and objects has more than doubled by architects and increased from 0 % to over 50 % by technical consultants from the year 2000 to 2011, (Samuelson 2012).

2.2 Master models

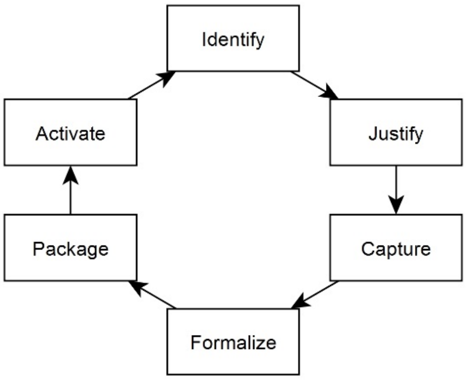
Master model (MM) approaches aim at creating a geometry representation that can be used for CAD, computer-aided manufacturing, and computer-aided engineering and other analyses. Every change in the geometry representation is automatically or semi automatically propagated to all domain-specific models. One of the first MM approaches was reported by Newell and Evans (1976); a number of researchers have elaborated the MM approach since, e.g.: Hoffman and Joan-Arinyo (1998) suggested an MM architecture centered around a server and a repository to which different clients can connect to. These clients can be CAD systems, geometrical dimensioning and tolerancing agents, manufacturing process planners, or other downstream clients. Each client receives their view of the design. Each design change made by one of the clients causes changes to other clients' views according to a change protocol and permissions. The architecture is semi-automated and user interaction needed. Today's CAD-system often support working linking of different modelling activities that are available within the CAD-system, e.g. geometric modelling and finite element modelling.

2.3 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

Figure 1 The MOKA phases, adapted from Stokes (2001).

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 computer aided 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’ (2001). Examples of KBE applications from the latest decades are e.g., (Sandberg et al. 2005; La Rocca 2012). KBE applications usually have geometry, configuration and engineering knowledge, (Lovett et al. 2000). Although KBE is not artificial intelligence (Hopgood 2001) per se KBE has been seen as a merger of AI and CAD which allow for implementation of analytical procedures and linking CAD-systems to external simulation models (La Rocca 2012).



MOKA is the most comprehensive methodology for KBE application development although other less detailed methodologies exist, e.g. (Lovett et al. 2000). The focus of MOKA is to describe how to capture engineering knowledge and implement it into a KBE application (Stokes 2001). 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. 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. CAPTURE and FORMALIZE are the most elaborate phases which are supported by template documents and a Unified Modeling Language-based approach.

2.4 Configuration

Product configuration can be described as a simplified design process of a product. In principle most of the steps within the conventional design process are executed, but the work is less comprehensive (Hvam et al 2006). Configuration is based on a generic product platform that capture a customer segment needs and values. Throughout the configuration process the specific customer requirements are specified, on the basis of a given framework (platform), and detailed product can be generated. Hvam et al. (2008:33) defined product configuration as “putting together a product from well-defined building blocks (modules) according to a set of predefined rules and constraints”. This mean that most of the design work of the building blocks have been accomplished in advance when developing the generic product platform. The development work also identified the rules and constraint considering how the buildings blocks can be combined and adapted to create a wide range of different products. Therefore, the product configuration process can also be denoted as the specification process (Jensen 2014). The modular product platform together with the controlling rules enables that a specific product can be specified within the platform limitations. Hence, the configuration work is about analyzing whether the required input data is complete. If not, the missing data must be complemented or developed before the configurator can be used (Hvam et al. 2004).

However, in most cases, it is too much information to manage manually why product configurators are needed. Configurators are software systems that supports the configuration process. Blecker and Abdelkafi (2006) define configurators as “software with logic capabilities to create, maintain, and use electronic product models that allow definition of all possible product options and variation combinations, with a minimum of data entries”. Hence, product configurators manage all necessary information of the product architecture, e.g. information about the modules, their constraints, variation rules and possible combinations, in order to specify a tailored product (Helo 2006; Jensen 2014). The configurator structures the information flow of the design work and reduces the iterations between the process steps to a minimum. This streamlines the specification process and creates performance improvements (Gerth et al. 2016).

