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EVALUATION OF PARAMETRIC MULTI-OBJECTIVE OPTIMIZATION AND DECISION SUPPORT TOOL FOR FLEXIBLE INDUSTRIAL BUILDING DESIGN

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Abstract

Parametric multi-objective optimization tools bear potential to integrate, optimize, and explore design spaces to support interdisciplinary decision-making. A parametric optimization and decision support tool was developed (POD tool), and an evolutionary multi-objective optimization algorithm implemented (PMOOD tool) to automate design search for flexible integrated industrial building design. Both tools were tested within a user study, simulating an interdisciplinary industrial building design process. The POD tool is rated slightly higher by evaluating the users' satisfaction with process, outcome, collaboration and technology through questionnaires for quantitative and qualitative feedback. The results indicate potential for improvement and future research regarding the PMOOD tool.

Introduction

Industrial building design is a highly complex task due to the need for a multi-disciplinary team and their deeply specialized knowledge. The desired high level of communication and collaboration represents the process' diversity (Hudson et al., 2011).

Various planning disciplines in industrial building design are needed to handle multifaceted projects. While the common goal is a durable, environmentally beneficial, and cost-effective building, the individual planning disciplines pursue different, often non-compatible sub-aims. Within state-of-the-art planning methods, compromises are agreed on regularly based on the experience and preferences of the stakeholders (Jung et al., 2018).

Parametric tools can support integration and collaboration at an early design stage. Building performances can be improved by exploring different value functions and generating and investigating many design alternatives (Haymaker et al., 2018; Ibrahim et al., 2019; Sakiyama et al., 2021).

The user study of Tünger (2020) compared parametric design to geometry-based modeling. It was concluded that the participants, when modeling geometry-based, focused more on the design, considering the actual use of the final configuration and generating more topologically different design variants. Nevertheless, planning disciplines are enabled to perform several iterations and make informed decisions through monitoring when applying the parametric design method. Additionally, advantages of parametric design are, for example, concurrency, coordination, accountability, and exploration of complex geometries (Asl, 2014; Suyoto et al., 2015; Harding et al., 2012).

Trying to achieve more design alternatives in less time, and to integrate various planning disciplines, data and knowledge often get lost through intersections amongst them. Many present tools are identified with little possibilities of integrating various data and software (Díaz et al., 2017).

While data- and software transfer problems still exist, different tools are developed to optimize and assist individual design processes. Evins stated a higher performance for lower costs in structural engineering designs applying multi-objective optimization (MOO) methods (Evins et al., 2012; Holzer, 2015).

Implementing MOO linked to parametric models for performance simulations has become a wide field of research and improved the design process (Brown et al., 2020). Integrating MOO to respect different aims from various planning fields can improve a building's environmental, economic, and ecological performance (Mueller et al., 2013; Holzer et al., 2008).

However, while parametric design and automated planning methods are increasingly finding their way into building design processes and individual areas of the planning disciplines are researched to be optimized, a holistic approach for integrated structural building design optimization is missing (Reisinger et al., 2021a). In our previous study we developed a tool to achieve integration and improve structural performance for flexible industrial buildings (Reisinger, 2021c; Reisinger, 2022b). Within this conducted study, we have implemented a MOO in the parametric design process, and the MOO tool is tried. The user study results and the evaluation of the PMOOD tool are the focus of this paper.

POD tool and PMOOD tool

The POD tool and the PMOOD tool were developed within the research project BIMFlexi to enable structural performance-based industrial building design.

In order to create an integrated BIM-based digital platform for the early design stage, the research project BIMFlexi investigates digitally supported integrated planning methods in industrial building design. The project intends to integrate production planning into the industrial building design process in an early design stage to maximize flexibility and expandability to minimize life-cycle costs and environmental impacts.

An evolutionary algorithm has been developed to automate design search and optimization for the objectives considering an industrial building's life cycle.

