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Development of BIM-supported integrated design processes for teaching and practice

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ABSTRACT
Building Information Modelling (BIM) promises to integrate the fragmented disciplines of architecture, engineering and construction, and to optimize the life cycle performance of buildings. BIM case studies have been used in university teaching to encourage and support its adoption by the building industry. This paper describes the development, over two consecutive years, of BIM-supported interdisciplinary design labs, involving students of architecture, civil engineering and building science. The performance of, and satisfaction with integrated design processes, and the functionality of the BIM software were evaluated using time recording, surveys and focus group discussions. A standardized evaluation procedure was adopted which allowed comparisons to be made between the two courses, and different results to be directly related to changes in course design. Our main finding over both iterations was that it is difficult to combine training in BIM software with learning about integrated interdisciplinary design processes. The first iteration was severely affected by lack of interoperability between BIM software systems. This was addressed in the second iteration by restricting software combinations to systems that were compatible. Despite significantly improved design quality, the focus in group discussions then shifted to problems with collaboration and teamworking within the interdisciplinary groups. Our results have implications for both the design of interdisciplinary BIM-supported design labs, and for building practice itself. In particular, lessons learnt in the areas of project management, software usage, modelling conventions and incentive mechanisms are directly transferable to the design of BIM-supported integrated design processes, and for practical application by the building industry.

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1. Introduction

Despite a very long and renowned Central European building design and construction culture, today's architecture, engineering and construction (AEC) industry stands at a tipping point. Its highly fragmented and traditional design and engineering methods cannot address the numerous challenges facing the industry, such as climate change, scarcity of energy and resources, an ageing population, the economic crisis, and global competition.

The development of new, collaborative planning methods and approaches, utilizing domain-specific knowledge and expertise, is therefore necessary to address these challenges, and to enable sustainable construction and refurbishment, while preserving economic, environmental and social assets.

Integrated building design (IBD), supported by building information modelling (BIM) as an enabling technology, is advocated as being capable of addressing the challenges of fragmentation. BIM supports more integrated planning and design processes and encourages innovation in the AEC industry (Succar, 2009; Linderoth, 2010) – both of which are urgently needed to address issues the industry is currently facing. However, neither IBD nor BIM is as widely used in Central Europe as they are in the US, UK or Scandinavia (Kiviniemi *et al.*, 2008; McGraw-Hill Construction, 2010). In particular, poor understanding of BIM-related interoperability issues, immature interoperability interfaces, lack of standardized modelling conventions and limited experience of integrated design processes, have all been instrumental in the slow acceptance of IBD and BIM by industry professionals.

In this paper, we present the results of a comparative study of two iterations of a BIM-supported integrated design studio. The paper builds on insights from the first iteration (Kovacic and Filzmoser, 2014), which included an extensive literature review of BIM in teaching and student experiments (Plume and Mitchell, 2007; Poerscheke *et al.*, 2010; Hyatt, 2011; Peterson, Hartmann, Fruchter and Fischer, 2011). The literature review revealed that most BIM studies based on student

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experiments use pre-existing models, or only implement BIM in the later stages. Such studies are mostly based on the optimization of already delivered architectural models in terms of cost, time, and thermal and structural analysis. Where it is used for concept development in the pre-design stage, BIM is still used in a mono-disciplinary, stand-alone manner, essentially replacing computer-aided design courses (Woo, 2007).

The novel aspect of this study is that BIM tools are integrated into the pre-design phase, where the initial 'concept' is developed. This was not the case in previous BIM studies involving students. Hardly any of the available courses have been evaluated quantitatively or qualitatively to gain insights into, or obtain empirical evidence of resource usage, potential benefits or problems. Woo (2007) identifies pedagogical challenges when teaching stand-alone BIM, based on student feedback – also observed in our research – such as the lack of reference projects, and inexperienced students having difficulty getting to grips with BIM.

The guiding research question for this paper is: How can interdisciplinary university courses be designed: (1) to develop effective interdisciplinary modelling and BIM skills and (2) to promote an integrated design approach in a multidisciplinary setting?

The paper links its findings to overcoming practice challenges, in particular to identifying barriers to the adoption of BIM-supported integrated design processes – whether due to discipline culture, modelling approach and so on. Overcoming such barriers is a precondition for an integrated design approach which exploits the full potential of BIM. For this reason, integrated design labs – involving students of architecture, civil engineering and building science – were set-up, run and evaluated over two consecutive academic years. Differences in results were analysed in the context of changes in course design between the two iterations, and the implications for university teaching and practice were derived.

The paper is structured as follows: Section 2, 'Course design', describes how the course evolved over the two years. Section 3, 'Data and method', describes the data collection and analysis methods used to gather the results. Section 4 presents the 'Results' and Section 5, 'Discussion', considers the implications of the results for both academia and industry. Section 6, 'Conclusion', summarizes the major findings and includes final remarks.

2. Course design

The development of interdisciplinary BIM courses is part of the 'BIM_sustain' research project at the Vienna University of Technology, which aims to introduce BIM-supported design into the curriculum, and promote it as a new skill and competence, via an interdisciplinary course: Integrated BIM-supported Design Lab (IDL). The IDL course promotes the development of BIM-specific knowledge to address the needs and requirements of industry – that is, the import and export of models, rules for joint working on models, interdisciplinary project management and so on. Another related aim of the project is to explore the potential and limitations of BIM to support integrated, interdisciplinary design processes. Finally, and in collaboration with the software developers, the project aims to improve the functionality of BIM modelling and simulation software in the AEC industry.

During winter term 2012/2013 and winter term 2013/2014, researchers and lecturers of the Vienna University of Technology established the IDL using student participants from the masters programmes of Architecture (ARCH), Civil Engineering (CE) and Building Science (BS). Because it was inter-faculty, the course had to be embedded differently in each of the curriculums. This resulted in differences in the number of accredited European Credit Transfer System (ECTS) points in each of the study programmes (Tables 1 and 2). An ECTS point represents a workload of 25 hours over the semester; therefore, tasks and deliverables were designed to correspond to the accredited ECTS points for each of the disciplines.