2.5 Modules and modularization

A flexible or configurable product platform must consist of modules or product parts. 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 components (Jensen 2014). In a modular product platform, the architecture of the components is arranged in such a way that cluster of components forms modules with one-to-one relation between a function or requirement to the physical cluster of components (Ulrich 1995). The development work of such a product platform is called modularization. Erixon (1998:58) define modularization as “decomposition of a product into building blocks [modules] with specified interfaces, driven by company specific reasons”. Hence, modularization is the development process of modular product platform. Ericsson and Erixon (1999) presented a methodology called Modular Function Deployment (MFD) for development of modular product platform consisting of five steps: 1) Clarify, customer requirements, 2) Select technical solutions, 3) Generate concepts, 4) Evaluate concepts, and 5) Improve each module. Holmqvist and Persson (2003), divide the modularization process into three steps; (1) decomposition of the product into functional or structural parts; (2) integration of modules and parts into a generic product platform and (3) evaluation of the resulting product’s modular characteristics. Smiding et al. (2016) describes how modular platforms within construction can be developed: (1) analyzing many different and realized projects blueprints to capture and evaluate market needs and requirements. Analyze and determine the variation in the requirements and technical solutions. (2) Decompose the generic product architecture into modules and parts, i.e. categorize the suggested technical solutions into modules. (3) At conceptual level, analyze whether the suggested technical solutions can satisfy the requirements identified in the previous steps. (4) Develop and determine the flexibility, capabilities and constraints of each module and part. (5) When the functional requirements, product architecture and product flexibility had been defined and controlled, the process of developing the product configurator can be initiated.

2.6 Platforms

According to Meyer and Lehnerd (1997:7) product platforms are “a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched”. A product family is derived from the platform and can be either module-based or scale-based (Simpson 2004).

Some benefits of using platforms for design and production include: a) greater ability to tailor products to the needs of different market, segments or customers, b) reduction of development cost and time, c) reduction of manufacturing cost, d) reduction of production investment, e) reduction of systemic complexity, f) lower risk and g) improved service.

Robertson and Ulrich (1998) presented a platform planning strategy with design methods that balanced client needs with production costs. Studies of the automotive, computer and telecom industries describe the product platform as a collection of assets, which are shared by a set of products sorted into components, processes, knowledge and relationships (Meyer and Lehnerd 1997, Robertson and Ulrich 1998).

By studying product development in product platforms, Meyer and Lehnerd (1997) presented the Power Tower model, showing the elements of market instantiation by product families, product platforms nurturing several product families and the four basic assets serving as building blocks in the platform. A focal point in Robertson and Ulrich's (1998) platform planning is the balance between commonality and distinctiveness.

Commonality refers to repetition of functions, physical components or technical solutions (Jiao et al. 2007) and can be used at different levels of a product as well as in and between products. Commonality is the common base of a platform and the driver for simplicity and cost. Common parts appear in every product model produced within the platform. From a client point of view, the commonality in a platform provides no variety between models. When adding distinctiveness, individual product uniqueness is created.

In a similar way, process platforms represent standard routings, thus facilitating production configuration for diverse product family design solutions to enable manufacturability and cost commitment (Jiao et al. 2007).

2.7 Simulation

Construction Process Simulation has been used for evaluating and redesigning construction projects since the development of CYCLic Operations Network (CYCLONE) (Halpin and Riggs 1992). It provides useful tools to evaluate the performances of construction projects under alternative resource allocation and process planning by modelling the dynamic interactions between resources and processes (Kim and Gibson 2003). Alvanchi et al. (2011) simulated the construction processes of a structural steel bridge to optimize the project duration by comparing potential plans associated with both the on-site construction process and off-site fabrication shops. Jeong et al. (2006) built a supply chain simulation model of manufactured housing to identify bottlenecks and hence improve flows of materials through the chain.

