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PARAMETRIC STRUCTURAL OPTIMISATION TOOL FOR FLEXIBLE INDUSTRIAL BUILDINGS: EVALUATION THROUGH EXPERIMENTAL STUDY

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ABSTRACT

Industrial building design is an interdisciplinary task, where data and software needed by production planning differ from the ones in building design. Constantly changing manufacturing systems demand highly flexible building structures. To achieve integration and improve structural performance a novel parametric multi-objective optimisation and decision support (POD) tool for flexible industrial buildings was developed. Through an experimental study within an interdisciplinary design class we have introduced and tested the tool, thereby evaluating students satisfaction on people, process and technology aspects. Results reveal strengths (quick variant studies, performance feedback), limitations (ease of use, interoperability) and future developments of the POD tool.

INTRODUCTION

Industrial building design is a highly complex task, involving interdisciplinary teams, processes and a huge amount of discipline-specific data. Integrating manufacturing system planning into building design is challenging (Näser and Wickenhagen 2018) as BIM (building information modelling)-based applications in manufacturing and interfaces and data exchange between the disciplines have been little researched (Ma et al. 2017). Furthermore, modern industrial buildings need to accommodate to constantly evolving manufacturing changes but the building's load-bearing structure is rigid, restricting the systems flexibility the most. As the element with the longest service life, the structural system has a vast impact on the life-cycle performance of production systems (Heravi et al. 2017; San-José Lombera and Garrucho Aprea 2010). In practice, structural considerations enter the design process late and are subservient to architectural and production goals, leading to suboptimal building structures. Most research and models for industrial building design improvement address the energy performance (Bleicher et al. 2014; Chinese et al. 2011; Gourlis and Kovacic 2016) or manufacturing system optimisation (Francalanza et al. 2017; Kluczek 2017) while holistic models receive little attention. Structural optimisation is seldom in the center of interest, although maximizing the flexibility of the load-bearing structure would prolong the building service life, thus reduce life-cycle costs and improve ecological performance. There is just a limited number of structural analysis methods allowing analysis and visualisation in a single environment and usually these tools provide feedback only to the structural engineer himself, not supporting an integrated performance improvement (Mueller and Ochsendorf 2015).

With upcoming sustainability requirements in building projects, a more integrated practice and focus on early design stages arises, enabling simultaneous collaboration of multiple disciplines offering real-time decision making support (Zanni et al. 2016). A high fragmentation of design processes disables the communication and management of complex design decisions and the information of the decision impact on the overall project performance (Boujaoude Khoury 2019). However, traditional building design and production planning processes are highly complex and run consecutively, lacking in feedback loops.

Parametric modelling in combination with performance analysis tools allow the quantitative and qualitative investigation of a variety of design options, assisting decision making at early design stage. Combined with multi-objective optimisation algorithms multiple designs can be automatically generated and evaluated, identifying best scoring design solutions (Harding et al. 2012). Interdisciplinary design optimisation techniques, integrating modelling and simulation technologies, such as BIM, parametric modelling, simulation and optimisation algorithms, have the potential to generate high performance building designs. However, it is not commonly used in current design practice and often limited to academic research (Rahmani Asl et al. 2015). Iterative design towards performance improvement requires the availability of methods and tools that can be easily used by designers, covering the selected performance criteria. However, this entails that BIM and performance-based simulation methods are compatible so that they can be effectively used in the design process to optimise multiple performance aspects at different stages of the design process (Jung et al. 2018).

With the introduction of parametric modelling tools and visual programming in CAD software the interest in generative design is increasing. Using optimisation methods and visual programming languages in early design stages can be useful for making interdisciplinary stakeholders better understand and receive improved building results. However, a parametric design approach still has limitations, as scripting languages are fundamental for implementing generative design systems (Celani and Vaz 2012). Efforts have been made in both academia and practice, educating architects and engineers to increase knowledge for computational design through visual programming. Yet, many practicing architects and engineers do not have the background knowledge, interest or time resources to code by themselves and designers, professional and academic, depend on existing software to suit their needs, although these tools may not exactly cover the requirements (Brown et al. 2020).