The IDL has two main objectives: (1) to introduce and enhance the BIM skills and competencies of architecture and engineering students by teaching them about BIM software, its use in different professional domains, modelling conventions and interdisciplinary data exchange and transfer and (2) to educate students in integrated design processes based on interdisciplinary collaboration.

In order to achieve these objectives, the course includes a number of specific activities and tasks. In the first week, a kick-off lecture introduces participants to the IDL, motivates them, and makes them aware of the importance of BIM, current challenges and

Table 1. Course details – winter term 2012/2013.

Discipline	Course/ECTS	No. of participants
Civil Engineering	Project Course 6,0 ECTS	11
Architecture	Elective Class 6,0 ECTS	9
Building Science	Project Course 8,0 ECTS	15

Table 2. Course details – winter term 2013/2014.

Discipline	Course/ECTS	No. of participants
Civil Engineering	Project Course 6,0 ECTS	8
Architecture	Design Class 5,0 ECTS	13
Building Science	Project Course 8,0 ECTS	23

interdisciplinary design processes. In the second iteration, a team-building workshop was added for group members to get to know each other, discuss their expectations, and start to develop a concept and first physical model in a building workshop. The next couple of weeks are dedicated to discretionary software training for group members to acquire the necessary software skills – if they do not already have them. A mandatory data exchange workshop then takes place covering BIM-specific software functionality and the exchange of models between software and disciplines. The whole semester is supported by weekly 'crits' (contact times in which the participants can ask questions and receive feedback on their design development and work) and three 'pin-up' presentations each semester, where participants can learn about the progress of other groups, and exchange impressions and feedback.

The teams used different modelling and simulation software configurations for building design and analysis, but were required to jointly develop concepts, and discuss and contribute to the development of the design. The course ran through the winter term, from October to January. It started with the team-building workshop, followed by an intensive one-week design workshop in which a conceptual pre-design and physical models were developed. Architectural modelling, as authoring modelling, started after the first pin-up and discussion of the pre-design. Data exchange, for follow-up analyses (structural and thermal), took place in specially organized data-transfer workshops, with software support. In parallel, participants attended software training workshops, delivered by software developers. Contact class time was offered each Friday for the whole team, as well as two intermediate presentations and one final presentation at the end of the semester.

The deliverables for the first IDL, during winter term 2012/2013, were (by discipline):

Architecture:

- Architectural 3D model, using BIM software, reflecting the spatial and functional specifications; the model had to comply with the sample files provided.
- A rough façade concept, presented as a schematic section; a layout for the structural concept, in collaboration with civil engineers and building scientists.

Civil Engineering:

- Design and dimensioning of the relevant structural elements.
- Load setting, calculation and simulation of the load-bearing structure using the proposed software (*RFEM, SCIA, SOFISTIK*).
- Structural BIM model, level of detail (LOD): design and permit drawings (detailing not required).

Building Science:

- Development of energy concept.
- Building Energy Model (BEM) and thermal simulation.
- Identification of optimization possibilities.
- Calculation of an energy certificate.
- Ventilation BIM model.
- Development of acoustic concept – that is, design and presentation of noise protection measures.

The course over winter term 2012/2013 was named 'BIM_sustain: Integrated Planning Concepts using BIM'. The course objective was to develop an integrated design for an energy-efficient office building with 7500 m^2 Gross Floor Area (GFA). In total, 11 teams (35 students) participated (Table 1).

Teams used software configurations predefined by the tutoring team in order to test the interoperability of all possible combinations of the software packages: *ARCHICAD, REVIT, ALLPLAN, REFM, SOFISTIK, SCIA, PLANCAL, TAS, DIALUX* and *ARCHPHYSIK*.

The course over winter term 2013/2014 incorporated lessons learnt from the first iteration into the course design for the next iteration. Incompatible software configurations caused many problems and much rework, due to the large size of the models. A less complex design objective was therefore set, 'BIM_station', an energy-efficient cultural centre (theatre and artists' studios), GFA = 3000 m^2 – allowing for greater freedom in design, and with software configurations limited to pre-tested and interoperable software. In total, 12 teams (44 students) participated in this IDL iteration (Table 2).

A key finding of 'BIM_sustain', the first BIM-supported IDL over winter term 2012/2013, was that BIM usage does not guarantee integrated design processes. Instead, teams worked together in the traditional sequential manner. Nor does using a common model guarantee an integrated design approach – individual disciplines tended to redraw models for their purposes, because of very significant import and export problems. Also, late completion of the architectural design put pressure on subsequent disciplines and led to tensions within the teams. All of these factors negatively affected the quality of results from the interdisciplinary teams (Kovacic and Filzmoser, 2014).

For 'BIM_station', the second iteration over winter 2013/2014, several changes were adopted to improve integrated design processes and BIM software usage for the student teams. First, standard software support by software firms was extended to include sessions explicitly focused on import and export functionality. Second, the IDL included a lecture on 'How to BIM', addressing common problems and modelling conventions across disciplines when working together on a model. Third, a moderated kick-off and team-building workshop was introduced, as well as an intensive follow-up project design week where architectural, structural and energy concepts were developed and presented collaboratively. This differed from the earlier IDL where each of the disciplines had specific presentations. These measures were introduced to improve team bonding, involve all disciplines early in the project, and facilitate integrated planning and the adoption of integrated design processes.

A strict schedule was introduced to standardize time factors, as far as possible, and to provide a 'designed process' which alternated intensive, collaborative design phases with more focused, introspective ones. Also, software configurations were restricted to those used to support data exchange via functional interfaces.

Deliverables for the second IDL, during winter term 2013/2014, changed slightly, were specified in greater detail, and were (by discipline):

Architecture:

- Presentation of the urban layout concept (1/500 scale).
- Architectural 3 D BIM model, reflecting formal and functional concept (1/100 scale).
- Floor layouts and cross-section (1/200 scale).
- Load-bearing structure layout (in floor plans and section).
- Façade cross-section.

Civil Engineering:

- Structural BIM model.
- Design and dimensioning of the relevant structural elements, and their verification.
- Load setting, calculation and simulation of the load-bearing structure, using the proposed software (*RFEM, SCIA*).

