

DIGITAL SIMULATION IN LEAN PROJECT DEVELOPMENT

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ABSTRACT

Skilled use of information technology such as Building Information Modeling (BIM) (Eastman et al., 2008) managed by Lean Construction principles (Koskela 1992; Koskela 2000) can have a significant positive impacts on the construction industry (e.g. Khanzode et al, 2005, 2008).

In an ongoing research program “Individual parametric Façade Modules with integrated de-central building services technology” we analyzed the digital information flow possibilities of today's BIM application on residential housing projects with timber facades and derived the following questions: How can we integrate engineering, manufacturing and construction knowledge in the early design and planning phases of the project development to increase the value for the customer and reduce variability for the construction process? And how can we use the simulation capabilities of BIM methods and technology to improve overall building performance?

We identified the bidding process as one of the areas with the highest potential to gain additional value for the customer and to improve upstream flow variability for fabrication and construction. This is done through improving the value stream by introducing and integrating knowledge of the downstream trades earlier than currently done in practice. We use an adapted “Functional Design and Bidding” methodology to achieve this. In order to change the information exchange from the current predominant drawing centred approach to a model-based paradigm, we developed a new module called Process oriented Product Model Interface (PPMI), which serves as an interface for integrating people, processes and information systems (Dave et al. 2008).

Using BIM enhanced model checking and simulation methods enables the purchaser to compare offers and their construction alternatives in terms of architectural design quality, building performances e.g. energy consumption, usability, comfort, flexibility of use, feasibility, impact on schedule, construction and life cycle costs.

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HYPOTHESIS

Current AEC design, planning and construction practices and contracts in Switzerland are based on 2D drawings. The process phases are predominantly sequential and show significant systematic information losses. The hypothesis is that by restructuring the bidding process we can improve the value stream and hence the value for the customer. This enables the planner to perform predictive performance simulations in early project phases on digital models that were not feasible before to improve the value for the customer. Restructuring in this case means making trade-specific knowledge available earlier, and more precise in the process. The restructuring is supported by BIM technology and the development of the PPMI which allow inter-company/disciplinary information exchange based on pre-specified standardized processes.

RESEARCH AND DEVELOPMENT SET-UP

According to (Sacks et al, 2010) *BIM* has a transformative power not only on the design, but on the construction process as a whole and *Lean* as a transformative approach to management can interact to transcend current constraints for performance improvement. We combine the two initiatives for our research.

For the lean management we use the “Functional Design and Bidding” approach described below and enable information exchange by using digital 3D product models and BIM tools. To integrate people, processes and information systems, we develop the concept and a prototype of the Process oriented Product Model Interface. We test and verify the Functional Design and Bidding Procedure and the related BIM technologies in the ongoing R&D project on timber facades and set up a full scale practice case using off-the-shelf available software tools. With the action research approach, we actively enable the BIM technology deployment and manage the change process, while at the same we observe the processes and study how model checking and simulation methods were used to enhance building performances and make downstream AEC processes more stable, effective and reliable.

FUNCTIONAL DESIGN AND BIDDING METHODOLOGY

The main idea of “Functional Design and Bidding” is to coordinate in a transparent way the competencies and responsibilities of all stakeholders and decision makers involved in the design, planning and construction process. Information flow and information exchange are organized according to collaboration rules and standardized procedures.

Design and manufacturing processes are organized in three phases with different stages. In the first phase, the planners and stakeholders involved concentrate on their core competencies. Within the frame of their responsibilities they determine the design on the lowest possible level by defining only core elements of their own discipline and boundary conditions and requirements for the next (sub-) planner. So

the design task is basically reduced to set up a frame and to facilitate the design work by the best qualified specialist involved in the planning process.

For the functional design of façade elements, architects will probably define initially the geometry, surface and appearance of the whole façade and of individual façade elements (see Fig 1, left). In most cases, the geometry will allow spatial tolerances for subsequent planning e.g. the positioning or size of windows or air boxes. In the first stage of a functional design model e.g. façade elements are therefore defined by architects as solids providing a shell that will later in the design process contain the final construction model. At this stage, architects concentrate on design aspects, interface specifications and performance requirements. This leads to the Functional Architectural Ordering Model (FAOM). In the next stage of the process, subsequent planners, e.g. structural engineers, production engineers and construction professionals will take the FAOM as input with the architect's design and specification as boundary conditions for their own design and engineering work. With every step the model becomes more detailed and the whole design process leads to a consistent 3D functional product model.