The MOO algorithm was now implemented for this user study to generate various structural building design options within a preset design space. The applied genetic algorithm optimizes, evaluates, and finally ranks the generated building options based on the performance results of the building on eleven objectives, including quantitative analysis of the life-cycle costs (LCC), life-cycle analysis (LCA), and a flexibility rating. In the context of this project, flexibility is defined as "the ability of the building structure to resist and adapt to changes in use through changing manufacturing conditions" (Reisinger, 2021a). The presets as well as the conditions the genetic algorithm respects when generating building structures around a previous optimized production layout, are briefly clarified within the next chapter (Reisinger et al., 2020, Reisinger et al., 2021b; Reisinger et al., 2022a; Reisinger et al., 2022b).

The POD tool was tested in 2020 through a pre-study. The experiment was conducted within an interdisciplinary design class with twenty-four students. Separated into teams of three, each group was given two weeks to develop a proposal for the design task of a real industrial production building. The design space was limited throughout the test to one desired variant where the parameters were preset manually. Subsequently, the users' satisfaction on different levels was tested by employing questionnaires. After evaluating the significant results, the POD tool was further developed (Reisinger et al., 2021c).

In this user study, the developed PMOOD tool is tested to answer the research question if the users meet the automatically generated structural variants of an industrial building in higher approval regarding their satisfaction with process, outcome, collaboration, and technology rather than the parametric script with manual handling of the parameters (POD tool). This paper presents the results of evaluating the two tools considering satisfaction with technology and on people-process level. Comparing the results among the two participating disciplines – architects and engineers – respecting their different perspectives and aims within a project, and the overall outcome are shown.

Experiment Design

A user study was conducted to answer the research question of higher satisfaction with process, outcome, collaboration, and technology employing the developed PMOOD tool rather than handling the POD tool with manually set parameters. The applied method to this experiment is based on empirical research.

Experiment Structure

Thirty-six students from the Vienna University of Technology served as participants in this user study. The participation was neither limited by previous knowledge about optimization or parametric modelling nor by any particular study program. Twenty-three architects and twelve engineers (eight civil engineers, three spatial planners, and one mechanical engineer) took part in the experiment. The participants were put into groups of two. A two-hour tutorial was held the day before the start of the user study to provide all students with the same information. As part of the tutorial, a team explained the general task (see Table 1), presented the POD tool and the PMOOD tool, and set the timeline for the two days of testing.

Table 1: Preconditions of the design task

Building Type	Production
Gross area	60.000[m²]
Location	Inntal, Austria
Outer dimensions of the production layout	210x130[m]

The assignment was to design a structural building around an already generated production layout with outer dimensions of 210x130m. As table 1 displays the preconditions of the design task, the gross area held 60.000 m² and was located in Austria, Tyrol.

The user study was carried out in one room, where three design teams were each testing both tools simultaneously. The time limit for one approach was set to forty-five minutes, including replying to the questionnaire. Then every team proceeded to test the other tool. Figure 1 presents the approach of both test runs:

- The participants manually generated structural building options by manipulating the variable parameters in the script and analysed the performance assessment. (POD tool)
- The applicants investigated the automatically generated building variants generated by the algorithm by the PMOOD tool and chose preferred options from the set of options the algorithm provided to further investigate the algorithm's results. (PMOOD tool)

Every design team was asked to generate at least three building options by manual handling of the parameters within the POD tool and to investigate several of the automatically generated variants by the PMOOD tool. To prevent the participants from learning the procedure, the order of conditions was randomized across teams: i.e., the first group started testing the POD tool, the second one the PMOOD tool, group number three started again with the POD tool, and so forth.

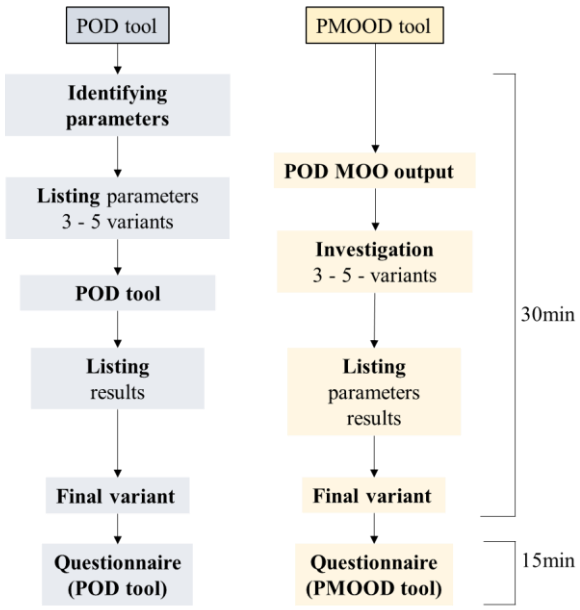

Figure 1 Approaches (POD tool) and (PMOOD tool) all participants are asked to conduct