Building Science:

- Development of energy concept.
- BEM and thermal simulation.
- Identification of optimization possibilities.
- Calculation of an energy certificate.
- Ventilation BIM model.
- Development of acoustic concept – that is, design and presentation of noise protection measures.

Table 3. Weighting of evaluation criteria.

Weight (%)	Criterion	Deliverables
25	Joint model	Joint BIM File (as *TEKLA* BIM sight file)
25	Discipline-related model	Architectural file – design in *REVIT, ARCHICAD* or *ALLPLAN* Structural file – structural model in *DLUBAL REFM, TEKLA* or *SCIA* BEM files – simulation, energy certificate
25	Integrated concept quality	Complete planning documentation, BIM files and presentation posters (functionality, energy efficiency, structure)
25	Interdisciplinary collaboration	Protocols Pre- and post-questionnaire workload (time sheet) Participation in focus group

- Development of light concept – verification using lighting simulation software.

The design quality measurement used in both iterations is summarized in Table 3 and is the equally weighted average (each 25%) of four indicators. The joint model (*TEKLA BIM SIGHT* file) was evaluated on technical quality (error-free; correct orientation; correct layers; LOD based on guidelines, quality of geometry). The quality of contribution from specific disciplines included an evaluation of both technical model quality and developed design (i.e. analysis and results). The architectural model was evaluated on technical quality (LOD; error-free; quality of geometry) and on architectural quality. The evaluation of the structural model included error checks, closed joints, correctly represented geometry, and sound analysis and calculation. BEM evaluation covered the validity of thermal simulation, and an error-free ventilation model. Integrated concept quality was evaluated qualitatively, based on the balance of presented architectural form and function, and the structural and energy concept. Finally, the interdisciplinary collaboration of teams was evaluated quantitatively based on their submitting the required protocols, and their participation in questionnaires and focus group discussions.

3. Data and method

The integrated design process and BIM software used in the IDL were evaluated at the end of the semester using two questionnaires with a number of constructs. The integrated design process questionnaire elicited responses to three constructs: 'satisfaction with the process', 'satisfaction with the outcome' and 'satisfaction with the cooperation' – each via four questions on a 5-point Likert scale (1 low to 5 high). The BIM software questionnaire used two major dimensions: 'ease of use' and 'usefulness' of the technology acceptance model (Davis, 1989). An 'interoperability' construct was also developed to evaluate the import/export and data exchange functionality of the BIM software. Each of these three software constructs was elicited via six questions on a 5-point Likert scale (1 low to 5 high). The questionnaires are available from the authors on request.

As well as *quantitative* evaluation of the design process and BIM software – using the questionnaires – focus group discussions were also used for detailed *qualitative* analysis of the iterations (Krueger and Casey, 2009). Focus group discussions allow the collection of qualitative data from a relatively homogeneous group on a specific topic. Due to group dynamics, these data can be both deeper and broader than data from either questionnaires or interviews. In terms of depth, focus group discussions allow interviewers to ask clarification questions, and other participants to react to statements – either supporting or challenging them. In terms of breadth, the importance of topics, as perceived by participants, determines their order and the duration of discussion on each. Unlike a questionnaire, topics can come up for discussion which a questionnaire designer might not have considered – or considered relevant. Focus group discussions are, therefore, especially suitable for exploratory research.

Discussion groups were based on roles, that is, there was a focus group discussion for architecture, for civil engineering and for building science after each of the two IDL iterations. This approach allowed students to exchange experience and information with members of other teams. Discussions were initiated with a general prompt from the moderator ('Describe your experience of the interdisciplinary BIM course'). If discussion stopped prematurely, additional prompts and questions were used, based on topics such as collaboration with other roles during planning, and BIM software use.

The discussions were audio recorded, transcribed and then analysed by two independent coders using quantitative content analysis (Srnka and Koeszegi, 2007). Because focus group discussions were in German, all discussion statements have been translated into English.

In the first 'unitizing step', the content of each discussion was split into 'thought units' that conveyed one single and coherent unit of information. The thought unit is used in analysis – rather than discussion time, for example – because one participant's long and detailed argument might only address one 'content category', and therefore only represent one thought unit. By contrast, a short statement by another participant in the focus group might address several content categories – for example, positive and negative aspects of collaboration. This is why unitizing – the determination of thought units – is necessary as a first step, before coding and content analysis can start.

In the second 'categorization step', a category scheme was developed based on theory and the analysed data. Table 4 lists the content categories used to describe thought units from focus group discussions, and includes

Table 4. Examples for the content categories.

Content category	Description	Example
Collaboration – negative reflections	Everything negative about collaboration and communication with other group members; problems encountered and bad experiences	'We got our.ifc file like one week ago and it's still not the final'[a]
Collaboration – positive reflections	Any positive remarks about collaboration and communication with other group members; best practice and positive experiences	'They supported me at the beginning of the project when I had not that much time'[a]
Confirmation	Confirmation of statements by others	'Yes, that's true'[b]
Course	Remarks about the content and organization of the IDL	'I think the crits were really helpful'[a]
Ease of use	How easy it was to use the software and access the functionality	'But in SCIA changing something was super easy'[b]
General discussion BIM	General discussion between students about their projects	'I found it great, the design process; this is something we do not experience so often during the studies' [a]
Interoperability	All statements about import, export and the interfaces between different software	'He returns the feedback into REVIT and receives a message that there was a problem with one construction part. Then on, has to check this again'[b]
Misc	Discussions on topics that were not relevant to the study	For example, the weather
Moderation	Questions from, and active listening by the moderator	'Similar experiences also in the other groups?'[a]
Suggestions	Constructive feedback for the design of the IDL	'It might be good if the architects have fixed deadlines and then the project moves on'[b]
Support	All statements regarding software support by the software developers	'I had an error when I wanted to make an opening in the ceiling, but the opening was invisible. So I contacted the support … '[b]
Technical discussion BIM	Discussion about technical details of the project in the different disciplines	'Which finite element net size did you choose?'[b]
Training	Discussion about the BIM workshop and software training	'Our REVIT training took two days and was very good. We learned a lot and could ask questions'[a]
Usefulness	Whether the software is effective and delivers correct and useful results	' … it was interesting to see what SOLIBRI is capable of'[a]

[a]From focus group discussions after iteration 2, winter term 2013/2014
[b]From focus group discussions after iteration 1, winter term 2012/2013.

illustrative examples. In the final 'coding step', thought units were assigned to categories. To minimize subjectivity, inter-coder reliability for the unitizing step was controlled for using Guetzkow's U, and for the coding step using Cohen's Kappa.