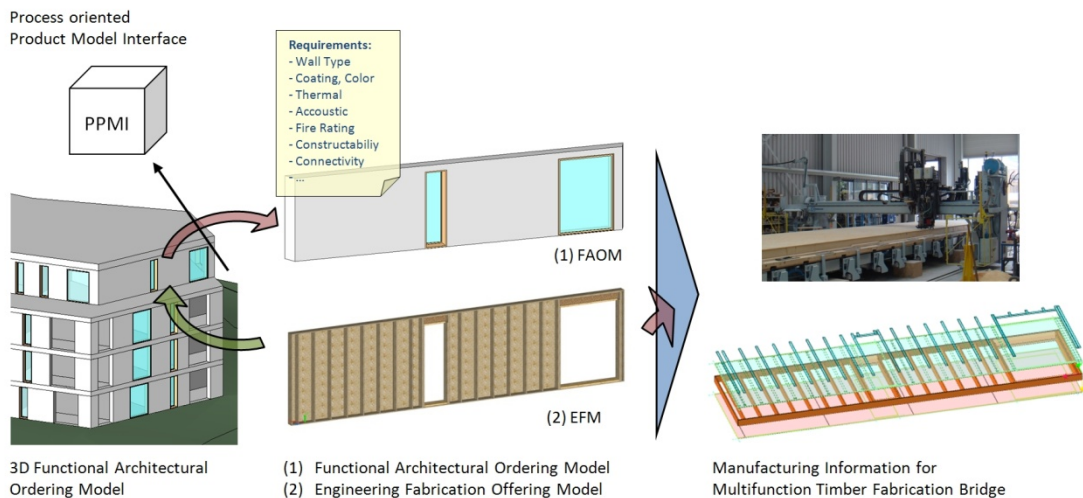


Figure 1: Practice case for the integration of engineering, fabrication and construction knowledge in the early project development phases for the façades of a residential building using Functional Design and Bidding Methodology and digital 3D product models.

In the next phase the manufacturer e.g. the producer of the façade elements takes this model - still containing minimal necessary definitions - as input for production planning. This will result in a detailed and complete construction proposal, optimized for the requirements of the manufacturer's specific internal processes and machinery. During the production planning process the model will be split into a public part showing the construction details, materialization and performance specifications necessary for the client to evaluate the proposal (Engineering Fabrication Offering Model EFM) and an interior, proprietary part containing the manufacturing data accessible only by the manufacturer (see Fig 1, right).

In the third and final phase the completed model goes back to the planners and finally to the planner responsible for the complete design process. In every stage on its way back, the model's compliance with requirements and boundary conditions

defined earlier will be checked and evaluated. Once a model is finally approved, freeze of design will be declared and later on manufacturing based on the frozen model shall be approved.

INFORMATION AND KNOWLEDGE EXCHANGE USING 3D PRODUCT MODELS IN ORDERING AND OFFERING WORKFLOWS

Today BIM tools for architects, planners, or developers only partially provide the functionality to create complete Functional Architectural Ordering Models (FAOMs). Corresponding BIM Tools on the engineering, fabrication, construction side likewise cannot completely respond with 3D Engineering Fabrication Models (EFMs). In addition the various BIM tools involved lack the interoperability to communicate seamlessly. Primarily it is necessary to integrate the people, processes and information systems involved and then to enhance the functionality of the tools. To address the integration, we developed a concept and a prototype for a Process oriented Product Model Interface (PPMI) for façade elements. We use the product model exchange standard Industry Foundation Classes (IFCs) and developed necessary extensions like requirements, performance descriptions and information which link order models with offering models and their version history. These extensions however are proprietary and they may be later standardized. To enable 3D product model information and knowledge exchange, it is not only necessary to develop a mechanism which allows individual modeling tools to import and understand these extensions – even if they are proprietary -, but to handle the processes and the involved stakeholders and decision makers as well. For our prototype development, we used Information Delivery Manuals (IDM) (Wix, 2007) and related concepts and technologies to develop generalized computer interpretable schemes which should later enable individual BIM tools to connect and communicate with the PPMI once the interpreter has been integrated. We develop a prototype of such an interpreter for the Gehry Technologies Digital Project. Our actual prototypes PPMI and interpreter can establish a typical workflow as shown in Figure 2. The technological aspects are described in (Breit et al, 2010).