Our hypothesis is, that a parametric multi-objective optimisation and decision support (POD) tool for automated structural and layout optimisation in industrial building design, integrating production planning, improves interdisciplinary cooperation, the design process and the design results to generate flexible industrial buildings in two ways:

1) By integrating stakeholder in a digital interdisciplinary platform, supporting collaborative decision making at early design stage.

2) Through a tool itself, which automatically analyses and optimises the building load-bearing structure according to the production layout, providing real-time feedback on the structural performance and fast impact exploration of different design decisions.

The POD Tool

The POD tool is developed within the funded research project BIMFlexi. The aim of BIMFlexi is to integrate production planning into building design by developing an integrated BIM-based digital platform for early design stage (Reisinger et al. 2020b). The POD tool is part of the digital platform, enabling structural performance based industrial building design and optimisation, striving for maximum flexibility to increase economic and environmental building performance in long-term. The POD tool aims to support in interdisciplinary decision making by allowing design teams to efficiently collaborate, understand discipline-specific goals and carry out fast variant studies. The POD tool framework, presented in Reisinger et al. (2020a), is based on the parametric modelling software Grasshopper for Rhino3D (McNeel 2020) for geometry generation and the Grasshopper components Karamba3D for structural performance simulation (Preisinger and Heimrath 2014) and the generative solver Galapagos for multi-objective optimisation of the structure and layout (Rutten 2013). A possibility is created to consider production layout planning in structural design with automated flexibility assessment of the building's structure and layout. The aim of this paper is to test and evaluate the developed POD tool and thus to increase its applicability by identifiying potentials for improvement.

Experimental Study: Goal and Scope

In order to test the developed POD tool, we have conducted an experimental study within an interdisciplinary student design course at TU Wien, which took place in the winter semester of 2020 with students of architecture and civil engineering. The aim of the experimental study is to (a) evaluate the benefits and improve the POD tool and (b) identify potentials for the optimisation of process-integration in industrial building design through the use of the POD tool.

Thereby we adress the following research questions:

Q1) Can a parametric structural analysis and optimisation tool designed for early industrial building design support interdisciplinary teams in efficient collaboration and provide effective decision making support?

Q2) Who is the primary beneficiary of the tool - civil engineers or architects; or is the benefit equal?

This paper is structured as following: In the next chapter we present the design and the structure of the empirical study (interdisciplinary design course), the team structure as well as the POD tool test framework. In the third chapter we present the results of the study obtained through quantitative and qualitative analysis of post-questionnaires and protocols. In the fourth chapter we summarise and discuss the results and concludingly, we draw the conclusion for the practical application of the POD tool as well as for the future research.

EXPERIMENT DESIGN

Interdisciplinary teaching can deepen both learning and teaching, aquiring a clearer holistic picture of complex systems in nature, society and real life (Karppinen et al. 2019). The employed methodology is based on empirical research, using an experimental study within an interdisciplinary design class involving 24 students (16 architects and 8 civil engineers). In order to answer the research questions, thus to verify and evaluate the POD tool in terms of

- Satisfaction on people and process level - potential of the tool to support collaboration, process and teamwork
- Satisfaction with technology - ease of use, usefulness and interoperability

we have conducted a simulation of an integrated design process supported by the POD tool within the interdisciplinary student design course "Integrated BIM Design Lab". The eight teams, two architects and one civil engineer per team, employed the following software:

- The POD tool for early stage structural design and multi-objective optimisation.
- Graphisoft ArchiCAD (Graphisoft 2020), as 3D BIM tool for architectural post-processing of the optimised structure.
- Dlubal RFEM (Dlubal 2021) as finite element modelling (FEM) tool for detailed structural analysis after parametric optimisation.

Students were experienced with the BIM tool ArchiCad (architects), and the finite element modelling software Dlubal RFEM (engineers) but were not familiar with parametric modelling in Rhino3D, nor with any visual programming language or optimisation theory. The introduction into optimisation and decision making theory was conducted in a single session and the introduction to visual programming language was conducted in two whole day sessions. Additionally, the students became tutorials on BIM modelling and data and model exchange from parametric to BIM and vice versa in a one day course. After the introduction of each technique the students were given about two weeks to develop a design proposal for the design task of a real industrial production project from packaging industry, consisting of the functional building and production program and the site plan with property requirements (see Table 1). The assignment also included consideration of future changes in use in the variant study.