In the iteration of winter term 13/14, the study additionally included time recording based on weekly questionnaires that participants completed using an online survey tool. We have no data collected on the time spent on different activities in the first iteration (winter term 12/13) so no comparisons are possible for these data. Students had to indicate the total time spent in the previous week on a set of 11 planning process subtasks. These subtasks related to: (1) process, (2) software and (3) people, and were used to analyse time spent during the second iteration of the project (winter term 13/14). The 11 subtasks were:

Process

(1) design – the actual design of the building;
(2) technical planning – thermal and load simulations;
(3) adaptation – design changes based on feedback from other disciplines;
(4) correction – feedback from, and discussions with, course supervisors;

Software

(1) interfaces – import and export of models between disciplines and software solutions;
(2) training – in modelling and simulation software functionality;
(3) external support – solving problems with software support;

People

(1) direct communication – face-to-face meetings of the project team;
(2) indirect communication – communication via email, Facebook, Skype, telephone, SMS and so on;
(3) project management – assignment of tasks, controlling of deadlines for deliverables and so on.

Miscellaneous

(1) time spent on tasks that cannot be assigned directly to any of the other activities (above).

The course instructors collected group time data on a weekly basis and resolved any issues directly with participants – for example, confusion over assigning task categories and so on. Immediate resolution was important because the project lasted only four months and later reconstruction of data would have been impossible. The minimum recorded time period was set to 15 minutes as this level of granularity provided sufficient detail – few project tasks took less than 15 minutes, based on winter term 12/13 observations – and was not too onerous for students. Students were encouraged to be as precise as possible in their time reporting – for example, to split time across categories when multi-tasking. Time recording data were used to evaluate critical periods in the course and workload fluctuation over time, by role and between each of the three disciplines.

4. Results

In order to evaluate IDL design quality, the two instructors independently assessed both project iterations, that is, the 11 groups in winter term 2012/2013 and the 12 groups in winter term 2013/2014. The projects were rated on a 7-point Likert scale ranging from 1 (poor) to 7 (excellent). Correlation analysis revealed high correlation between the two evaluations ($r = 0.91$, df = 21, $p < .001$). The average design quality of the groups was lower in the first iteration (3.45) than in the second iteration (4.54), which indicates an improvement over the two years. Despite the small sample size, a t-test showed that this improvement is statistically weakly significant ($t = -1.92$, df = 18.45, $p < .07$).

Focus group discussions were used to evaluate the efficacy of course tasks and activities from the students' point of view – that is, the kick-off meeting, teaming workshop, model-building workshop, software training, data exchange workshop, pin-ups and weekly crits – all described in Section 2. The kick-off meeting was included in both iterations of the course and was intended to increase student interest and motivation regarding BIM topics and integrated interdisciplinary design within the IDL. By contrast, team-building and model-building workshops were only introduced in the second iteration, in winter term 2013/2014. The intention was to encourage team bonding and joint integrated design working from the start – both of which were seen as weaknesses in the first iteration. The instructors noted improvements in cooperation between the two iterations, and although subjective, some statements from focus group discussions after the second iteration do provide evidence for this: 'We were part of the process, therefore we had some idea what the architect had in mind. It is easier to talk with each other when you know what the other side wants' and 'I believe it is good to learn how other disciplines think and what their perceptions are.' Software training was not regarded positively by students; they saw it as standard training with no specific relevance to BIM; it was regarded as impossible to learn software on such a brief course – better to learn by doing: '… those were standard courses, they are provided every year. They had nothing to do with our project'.

The data exchange workshop – introduced in the second iteration to address multiple problems and conflicts in the exchange of models between group members – received very positive feedback from participants. Some even suggested extending course time spent on data exchange, as it was seen as one of the main course objectives: '… and so I think one should do more work on data export and data exchange'. The 'crits' weekly feedback sessions were also appreciated by participants: 'I think the crits were really helpful'. The pin-up presentations – also part of both iterations – were not explicitly mentioned by students; however, the instructors felt that they were important, otherwise the IDL would lack coherence and risk being just a series of parallel projects. In our opinion, the pin-ups allowed participants to learn about other groups' projects and swap positive and negative experiences of BIM software and integrated design processes.

The remainder of this section analyses the data collected via participant questionnaires, focus group discussions and time recording. As the questionnaires were identical for the first and the second IDL iterations, the responses to the integrated design process and BIM software can be directly compared. The small sample sizes preclude statistical comparison of differences between disciplines, so the statistical comparisons are across all disciplines. The box plots in Figures 1 and 2 show the aggregated results for all disciplines, and individually for architecture, building science and civil engineering (winter term 12/13 and winter term 13/14). Figure 1 shows the results for the integrated design process questionnaire, and Figure 2 for the BIM software questionnaire. The response rate among participants – that is, those who answered the anonymous integrated design process and BIM software questionnaires – was 32 out of 35 for the first course (response rate 91.4%) and 32 out of 44 for the second course (response rate 72.7%). All six constructs yielded satisfactory validity values – Cronbach alpha above 0.7 for all six constructs – so we were able to calculate means for the four integrated design process items and the six BIM software items, for use in the subsequent analysis.

Figure 1 illustrates how 'Process Satisfaction' with integrated design processes, for all disciplines aggregated, differs only marginally between the winter 12/13 and winter 13/14 courses. 'Outcome Satisfaction' and 'Cooperation Satisfaction' (within the planning team) for all disciplines seem to be slightly lower for the winter 13/14 course; however, the differences are not statistically significant. This result surprised the course designers, as they had expected the team-building workshop, in particular, to have a positive effect on cooperation satisfaction within the team. Similarly, the design week and tighter schedule had been expected to have a positive effect on Process Satisfaction, although negative aspects of these interventions may have outweighed the benefits. The quantitative, and particularly the qualitative content analysis (below) sheds some light on this.