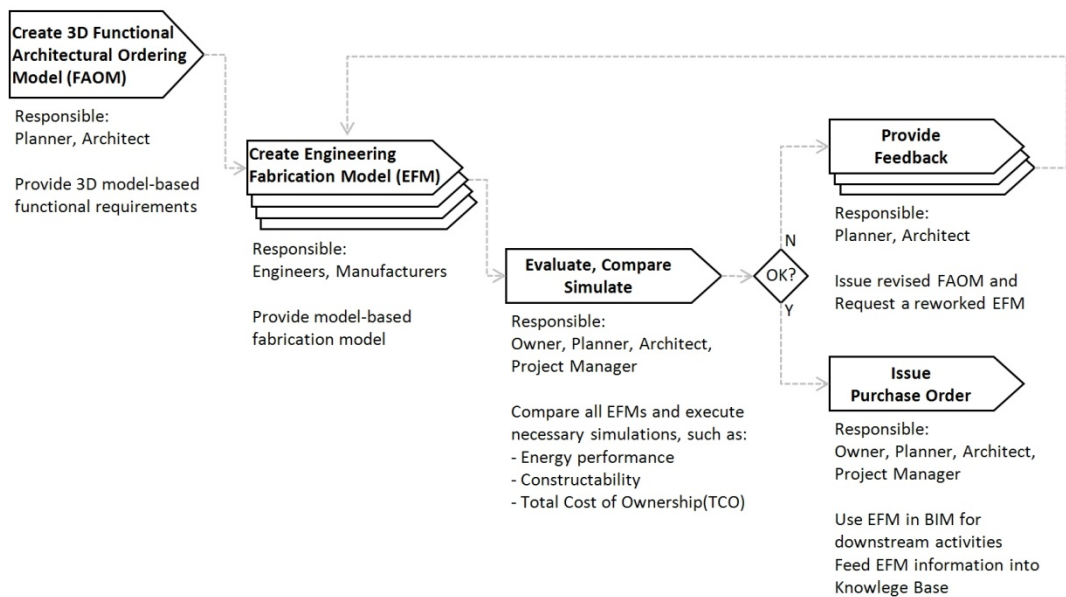


Figure 2: Integration of people, processes and information systems with the Process oriented Product Model Interface (PPMI) – model based ordering and offering workflow and BIM enabled analysis, checking and simulation

For every action in Figure 2, the PPMI handles input and output models, responsible actors, resources, and the possible exceptions for the workflows. One of the major obstacles to a wider deployment of IFCs in practice is that information is only partially transferred between two applications and differently mapped to the applications BIM objects. Our approach tries to solve this problem using generalized computer interpretable schemes which define via IDMs what parts of a 3D product model and related information are needed and expected and for the extended information e.g. classes, attributes etc. how they are defined and where the corresponding information is stored. All model exchange is validated and the PPMI delegates the duty to produce valid models in every case to the responsible stakeholder that creates the model. The interpreter that the software provider will have to develop will be able to deal with general functional design element representations, which will be the basis for a wide-spread deployment of the proposed methodology in AEC.

CURRENT STATE

For the proof of concept the PPMI prototype was developed and tested for the exchange and validation of FAOMs and EFMs for timber façade construction successfully. The current work focuses on the development of interpreters and the enhancement of functionality:

for the FAOM in Gehry Technologies Digital Project

for the EFM in cadworks and Gehry Technologies Digital Project

for the redlining, checking, comparing of FAOMs and EFMs (especially for managers) in Solibri Model Checker

FULL SCALE PRACTICE CASE:

Within our joint R&D project “Individual parametric façade modules with integrated de-central building services technology”, we set up a study, where the process flow shown in Figure 2 has been applied in today’s AEC business in Switzerland using commercial off-the-shelf BIM modeling software to study the effects of the Functional Design and Bidding approach.

The group consisted of the following participants: a general contractor (GC), who leads the bidding process; an architecture office, who provided the initial project design in form of 2D drawings; a timber construction company with a prefabrication shop, who has been using sophisticated timber design and detailing software for many years and has well established digital supported fabrication and construction processes; and the authors, providing the support for the modelling of the FAOM and the BIM enabled analyses, checking, comparing and simulations of the EFM and carrying out the study.