Table 1: "Integrated BIM Design Lab" class assignment of the production building and the optimisation framework

Buildingy Type	Production Hall
Gross area	1700 m²
Location	Innsbruck, Austria
Decision Variables	**Objectives**
v1 Structural system type	f1 Minimum net cost of construction (€/m²)
v2 Construction material	f2 Maximum free room height
v3 Axis grid (x- and y-)	f3 Minimum column amount (max. span width)
v4 Clear room height (z-)	

The design process of the conducted experiment and the assessed POD tool is presented in Figure 1. Data and information for building and production planning of the given industrial building design task, as well as the assessment criteria for optimisation is compiled as input. Within the processing phase the POD tool is used, aiming for structural and layout optimisation, fast variant study generation with real-time performance feedback and decision making support. For pre-processing the best-scored design solution of the optimised layout and building structure is transferred to the BIM and FEM modelling software in order to generate a detailed integrated industrial building design model.

RESULTS

The conducted study was evaluated through quantitative and qualitative survey based on the evaluation of post-questionnaires and weekly protocols compiled by the students. On the one hand the questionnaires included inquiries related to the satisfaction working with the POD tool in terms of process, outcome and collaboration and on the other hand the satisfaction according to the technology acceptance model (TAM) of Davis (1989), including satisfaction with ease of use, useability and interoperability. The qualitative evaluation was carried out in form of open questions at the end of the questionnaire, regarding questions about suggestions for improvement in terms of process, collaboration and interdisciplinary decision making, and suggestions for improving the technology of the tool.

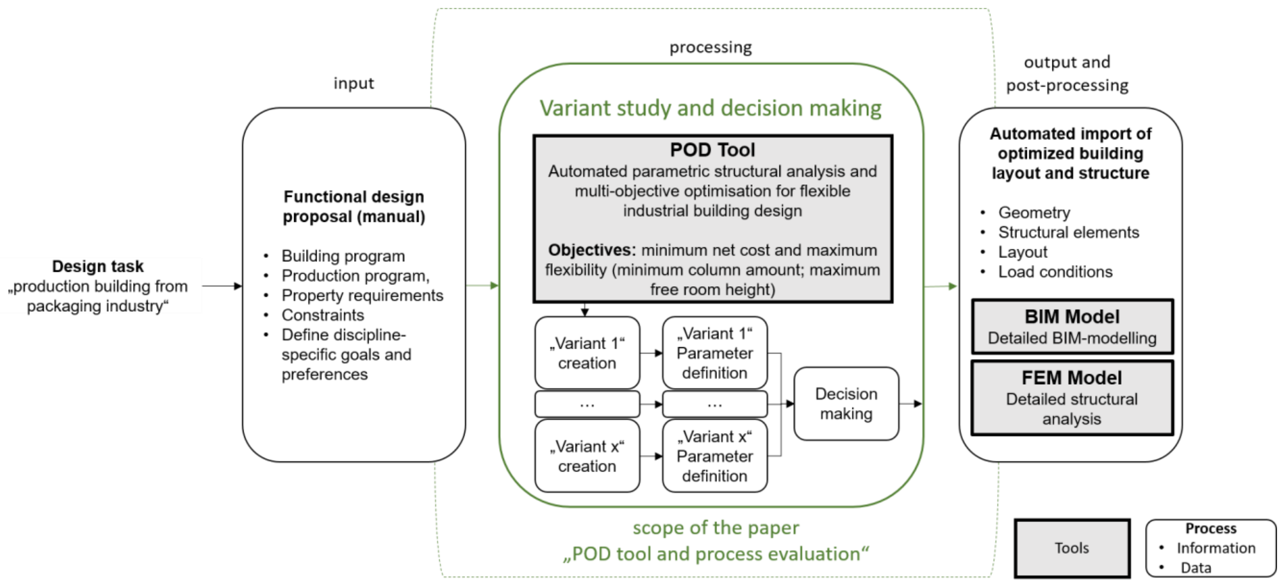

Figure 1: The interdisciplinary industrial building design process within the conducted experiment and scope of the paper.