As regards evaluation of the BIM software, Figure 2 illustrates similar results for 'ease of use' and 'usefulness' – unsurprisingly, as software functionality did not change significantly over the six months between the two courses. However, BIM software 'interoperability' on the 13/14 course was regarded as significantly better than on the 12/13 course ($t = -2.338$, df = 89.54, p-value = .02162). This is probably because supervisors limited the software configurations on the 13/14 course to those that had interoperated relatively well on the 12/13 course.

Table 5 describes the participants in the six focus group discussions – three after each IDL iteration. Each discussion took on average one hour. Figure 3 illustrates the analysis which was described in the previous section. The 'content category' codes (on the x-axis) can be subsumed under three broad groupings: (1) process, (2) software and (3) participants – similar to the subtask groupings used in time recording. In addition to these groupings, the context in which BIM planning took place was also discussed, that is, the university course and suggestions on how to improve its design. An additional block of communication can be categorized as group discussion (*moderation* – i.e. speaking time by the moderator, for questions and so on – and *confirmation* – interjections like 'yes', 'hmm', 'exactly', etc.).

In line with the results of the integrated design process questionnaire, significantly more statements describe negative aspects of collaboration with team members in the second than in the first IDL iteration, and more statements describe negative aspects of collaboration than describe positive aspects. Software also became less of an issue, mainly because participants could choose the software instead of being assigned to the software they claimed to have most experienced of – the assignment method used in the first iteration. In particular, interoperability was no longer an issue because the second iteration only used interoperable software configurations.

In order to investigate the reasons for the lower process and collaboration satisfaction reported in the

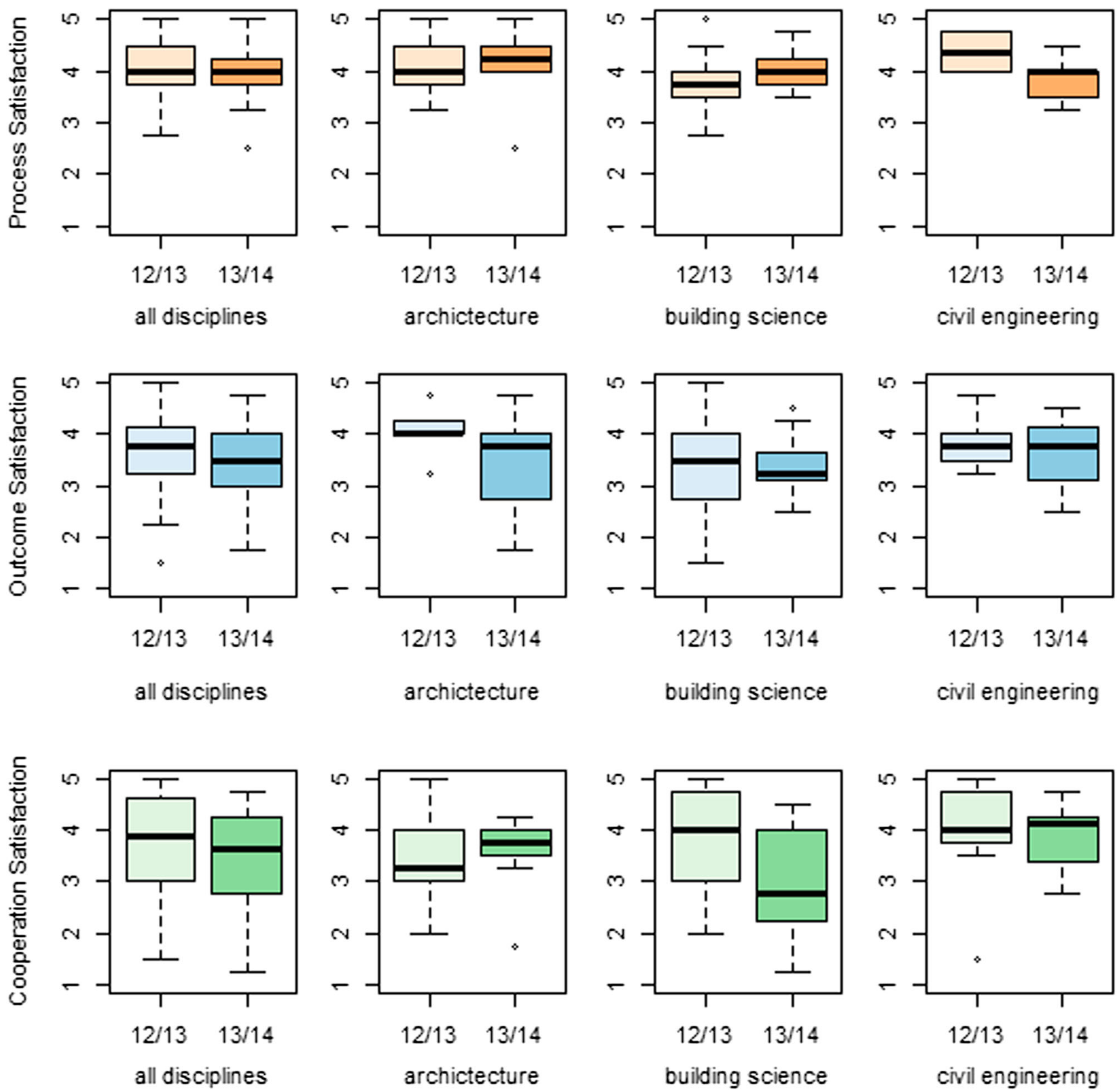

Figure 1. Evaluation of satisfaction with the integrated design process.

questionnaires, and the higher number of negative statements about collaboration in focus group discussions, qualitative content analysis was applied to the transcripts. The analysis revealed that participants in both iterations appreciated the interdisciplinary aspect of the IDL. In the second iteration, building science and civil engineering students appreciated the interdisciplinary aspect even more, because they gained insights into the architectural design phase as a result of their involvement in the team-building workshop and the design week. However, the higher satisfaction of 'later' disciplines with the integrated design process came at the expense of the architecture discipline. Architects consistently reported feeling time pressure, and that their creative process was constrained – through supervision, influence and restrictions – as a result of the close interaction with other disciplines in the early phases of the integrated design process. This may help to explain why negative aspects of the interventions outweighed the benefits – as described above.