The GC started a bidding process for a project which includes 3 pentagonal shaped 5 storeys residential buildings with prefabricated timber façades and distributed HVAC and MEP systems (see Figure 1 left, 3, 4). The buildings are connected to a shared underground parking facility. The FAOM was created with *Autodesk Revit*

Architecture 2010 (RAC), based on the project development plans (2D) of the architect. The timber engineering and construction company used *cadwork*, a parametric 2.5 to 3D timber construction detailing and fabrication software. They imported the FAOM in *.sat format and created the EFM as DWG/IFC product models which were later imported to *RAC*, *Solibri Model Checker* and the *Design Performance Viewer*, a plug-in for RAC for energy performance simulations (Schlüter and Thesseling, 2009). The ordering requirement and the offering performance and price information were exchanged in *Excel* sheets.

OBSERVATIONS AND RESULTS

We use the framework of interconnections of Lean Principles and BIM Functionality proposed by Sacks et al (2010) to structure and assess the impact and synergies of our management and technology approach.

The creation and visual exploration of a 3D BIM on basis of the 2D drawings of the architect for the bidding preparation alone helped the GC to gain a better understanding of project scope and to early identify critical, cost driving elements in the project. Current practices for quantity take-off (QTO) at that project stage using small-scale (e.g. 1:200) plans result in rather imprecise quantities and adds risk allowances on prices, which often are the decisive factor for winning and losing a project. The model based QTO lead to significantly more precise and reliable bidding documents. [In our case documents refer to 3D models the FAOMs]. The GC states that they were also more consistent among different authors, who created them.

Even before creating the FAOMs for facade elements, the GC started exploring and evaluating the 3D BIM regarding functionality, architectural design quality and constructability. This reduces the variability commonly introduced by late changes during fabrication and construction. We observed that the GC created and evaluated alternative design solutions thus identifying the potential for optimizations. Of special concern was the design of the underground parking garage. A simplification of the structural design combined with a level adjustment led to significant cost reductions. The designing architect however was not directly involved in the procedure. Request for changes were only made after decisions had been made by the GC.

The modelling of the EFM - for the first time in history of the timber engineering and construction company - was a one-step-operation based on the provided digital FAOM with no additional information needed. All necessary fabrication models and information was created in the same process. Bidding prices were not based on quantity estimates but on precise QTOs from the fabrication models. They produced different EFM's offering price options for distinct levels of performance and quality of the facade elements. The façade manufacturer stated that, when client start using parametric building models of the provided quality, the time to prepare an offer can be cut down from two weeks to two days. The time gained can now be used to explore more options to arrive at the most valuable solution for the client. To import a precise 3D FAOM with a clear scope and assignment direct into the 3D EF design and fabrication tool omits the errors typically emerging from manual entering 3D data from 2D paper plans and the possible different interpretation of the information provided. Here BIM enables lean construction and prevents "making do" (Koskela 2004)

In fact, the creation of the EFM was a by-product of creating the product model to provide the necessary fabrication information to run the automatic fabrication process. The provision of spacial tolerances for the window and air box positions allowed for more options to place and design the structural elements of the façades and to sub divide the wall into elements, a better use of oriented strand boards (OSB) plate sizes available at stock and adapted purchasing orders. Further results were optimized cutting schemas and a better workflow planning for the multi-functional fabrication bridge (see Fig. 1, top right). The timber construction company presented also a complete new and innovative façade element with very slender OSB strands as columns. This is an example, where contractors and manufacturers will gain more room to come up with tailored and innovative solutions.

The provided EFMs transferred fabrication and construction knowledge back to the ordering GC and the associated architect. Importing the EFMs into the FAOM resulted in two or more models laying over each other, which is hard to visually analyze. Current visualization capabilities in modelling tools are not well prepared for model comparison. Thus it took extra efforts, e.g. choosing different transparency, different positions of the models and/or temporal exchange of elements at the original place of the FAOM to evaluate visually the different offers against the FAOM. The comparison of different offers and their performance parameters using the different models alone was straight forward and easy. The GC checked the architectural design against the ready to fabricate and construct EFM elements. Constructability evaluation was performed in different aspects e.g. the interconnection of facade elements or the design of the air box openings or the system of the outer plies of facade finishes. It was obvious that the early introduction and integration of fabrication and construction knowledge led to significant better quality.