The post-questionnaires assess the satisfaction working with the POD tool regarding to:

- **process** (e.g.:"The tool helped me to perform my tasks efficiently.") – 4 questions
- **outcome** (e.g.:"The tool aims that the goals I have set have been achieved.") – 4 questions
- **collaboration** (e.g.:"The tool supported effective team communication and collaboration") – 4 questions .

while the tool specific questions where related to:

- **ease of use** (e.g.:"The tool increases my productivity.") – 6 questions
- **useability** (e.g.:"In total I think the tool is useful for decision support tasks.") – 6 questions
- **interoperability** (e.g.:" Overall, I think the tool is compatible with other systems."– 6 questions.

These latent constructs where measured by multiple items on a 5-point Likert scale ranging from low/disagree (1) to high/agree (5). After examination of the quality of scale using Cronbachs α, the median per construct was built and the evaluation was carried out according to the discipline of architecture and civil engineering each as well as over both.

The overall **quantitative results** of the questionnaire evaluation (all eight teams clustered per discipline) are presented in Figure 2 for work satisfaction and in Figure 3 for TAM.

Figure 2 shows that there is a tendency that architects rank the satisfaction working with the POD tool higher than the civil engineers. The architectural students rate the satisfaction with the process and the outcome both with an average of 3,9 and the satisfaction with collaboration with an average of 3,8. Meanwhile, the civil engineers rate the satisaction with the process with an average of 3,6, with the outcome with 3,7 and with the collaboration with 3,0.

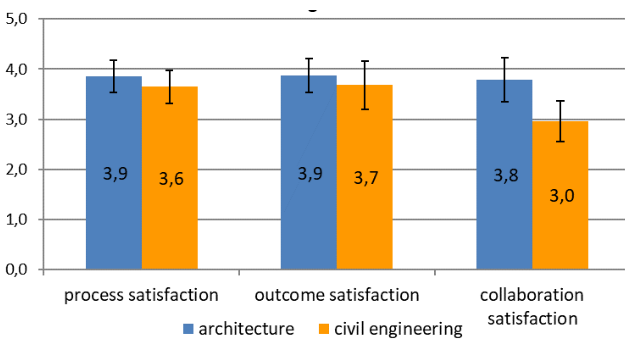

Figure 2: Evaluation of satisfaction with process, outcome and collaboration working with the POD tool per discipline

Figure 3 presents the evaluation results of the TAM survey. Within the the tool specific survey architects rank the technology of the POD tool slightly higher than their civil engineering colleagues. The architectural students rate the ease of use with 2,7, the usefulness with 3,7, and the interoperability with 3,1. While the civil engineers assess the ease of use and the interoperability with 2,5 and the usefulness with 3,0.

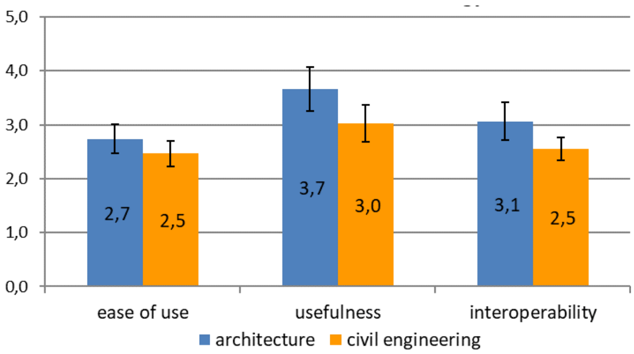

Figure 3: Evaluation of the POD tool technology per discipline: ease of use, usefulness and interoperability

Figure 4 presents the evaluation of work satisfaction and technology with the POD tool over both disciplines. Regarding the evaluation of satisfaction working with the tool, the evaluation results reveal that the process satisfaction is perceived as the category with the lowest performance, rated in average with 3,5. The satisfaction with the process and the outcome are both rated in average with 3,8. Ease of use (2,7) and interoperability (3,0) is perceived for both disciplines as the categories with the lowest performance within the TAM survey. Meanwhile, the usefulness of the tool is rated by both disciplines with 3,6.