Setting POD tool

As displayed in Figure 1, within the manual approach (POD tool), the participants were asked first to discuss different building variants they further want to investigate and to decide on several parameters (see Table 2; not availabe options are marked with "[]" in Table 2).

After manually setting parameters within the developed tool, the POD tool ran its quantified assessment on three objectives:

- Life-cycle costs (LCC)
- Global warming potential (GWP)
- Flexibility rating

Based on its' results, the design teams then studied and investigated between three to five manually shaped structural building designs. Every design team was asked to fill in a form with the agreed parameters of their manually formed building structures and the quantified results provided by the tool. After discussing the outcome within the teams, each team member was expected to reply to the questionnaire for the manual approach of the user study.

Setting PMOOD tool

For the investigation of the automatically generated building variants (PMOOD tool) the participants were shown results of the PMOOD tool within the tool itself. Since the calculation time of the PMOOD tool adds up to several hours, the MOO output was calculated beforehand. Therefore, the tool was preset not to investigate the whole possible design space (see Table 2; not considered options are marked with "[]" in Table 2). Regarding the bracing type only one of the two options was in calculation, and only two of three possibilities for the retrofitting load, representing possible future load capacity, were considered for the test run.

The tool ran for about seven hours within the pre-set design space and calculated 1.000 variants of building structures. Only the 50 best-ranked options were made available to the participants for further investigation. Within those the design teams were able to sort the results by prioritizing calculated objectives. Figure 2 shows the radar diagram of the best-ranked structural building design. One can see that the tool assesses eleven objectives (clockwise from the top): LCC, GWP, Acidification potential (AP), Primary Energy Volume renewable (PEI), Primary Energy Volume unrenewable (PEInt), Recycling Potential, Retrofittability, Expandability, Flexibility in space, Flexibility in floorplan and Production layout. The design teams were asked to investigate various building options with their quantified results provided by the PMOOD tool.

After discussing on various building variants among the automatically generated options, every participant was asked to reply to the specific questionnaire.

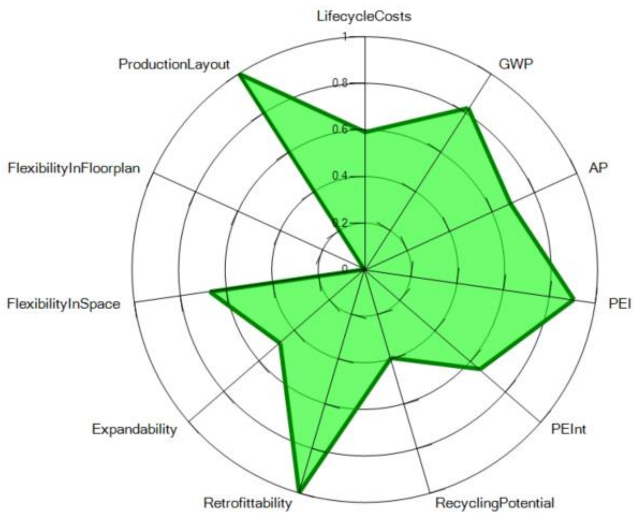

Figure 2 Radar diagram of the best-ranked option within the user study (PMOOD)

Table 2: Variable options for POD and PMOOD tool

Variables	Options POD tool	Options PMOOD tool
Primary axis grid [m]	8, 12, 16, 20, 28	8, 12, 16, 20, 28
Secondary axis grid [m]	6, 12, 18	6, 12, 18
Primary structure	Timber framework, Glued laminated timber beam, T-beam precast concrete, Steel framework, Steel profile	Timber framework, Glued laminated timber beam, T-beam precast concrete, Steel framework, Steel profile
Secondary structure	Timber beam, Beam precast concrete, Steel framework, Steel profile	Timber beam, Beam precast concrete, Steel framework, Steel profile
Column types	Precast concrete-quadratic, Steel-HEM	Precast concrete-quadratic, Steel-HEM
Bracing types	Clamped, [Joint XY-2-X-2-Y]	Clamped, [Joint XY – 2-X-2-Y]
Retrofitting load	0,1	0, [0.5], 1

Quantitative and qualitative assessment

Both questionnaires, specified for each approach, were measuring the user's satisfaction on people-process-level and with technology (see Table 3).