Turning to BIM's positive effects on collaboration, BIM requires representatives from different disciplines to work on a joint model. This fosters interdisciplinary communication and coordination within teams, and the focus group discussions elicited many examples of the resulting benefits (under the content category

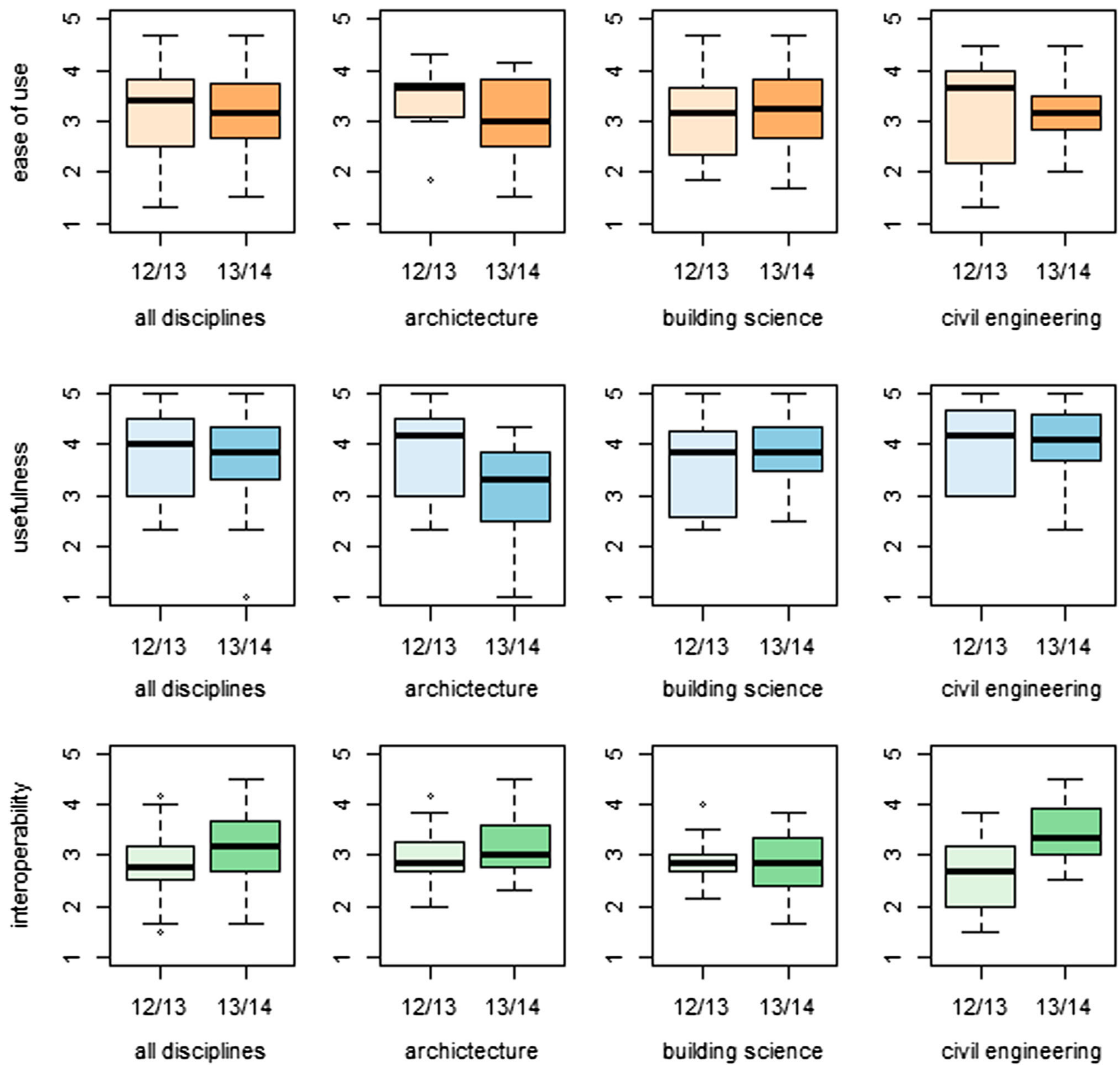

Figure 2. Evaluation of the BIM software.

'collaboration positive' – see Figure 3). These benefits included: (1) innovative ideas from other disciplines for architects in the early design stage; (2) better definition of basic processes – thus avoiding later revisions – as a result of the involvement of disciplines which would otherwise only be involved much later in the building planning process; (3) improved motivation and identification with the project by civil engineering and building science disciplines, due to early involvement; (4) better understanding of the operations and requirements of other disciplines involved in a project and so on.

Table 5. Focus group participants by year and role.

Role	Winter term 2012/2013	Winter term 2013/2014
Architecture	9	13
Building Science	15	20
Civil Engineering	11	7
Teams (total)	11	12

Figure 4 shows the time recording results, based on tasks identified in the first IDL iteration. The results are quite consistent across the disciplines involved. Technical planning and analysis are the most time-consuming tasks for civil engineers in the groups, while design corrections and actual design are more time-consuming for architects. The average total time groups spent on the project in the second iteration was approximately 880 hours, which equates to approximately 160 hours per participant.