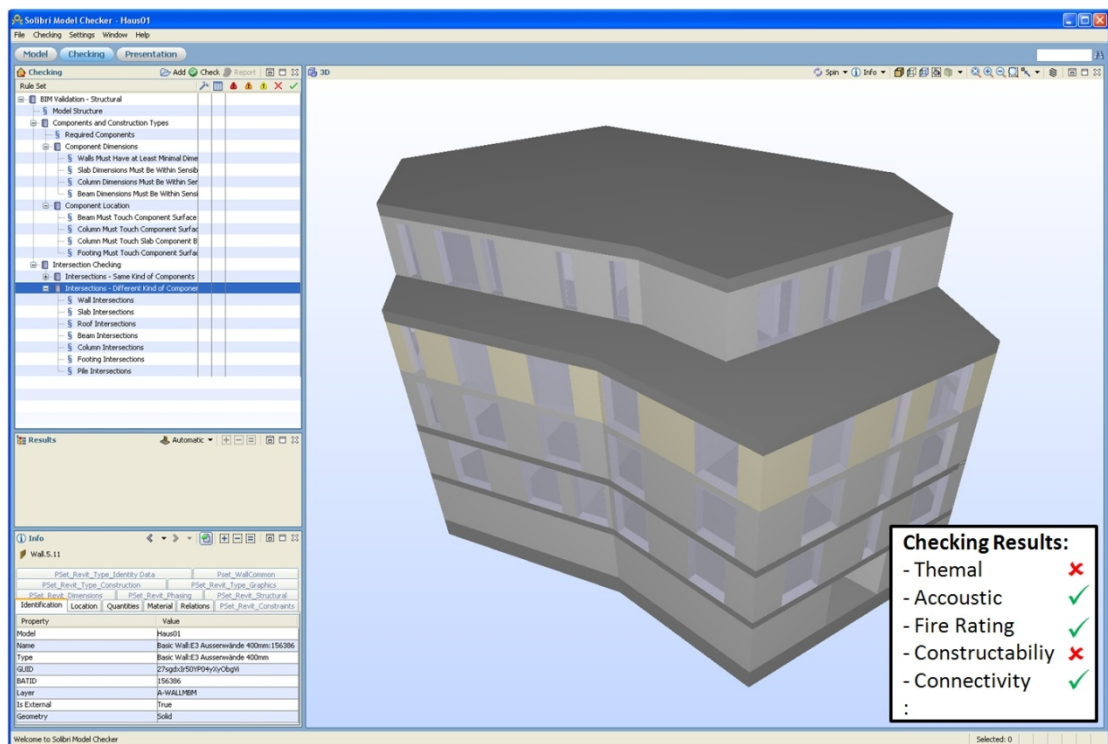


Figure 3: (Semi-) automated checking and comparisons of alternative offers

To include stakeholders who need to be integrated in the decision making process, we introduced Solibri Model Checker (see Figure 3) to show that different aspects of checking, evaluation and comparison of construction alternatives that can be partly or completely automated, e.g. program, usability, code compliance checking. For comparing construction and life cycle costs – more for demonstration of future possibilities new rule sets had been implemented and tested. The red lining capabilities need to be improved to establish a work flow to actively communicate, negotiate and decide using models. These concepts, focus on the improvement of the value generation process (Sacks et al, 2010) and tries to integrate people, processes an technology.

Figure 4 shows the energy performance simulation with Design Performance Viewer (Schlüter and Thesseling, 2009). This plug-in for Revit Architecture is a tool especially developed for architects that calculate the energy performance of the current design and the subsequent changes such as using different HVAC systems, walls and windows with different energy transmission values. Thus, a big step towards performance based design can be achieved, as the designers visually experience what the effects of different design options are. In our case, the different EFM could be directly loaded into RAC and price and energy performances could be simulated and compared.