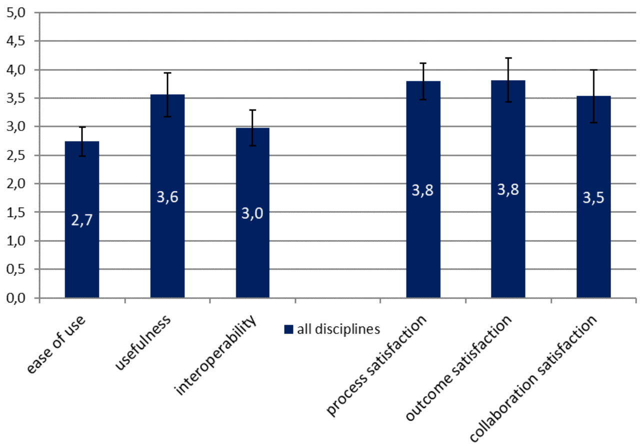

Figure 4: Evaluation of technology and satisfaction with the POD tool over all disciplines

Additionally, the students were asked if they have previous experience with parametric modelling and computational tools as well as experience with optimisation and decision making support tasks. The engineers, who rated the POD tool in both terms work satisfaction and technology slightly lower than their architectural colleagues, indicated that they had almost no experience in computational design and optimisation. 67% of the civil engineers has never worked with parametric software and modelling and 75% lack in experience of optimisation and decision support theory. The architects already gained more experience in these areas - 36% are experienced with optimisation and 16% with parametric modelling. (see Figure 5).

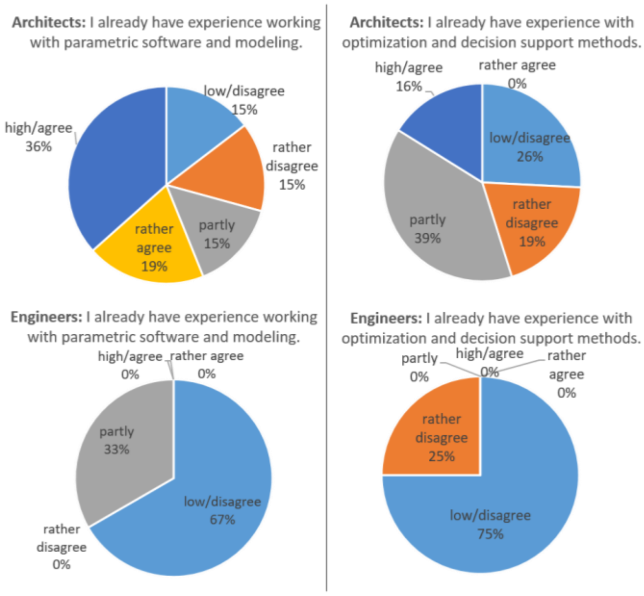

Figure 5: Disciplines experiences with computational design and optimisation

However, **the qualitative questions** asked at the end of the survey and received from the protocols reveals, that once the students had understood the parametric script and implemented the interfaces to BIM successfully, they felt benefits in process and design improvement - e.g.:*"The ability to integrate structural design early in the design process has brought benefits to my architectural concept"(architectural student). "The early integration of strucutral analysis into the design process has brought advantages for the structural design of the hall and a reduction of workload through quick variant studies"(civil engineering student).* "*I now better understand the impact of my design decisions on the load-bearing structure*". However, a majority of the study participants recommend to "*offer more training on parametric modelling and optimisation in advance to increase the applicability of the POD tool".* Furthermore the qualitative study reveals, that the POD tool can support in interdisciplinary decision making but *"an additional information and data exchange strategy has to be set up within the team at the beginning of the project"* in order to be able to work efficiently with the tool. Students also recommend "*the development of a graphical interface to make the tool more applicable in practice".*