Table 3: Examined categories within the questionnaires and number of questions

Satisfaction with	Technology
Process (4)	Ease of Use (6)
Outcome (4)	Usefulness (6)
Collaboration (4)	Visualization and Decision Making (9)

For gaining quantitative assessment the Likert scale was implemented to give the students the following response options for each question: strongly disagree, disagree, neutral, agree, strongly agree (Likert, 1932).
The technology acceptance model (TAM) by Davis (1989) was applied to the related questions to assess the students' satisfaction with technology. The questionnaires also included questions to enquire the participant's

- study program (architecture, civil engineering, spatial planning, different),
- years of studies,
- experience with parametric modeling, and
- experience with optimization and decision supporting tasks/tools.

Moreover, open questions were asked at the end of the surveys to request qualitative feedback regarding the handling and visualization of the tool and improvement suggestions for making interdisciplinary decisions.

Results

In this chapter, results based on the evaluation of thirty-six post-questionnaires for each approach are presented. The questionnaires included both quantitative and qualitative statements.
Three open feedback questions were asked at the end of each questionnaire and represent the qualitative assessment. Suggestions were requested to increase satisfaction with the process, make collaboration more effective, and to make interdisciplinary decisions more accessible. Further input was requested to state possible improvements regarding handling, visualization, and results in output.
For quantitative assessable answers, the users' satisfaction on people-process level was investigated - satisfaction with the process, the outcome, and collaboration. Questions based on TAM evaluated the tool's ease of use, usefulness, and visualization. For the quantitative evaluation of the questionnaires, the response options were rated from 1-5, implying "strongly disagree (1)" to "strongly agree (5)". Since only one of the quantitively assessable questions intended negative feedback the answering choice "strongly agree (5)" was rated best. For the specific question, the invert of the rating was performed to combine and compare all answers.
The quantitative analysis was performed in Microsoft-Excel. Before forming the median per construct, the scale quality was evaluated using Cronbach's α. The median was then built for each discipline, architecture, as well as engineering, and the totality of the participants.

POD Tool

The following two figures present the participants' satisfaction with technology (Figure 3) and work satisfaction (Figure 4) for the parametric script with manual handling of the parameters. In order to evaluate the results with respect to the different goals and perspectives of the two main disciplines, the results are presented by field.

Figure 3 displays, that engineers rank the POD tool higher than architects in every sub-category regarding TAM. Engineers rate the ease of use with an average of 4.42 (vs. architects: 4.11) and usefulness with 4.43 (vs. architects: 4.01). The tool's visualization is rated highest amongst TAM-related categories by both disciplines – engineers' rating of 4.59 and architects' of 4.19.

Results within the same approach (POD) but regarding work satisfaction are presented in Figure 4. The engineering students rated the outcome with 4.35 and the collaboration with 4.52. For these sub-categories, the satisfaction is ranked higher by the architects – 4.37 for outcome satisfaction and 4.73 for collaboration. Regarding process satisfaction, engineers reviewed the tool marginally higher (4.15) than the architectural students (3.97).

PMOOD Tool

The same categories concerning technology and work satisfaction were evaluated to investigate the automatic approach, applying the MOO. Figure 5 and Figure 6 display the quantitative evaluation of the specified questionnaire.

For this approach, the results suggest that the participating engineers were more satisfied with the usefulness and visualization regarding TAM. The ease of use was assessed on higher performance by the architects. While engineering students rated ease of use on average with 3.85, architects were more satisfied, rating on average 4.09. For usefulness and visualization, engineers ranked 4.28 and 4.46; architects only rated 4.03 and 4.18.