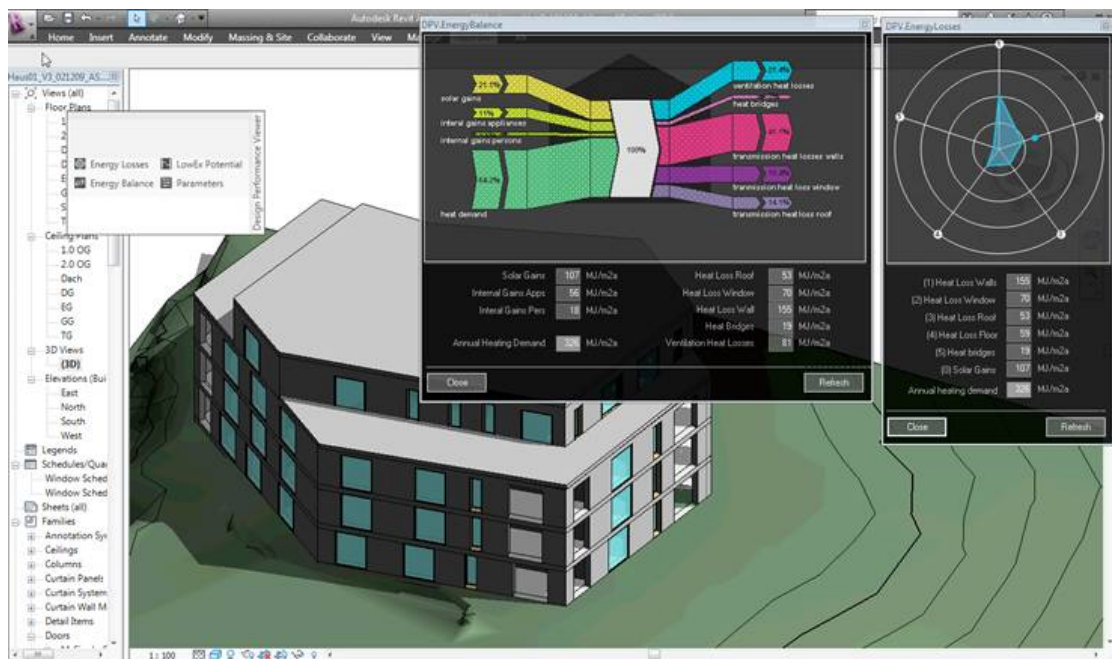


Figure 4: Energy Performance Simulation with DPV

Using 4D models (3D BIMs with assigned processes which can be visualized, analyzed and simulated over time as the 4th dimension) on basis of EFM was discussed as future option. The GC was interested to see the impacts on schedule and costs of using precast elements in comparison to traditional cast on site concrete.

The described new technological features for enhanced model checking and simulation methods led the manufacturer consider about the benefits and value of the

knowledge transfer to the GC and despite of the obvious advantages of the model based bidding process for himself, it let him become hesitant to generally apply this approach. This issue is related to the lean construction principle "cultivate an extended network of partners" (Sacks et al, 2010)

CONCLUSIONS

The hypothesis "that by restructuring the bidding process we can improve the value stream and hence the value for the customer" has been positively tested. The "Functional Design and Bidding" methodology presented can be viewed as a lean management approach for integrating people, processes and information systems to achieve lean principles: Lean and BIM can be used as mutual enabler and to create significant synergies. The involved stakeholders communicate by the means of 3D digital models, which are conceptual designs (FAOMs) with bounding geometries and requirement descriptions on the ordering side (architects, designer, etc.) and detailed 3D building information models - ready for manufacturing and construction - with performance and cost information (EFMs) as bidding responses from the contractors (engineers, manufacturers, constructors). The process oriented information exchange by digital 3D Building Information Models enables the transfer of engineering, fabrication and construction knowledge since the offering models meet fabrication and construction quality levels. A significant reduction of waste was observed in comparison to the traditional and current 2D drawing based process e.g. work, re-work, wait, need for additional information, latency etc. Digital models allow for early and repeated analyses, checking, evaluation and simulations and in our case they enhanced and optimized both, the design, construction and building performances and the downstream AEC processes, which become more predictable; the value generation process has been significantly enhanced. The "Functional Design and Bidding" methodology gives more room for innovative solutions for both, the product and for designing the "production system" focusing on flow and value, as the ordering side focuses on concept design.

On the technology side, we develop a concept and a prototype PPMI that uses computer interpretable schemes to handle the workflows of the design and bidding processes. The computer interpretable schemes of the PPMI are concept extensions which should reduce the software developers' efforts significantly to make BIM tools interoperable. The objective is to let the stakeholders involved in the bidding process use their preferred and appropriate BIM application.

Discussion with project participants showed, that the results are not restricted to the field of prefabricated timber facades, but can be transferred to a wider deployment in AEC, especially HVAC and MEP. In building and cultivating an extended network of partners, the role and contribution of the engineering, fabrication and construction knowledge provider needs intensive discussion.

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