DISCUSSION

The POD tool aims to support in structural and layout optimisation and interdisciplinary decision making in integrated industrial building design. Results confirm our hypothesis, that the integration of the tool supports interdisciplinary design teams in collaboration. There is a tendency that architects rank the satisfaction working with the POD tool higher than the civil engineers, since their design draft profits from the early structural analysis integration and the design decision feedback. The use of the POD tool in the early design stage allowed efficient cooperation within the teams, enabled a fast exploration of design decisions and provided real-time feedback on the structural building performance. In some cases, there was dissatisfaction within the interdisciplinary team environment, regarding the distribution of tasks and resources. The qualitative evaluation revealed that within the teams mainly civil engineers were assigned with the investigation and application of the POD tool. Especially the engineering discipline was responsible for the interface development of bi-directional coupling of the POD tool to the BIM and FEM software. Students from civil engineering where more overwhelmed and would have expected more support from their architectural colleagues. A well defined process strategy in allocation of tasks is still necessary prior working with the POD tool.

The POD tool is developed, carrying out structural and layout optimisation automatically according to the design optimisation goals of minimum costs and maximum flexibility. A careful team communication before starting the design process, defining discipline-specific and overall goals is necessary in order to successfully work with the tool. The participants of the study pointed out the importance of assigning aligned weightings of single objectives within the team. An additional proper design discourse besides using the tool is inevitable, so a communication strategy has to be set up in advance.

However, ease of use and interoperability is perceived for both disciplines as the categories with the lowest performance within the TAM survey. The identified lack of interoperability is resulting in the task given, that the students where responsible for developing the bi-directional interface from the POD tool to the BIM and FEM software by themselves in the experiment. This task was new for most of the participants and required exposure to new tools and working methods, not common in regular design processes and universitary teaching. The student's lack of prior optimisation and visual programming knowledge revealed that the tool is not yet self-explanatory and difficult to apply without prior knowledge, requiring learning and practice time of the users.

Digital communication was a major topic in the qualitative evaluation. Due to the Covid-19 situation the interdisciplinary course had to be carried out fully in remote modus. A large part of the participants found the online teamwork difficult. Constant exchange with the team members was described as essential, but difficult due to the online remote learning and teaching.

CONCLUSION

University graduates are introducing parametric design into practice as a method that is in most cases new to practical working contexts (Holzer 2015). Testing the POD tool in interdisciplinary academia environment seeks to bring further application of parametric design exploration methods in practice. Due to the greater level of coding accessibility within parametric design compared to raw coding for pracitioners, the POD tool offers a computational and visual programming framework as viable medium for structural industrial building design exploration. The experimental study revealed that although there is already increased recognition and awareness of computational design among trainees, the supply and knowledge about computational design and optimisation tasks is not yet sufficient. In order to achieve a broader and more efficient application of parametric optimisation solutions, more attention should be paid to this in teaching, since these are the new generation in practice. Results of the study point out that the POD tool is not yet self-explanatory and challenging to apply without prior parametric design and optimisation knowledge and additional training time is needed.

However, the integration of discipline-specific design elements and goals from production planning, architectural and structural design within the POD tool enabled the interdisciplinary teams to carry out rapid variant studies, simultaneously respecting needs from other disciplines to develop building designs which focus on flexibility. The use of the tool helped to understand discipline-specific interdependencies, associated construction needs and to deeper understand the impact of decisions on the structural building performance. The possibility of the tool to support interdisciplinary working environments, getting more exposure to the concerns of other disciplines in early conception and the possibility to ease the information flow streamlines cooperation between architectural and engineering designers.

Primary beneficiaries of the POD tool were the architects, rating the tool better than their engineering colleagues. The civil engineers rate the POD deployment as good, but see potential for improvement in terms of ease of use and interoperability.

Finally, we see the hypothesis confirmed that the POD tool is useful for interdisciplinary collaboration and decision-making in early integrated industrial building design; however the process requires still intensive communication and prior knowledge in parametric and computational design.

Future research will focus on the simplification of processes and the improvement of the handling regarding interoperability and ease of use of the POD tool, which will then be tested with experts from practice. Additionally, methods will be developed to couple the POD tool to a multi-user virtual reality (VR) platform to further streamline interdisciplinary decision making through collaborative visualisation support.

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