Based on construction process simulation, database driven simulation has been proposed as a more intelligent and automatic modelling approach. In this approach, a simulation model can be parameterized by data provided through a set of sources such as data forms, tables, and spreadsheets. Nasereddin et al. (2007) introduced an approach to automatically develop simulation models of modular housing manufacturing processes. The production system parameters (e.g., activity name, average processing time, and activity precedence) are entered into a Microsoft Excel spreadsheet, which is used to automatically generate a simulation model. A BIM–DES framework has also been proposed by Lu and Olofsson (2014), in which a building information modeling process exports the product and process information to database; the database driven simulation model evaluates the construction performances and provides valuable feedback to the BIM process for decision support. Akhavian and Behzadan (2014), proposed a framework for knowledge-based simulation of construction processes, which extracted knowledge and data-driven simulations were used to update corresponding simulation models. Wang et al. (2014) investigates the mechanisms that collect, store, and transfer information among various software packages, thus uses the BIMs ability with regard to quantity take-off of materials to support construction process simulation.

3 Analysis and discussion

One way to show the connection between the different design automation approaches mentioned here is as shown in Figure 2. We see BIM, KBE, configuration and simulation having direct connection to design automation while platforms, modularization and master models have indirect connection to design automation. In this section similarities and differences between some of the different approaches are discussed as well as the roles of other approaches in construction. It ends with a discussion of design automation methodologies.

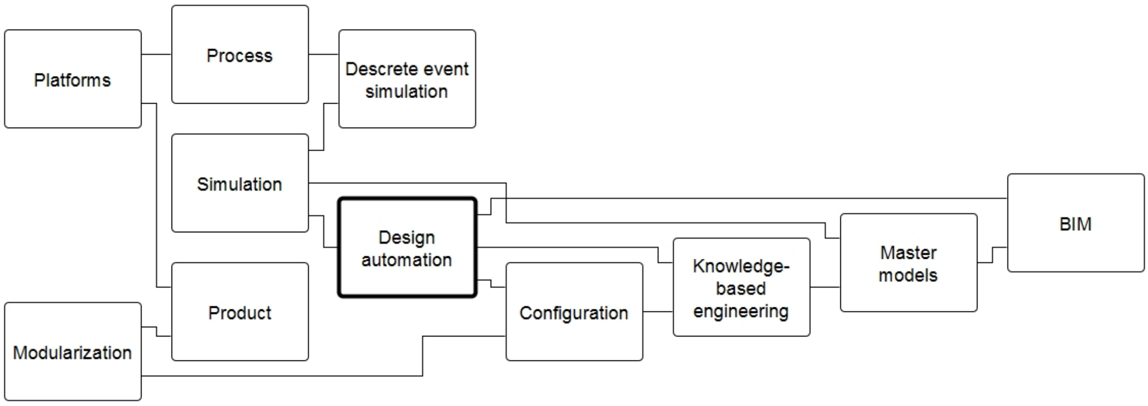


Figure 2 Map of chosen design automation approaches in construction.

3.1 Similarities between BIM and master-models

BIM can be seen as an umbrella term for design automation in construction. One of the foundations of BIM; that information should only be created once and stored in one place has connections to master-models. Having one master model where the information about the definition of the product, i.e. its design, governing logic is stored in one model instead of several models.

Using the neutral format IFC it is possible to link models although some manual work usually is required to get the second model usable. For example, when doing 5D BIM the first model created in a 3D-BIM environment can be linked to another software for cost estimation and scheduling but the default setup requires quite much manual work. To be able to increase the automation of such 5D BIM activities there is a need to repetitiveness in the construction project so cost recipes can be reused, and building objects can be labeled consistently. In Figure 3 a representation of an arbitrary Master model for construction is presented where different domain models are linked. Master models can be built using KBE.

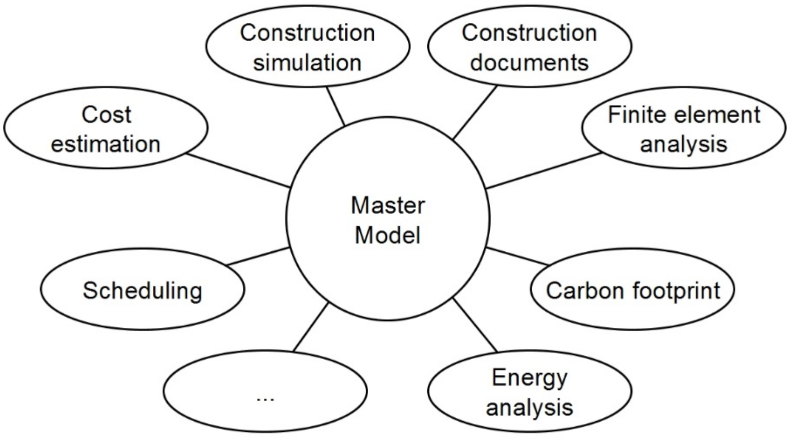


Figure 3 An arbitrary master model for construction.