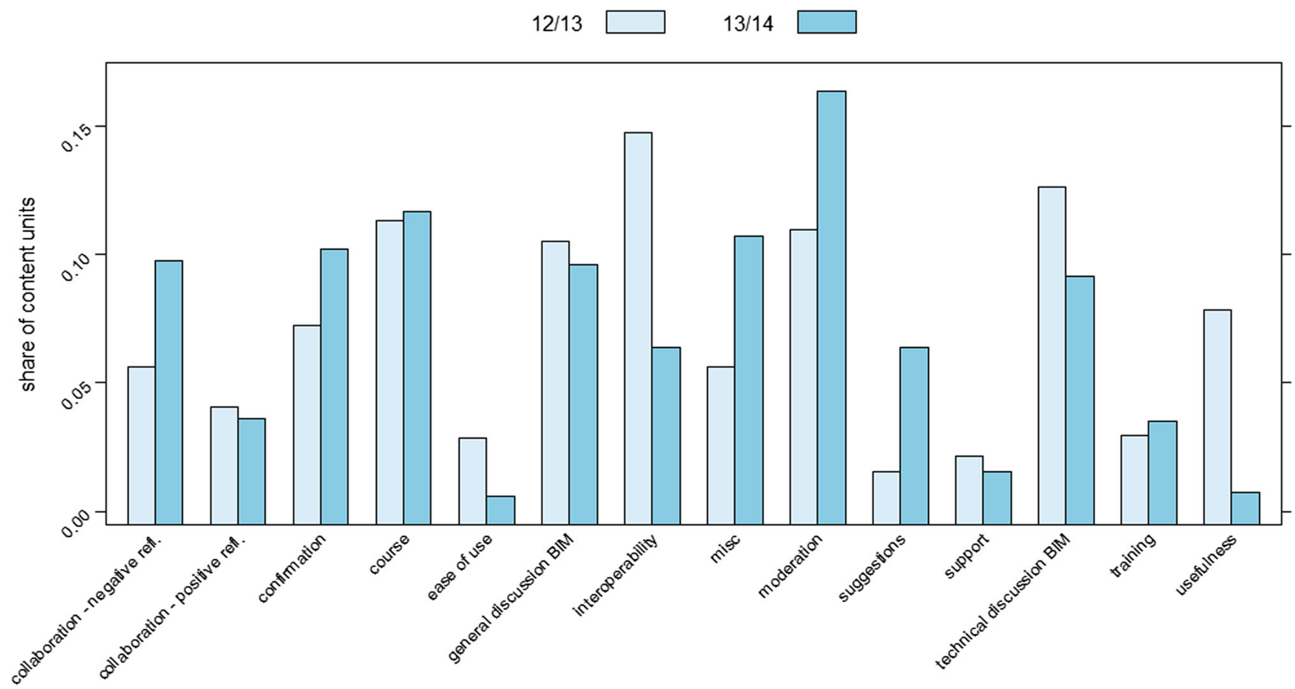

Figure 3. Analysis of the 2012/2013 and 2013/2014 focus group discussions.

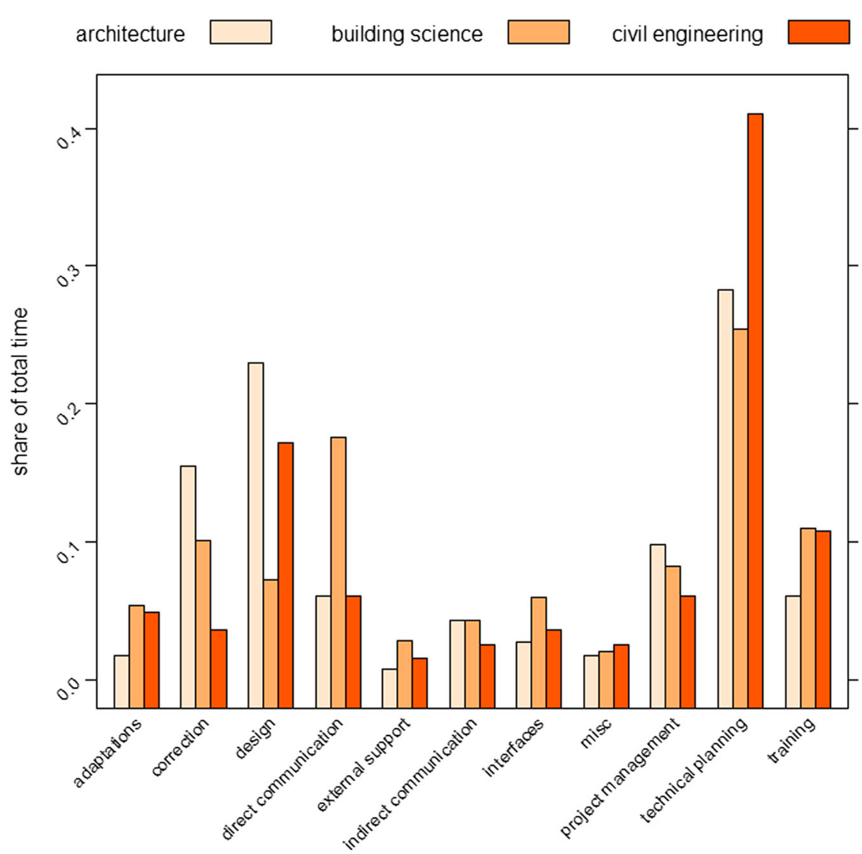

Figure 4. Activities of the disciplines (share of total time) in the second course 2013/2014.

5. Discussion

As BIM education is a relatively young discipline, most traditional universities do not yet run basic BIM courses on which students can learn 'the first steps'. For this reason, courses such as IDL are used as platforms for teaching both basic BIM software skills and interdisciplinary BIM-supported collaboration. This sets very high expectations on IDL that can hardly be met in one semester, and can lead to excessive pressure on both lecturers and students. The dilemma for BIM teaching – which has already been recognized by the academic community (Bercerik-Gerber *et al.*, 2011) – is whether to focus on acquiring the required software skills, or to focus on data exchange and interdisciplinary collaboration where students are expected to already have a certain level of skill and experience.

Barison and Santos (2010) developed a proposal for a BIM curriculum consisting of three stages – from the acquisition of basic skills through to interdisciplinary collaboration – which was based on a framework proposed by Kymell (2008):

- Introductory: digital graphic representation, acquiring software skills.
- Intermediary: integrated design studio, acquiring conceptual skills.
- Advanced: interdisciplinary collaborative design studio, acquiring social skills.