Figure 6 presents the users' satisfaction on people-process level. While architects rated lowest for the process satisfaction with an average of 3.62, engineers were the least satisfied with the outcome, ranking 3.92. The satisfaction of collaboration and process was higher amongst engineers, with a rating of 4.50 and 4.19. The architectural students only ranked collaboration with an average of 4.25 but the outcome satisfaction with 4.05.

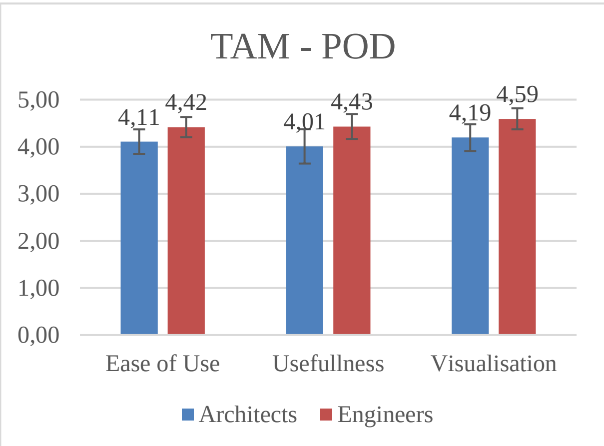

Figure 3 Evaluation of the POD tool technology requesting the ease of use, usefulness, and visualization for each discipline

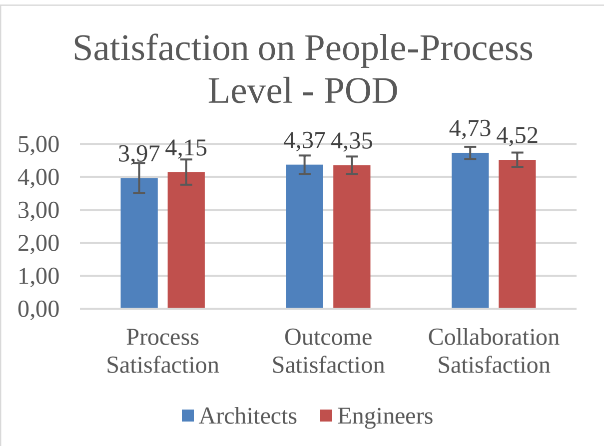

Figure 4 Evaluation of the POD tool regarding satisfaction with process, outcome, and collaboration for each discipline

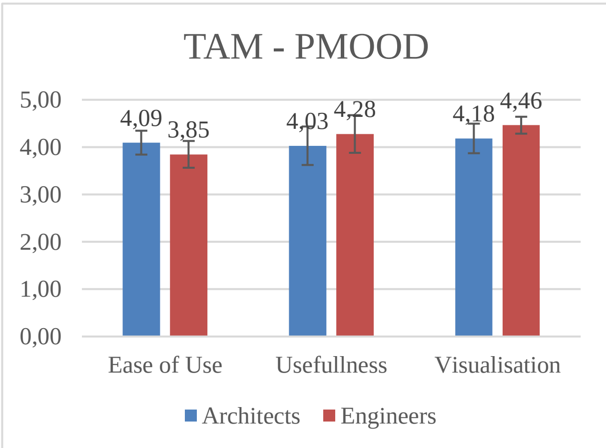

Figure 5 Evaluation of the PMOOD tool technology requesting the ease of use, usefulness, and visualization for each discipline

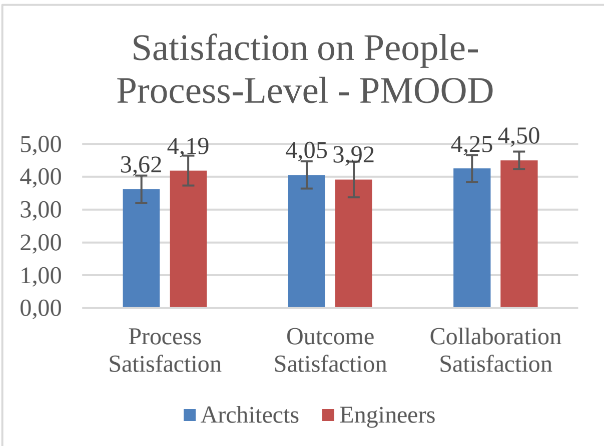

Figure 6 Evaluation of the PMOOD tool regarding satisfaction with process, outcome, and collaboration for each discipline

Comparison of POD and PMOOD tool

Figure 7 compares the two approaches of the tool evaluating the surveys across all disciplines. Results show the overall satisfaction is higher with the manual tool approach (POD) than with the application of the MOO (PMOOD). Satisfaction with technology and on people-process level are ranked higher for the manual tool approach in every sub-category.