3.2 Differences between configuration and knowledge-based engineering

According to Lovett et al (2000) configuration is part of KBE as the matching of valid combinations of components. KBE is also more than configuration and offers both the implementation of analytical procedures and linking to external models (La Rocca 2012).

Configuration examples from construction (Jensen et al 2015) are usually for detailed structural design while KBE examples (from the manufacturing industry) also can be for stages prior to detailed design (La Rocca 2012). Developing similar KBE applications which offer configuration and linking to analysis models for earlier construction design activities should be possible.

3.3 The importance of platforms in configuration

Product platforms arguably have the largest importance for configuration compared to process platforms since product platforms define the design space possible for configuration through commonality and variability. Process platforms affect the constructability of the design in terms of efficiency and cost. The configuration activity can be done without a process platform but would probably be more efficient if a process platform is at hand.

The subsystems and components within a platform can be either modular or scalar as Simpson (2004) noted. If being more scalable more effort is needed to define the rules that should handle the morphological and topological transformations, compared to being more modular where more effort is needed to develop each module and their interfaces.

3.4 The importance of simulation for construction

Data-driven simulations are particularly suitable for construction projects where product, process and supply chain configuration data and related knowledge are stored and maintained in a database, and the main purpose of simulation is to evaluate alternative configurations, such as industrialized construction project.

By comparing performances of alternative configuration, different product design, process planning and supply chain can be explored in order to identify the optimized configuration according to the specific requirements of projects. Data-driven simulation might be systematically integrated with BIM, knowledge based engineering, product and process platforms.

3.5 Balancing structure and flexibility of design automation methods

Even though the MOKA methodology (Stokes 2001) is the most comprehensive methodology within KBE there are few examples presented where MOKA has been adopted. The reason for this might be that MOKA is too structured and does not permit enough flexibility or that some companies, at least within the aerospace and automotive industries, already have their own best practice for design automation. But within construction the design automation methodologies are probably not as common although there may be exceptions within the advanced structural engineering field of construction which depend more on calculations and computer simulation.

Examples of successful bottom up developments of methodologies or processes within construction have been presented by e.g. (Jensen et al 2015; Smiding et al 2016) where challenges are noted as for example maintaining the configurators during their life-time (Jensen et al 2015). The possibility of having more flexible or less defined methodologies is dependent on the staff being more experienced in the design automation field. Having people with both construction background, e.g. civil engineering, architectural engineering, and computer science is a big advantage.

3.6 When is it valuable to automate and not?

Activities being routine, repetitive and time demanding are usually more suitable for automation since they usually handle explicit information and knowledge and therefore are easier to formalize compare to more tacit information and knowledge. Computational intelligence, (Hopgood, 2001), more numerical or soft computing approaches such as neural networks, evolutionary algorithms, fuzzy logic, is one way to handle more tacit, intangible information. According to Stokes (2001) knowledge availability, organizational readiness (IT maturity), hardware and software availability is important to consider before choosing to automate. If the experts are unwilling to share their knowledge, then it is hard to do knowledge acquisition. There is also a balance of knowing how much to automate, what variance to provide in the design automation tool. This can be evaluated by analyzing previous orders to find similarities and defining the product variance. The success of such decision are dependent on future orders.

4 Conclusion

In the map presented in Figure 2 we have deliberately chosen to include a specific number of fields which we argue have a connection to design automation. The map could be developed and expanded with other approaches as well e.g. AI, genetic algorithms, fuzzy logic (Hopgods 2001). The map show our view of design automation and work as input to the discussion of what design automation within construction is, to be able to form a future more comprehensive overall picture that helps researchers and practitioners within construction to explore new digitalization possibilities.

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