In our opinion, the full potential of BIM is best realized through interdisciplinary data transfer, and only to a lesser extent via mono-disciplinary modelling. The acquisition of BIM software skills can start during bachelor studies. In master studies, however, the focus has to shift towards interdisciplinary collaboration – that is, intermediary or advanced level (as above). At graduate level, students should already possess modelling skills, and can concentrate on data exchange and interdisciplinary collaboration. This approach also aligns with the European educational system in which bachelor studies focus on extensive teaching of the fundamentals, and the focus shifts to application and specialization during master studies. The phased introduction of BIM in bachelor and master courses reflects this educational tradition, and the separation of theoretical and practice-oriented study has encouraged acceptance of the curriculum changes required to integrate BIM into university education. As the majority of students in the EU obtain a 'masters' after their bachelor degree, there is less risk of them receiving only a partial BIM education. The reason for the higher number of masters compared to bachelor degrees is that much of EU industry considers bachelors – with basic education but no specialization or application – as 'unemployable'.

Comparing the two IDL iterations, the first was characterized by sequential work, with modelling tasks carried out in consecutive order. The groups did not feel themselves to be part of a team until the last presentation, when a joint model was finally created. For the second iteration, we therefore introduced a number of team-building events, to promote process and team integration, such as a kick-off meeting, a team-building workshop and a one-week design workshop. The main challenges during the first iteration were technological – around interoperability and non-functioning interfaces – whereas the challenges during the second iteration were around collaboration, including leadership and work organization. Despite the planned interventions during the second iteration – that is, the team-building workshop, the design week and a tighter schedule to reduce pressure on later disciplines – process and cooperation satisfaction did not improve. The architects in particular responded negatively to the interventions because the measures were perceived as reducing creative freedom and increasing time pressure on them. The interventions were regarded positively, however, by building science and civil engineering, because they increased the influence of other disciplines during the design phase.

A further explanation for the lower satisfaction could be that group members adopt a 'team challenge' mentality and push each other on, which may result in higher design quality – which we observed in the second iteration – but may also reduce cooperation satisfaction within the team, as a result of discussions, conflicts, additional work and so on. However, the focus group discussions did not elicit evidence for any of these possible relationship issues.

Software issues (like usefulness and ease of use) were less significant in the second IDL iteration, probably because participants could choose which software to use. Interoperability also improved because software configurations were limited to those that had worked successfully, in terms of interoperability and data transfer, during the first iteration. This was also reflected in questionnaires and focus group discussions where interoperability was assessed favourably and no longer considered a relevant topic for discussion.

The second IDL achieved slightly higher design quality, possibly because participants could focus on how to exploit the technological possibilities of the tools to implement their design ideas. There were fewer problems and less time spent on technical concerns about software. Focus group discussions revealed that the majority of participants in most teams appreciated integrated design practices, particularly civil engineers and building scientists who felt more involved in the conceptual architectural design. Some architects, on the other hand, felt pressure from other disciplines and restrictions on their creative expression.

6. Conclusion

This paper addresses the design of BIM-supported IDL to implement BIM education at university level, in order to provide students from different disciplines with BIM skills and experience. The underlying premise is that BIM supports process integration and can thereby reduce fragmentation and increase innovation in the AEC industry. In two iterations of an IDL, with students from architecture, civil engineering and building science, we compared different course designs. The comparisons were based on: design quality; satisfaction questionnaires on both the integrated design process and the BIM software; focus group discussions with participants and time recording by groups.

Regarding the integrated design approach, and based on the generally positive feedback from participants in focus group discussions, we conclude that BIM can act as a catalyst for more integrative design practice and for building a shared knowledge base between specialist disciplines. In both iterations and for all disciplines (see the content category 'general discussion BIM' in Figure 3), focus group discussion participants emphasized and acknowledged the insights and contributions they had received from other disciplines while working in an interdisciplinary group on a joint project using BIM.

For example, after the second iteration over winter term 2013/2014, participant comments (translated from German) included: 'it has been a very good experience to try to combine disciplines' and 'something like this project is not usual in our studies'. Participants specifically described having improved insights into the whole project, and how they would consider the same approach in their own work: 'We were part of the process. Therefore, we had some idea what the architect had in mind. It is easier to talk with each other when you know what the other side wants' and 'I believe it is good to learn how other disciplines think and what their perceptions are'. This improved understanding by the group was well illustrated in the very 'concrete' example of the building façade:

> … especially during the design process at the beginning one saw, I don't know, for example the façade. I did not know why the façade had to look this or that way, and then the architect tried to explain it a bit – perspectives, axes, and so on.

However, introducing BIM alone is not sufficient: a carefully designed process, as well as experience and skills in interdisciplinary design, needs to be developed as part of a university programme. A novel aspect of the curriculum –interdisciplinary collaboration – was highly valued in student feedback, because traditional curriculums do not normally incorporate such an approach. It was also a novelty for students because interdisciplinary work and collaboration have to be learnt, and take time to learn.

As other researchers have noted (Dossick and Neff, 2011), BIM tools can facilitate the transfer of explicit knowledge; however, they are too inflexible to handle implicit knowledge. New tools and methods have to be found to support the creation and transfer of implicit, data-rich knowledge within interdisciplinary teams during the earliest planning stages. In this respect, a potential obstacle to BIM was illustrated in the negative feedback from architects, who described 'collaboration inhibiting creativity'. Practising architects in German-speaking regions are traditionally sceptical about BIM because they fear it will limit their creativity.

There is also a financial penalty in adopting BIM technology, especially for smaller offices. BIM-supported processes are more time-consuming and coordination-intensive than traditional ones. Significant effort has to be invested in the pre-modelling and process-design phase to establish modelling conventions and standards. It is questionable whether the highly fragmented Central European AEC industry is ready for this level of process change. In order to change the current rationale of the AEC industry – which is also reflected in the education system – new curriculums need to be adopted to develop future change agents for the industry. Participants in integrated design labs can act as such agents of change, by understanding the opportunities to adopt new technologies – like BIM or computational design – and combine them with early-stage collaboration in planning processes.

But changes to the education of future designers and engineers – to incorporate integrated design processes and improved planning practices – will not, alone, be sufficient to drive acceptance and dissemination of BIM and integrated design within the AEC industry. Building on appropriate university courses, the essential next step is to raise *investor* awareness of the benefits of BIM-supported, integrated design processes.

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