Regarding the assessment of work satisfaction, the evaluation reveals that process satisfaction is perceived as the category with the lowest performance for both approaches (POD: 4.03 and PMOOD: 3.81). For the other sub-categories of work satisfaction, the manual approach is rated higher within all categories (collaboration: POD: 4.66 and PMOOD: 4.34; outcome: POD: 4.36 and PMOOD: 4.01). The questionnaires also reveal the highest difference in performance between the two approaches in the sub-category outcome satisfaction by 0.35.

Results for TAM show the visualization category performed highest in both approaches (POD: 4.33; PMOOD: 4.28). Usefulness (POD: 4.15; PMOOD: 4.11) and ease of use (POD: 4.21; PMOOD: 4.01) were within either approach ranked lower.

Comparing the overall rating of all sub-categories of TAM and work satisfaction, results reveal a higher overall score of the manual approach. While the automatic approach is rated on average of 4.09, the manual approach has an average rating of 4.29. This equals to a 5% lower performance of the PMOOD tool.

Qualitative assessment

The qualitative questions of both surveys asked for possible improvements to increase the efficiency of the multi-disciplinary collaboration. They were also aimed for suggestions on improvements of the tools' handling and visualization.

Participants stated storing variants while manually setting parameters to investigate another option as a possible improvement concerning the manual approach POD.

Replying to the specific survey for the automatic approach (PMOOD), a more refined user interface with detailed descriptions of the MOO output was suggested as an improvement. Many participants also asked for the prospect of a more specific visualization of the variants' material. While the tool assigns indices for each material, the users would understand names or colors within the output as better solutions.

One third of the participants also argued the missing transparency of the outputs' calculations, concerning LCC, GWP, and flexibility, within both approaches.

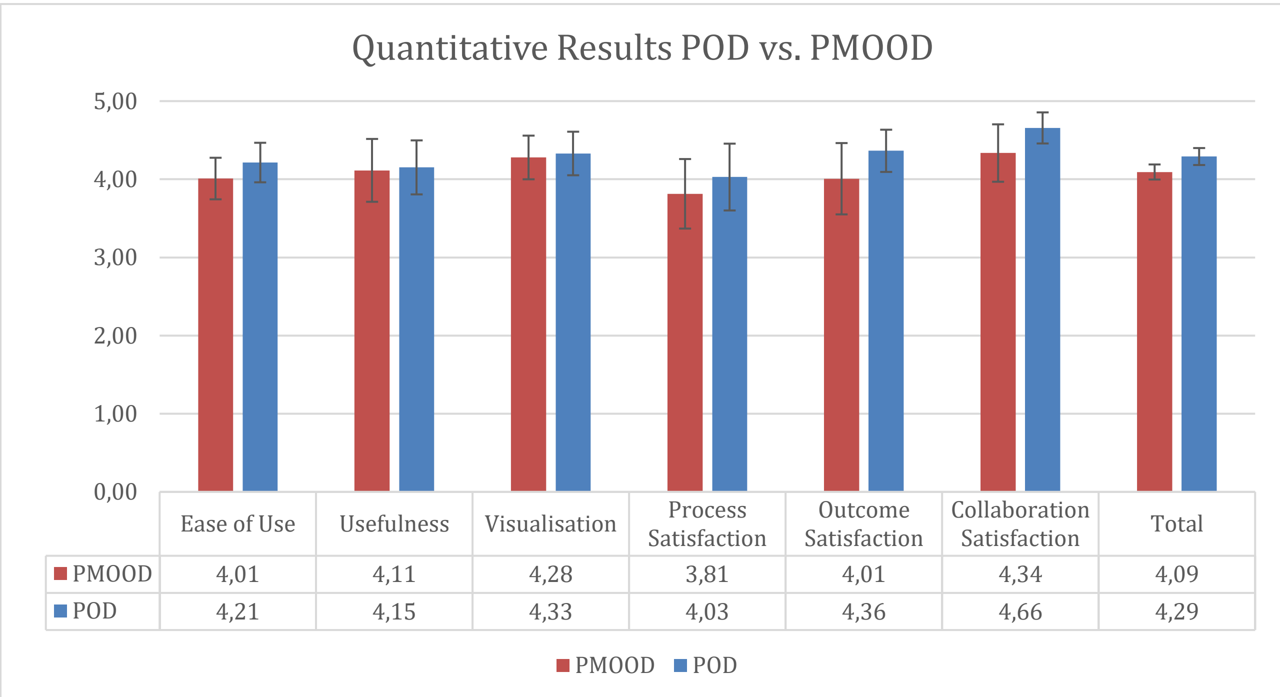

Figure 7 Evaluation approach PMOOD and approach POD regarding all categories for all disciplines

Discussion and conclusion

A parametric optimization and decision support tool was developed (POD tool), and an evolutionary multi-objective optimization algorithm implemented (PMOOD tool) to automate design search for flexible integrated industrial building design. Parametric design is crucial in solving multi-objective problems encountered in industrial building design. Exploring many more design variants when creating relations between criteria takes industrial building design to a new level. A set of solutions is generated when applying MOO algorithms and can further be investigated on quantified findings.

A user study was conducted with thirty-six students, grouped into eighteen design teams, simulating a design process for an existing industrial production facility. The research question of the conducted study was the users' satisfaction with process, outcome, collaboration and technological aspects on both tools (POD and PMOOD). Questionnaires requested feedback on those categories from every participant and concluded quantitative and qualitative results.

Assessing the conducted questionnaires appraised a marginally higher preference of applying the POD tool instead of the PMOOD tool. The manual approach was rated higher in all questioned categories, satisfaction on people-process level and technology. Regarding process, outcome, and collaboration satisfaction, the possibility for collaborative working performed highest for both tools. Also, the qualitative assessment revealed that the participants described the tools as great assistance in early planning phases. Whereas state-of-the-art planning methods apply sequentially working of the different disciplines, the tools make it possible to work amongst disciplines simultaneously. Findings indicate that the students' satisfaction with visualization and collaboration was ranked high. While the tool was seen as beneficial, the categories ease of use, process satisfaction, and outcome satisfaction were criticized.

A restricting condition of the user study was the limited explored design space. The students could not interact with the preset design space of the algorithm since calculation time would significantly delay the user study in time. Thus, it was not possible to let the participants set their preferences on parameters, such as limiting the calculation to their choice of materials. The participants could therefore not investigate the overall best-ranked option of the PMOOD tool considering their chosen preferences while yet industrial building design still is a discipline where stakeholders' desires and experiences are significant planning factors.

Comparing the approaches by discipline and category, results show engineers were more satisfied with the technology regarding the usefulness and visualization within both tools. The fact that engineers find the tool better than architects in this respect is a logical consequence of the tool's composition. The PMOOD tool optimizes structural building variants of industrial building designs and visualizes the primary and secondary structures. Still, architectural students were more satisfied with the tool's ease of use. It could be recognized that the tool can also be used profitably by architects. Sequences that are not necessarily within their concern can be quantified and quickly recorded.

However, the research question revealed a higher satisfaction performing with the POD tool. Despite the overall better performance of the POD tool, the PMOOD tool ratings are in five out of six requested categories on average greater than 4 with the highest possible rating of 5. The high ratings indicate that the tool helps in early planning phases designing more flexible, economically, and ecologically sustainable structural designs for the building's life cycle.

Prospects for further development in research will include simplifying the tool's handling and the user interface as revealed from the feedback of the users throughout the conducted questionnaires. One aspect constantly under development is calculation time. Based on the results of this study the PMOOD tool was coupled to a multi-user virtual reality (VR) platform (Podkosova et al., 2022). The testing of the evaluation of the VR PMOOD tool will be conducted in future research.

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