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EVALUATION OF LEVEL OF DEVELOPMENT IN STUDENTS' DESIGN MODELS IN ENGINEERING EDUCATION

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Abstract

Designing is a process, which requires designers with high levels of knowledge, skills, and competences with respect to design modelling and knowledge management. Much focus has thus been extended towards collaboration and development of well-defined models, without, however, evaluating the current level of development of design models or knowledge, skills, and competences of designers. This study, therefore, presents an investigation of design models from a learning event for students of architecture, engineering, and construction, evaluating the current level of development of design models and a discussion of how to improve learning events in engineering education.

Introduction

Designing buildings is a complicated process involving a multitude of actors, tools for geometric, and informational modelling and simulation, as well as various organisational, procedural, and legislative affecting factors. Every building project is, additionally, unique in its nature (Zou and Tang, 2012; Molwus, Erdogan and Ogunlana, 2017), making every design management process complex and hard to manage, even for experienced project managers.

The design and pre-construction phases, significantly affect the building process and quality of the building when it is constructed, calling for synergy between pre-construction and construction as the two main phases (Mpofu *et al.*, 2017). Planning before construction initiates, through carefully considering the project, its obstacles and processes, increases the likelihood of success, as described by Larsen *et al.* (2018), who further add that quality pre-planning is one of the key parameters which must be handled to ensure high performance with respect to time, cost, technical issues and end-user satisfaction. Time, cost, and quality is, as described by Radujković, Sjekavica Klepo and Bosch-Rekveldt (2021), furthermore, the traditional project success criteria, also known as the "iron-triangle", in which project success is measured.

One of the most important factors affecting efficient interdisciplinary design processes and pre-construction phases, is the availability of design knowledge, such as design intent, describing the objectives, constraints, functions, and goals of a design (Peña-Mora et al., 1993) and the design rationale, describing why a solution is the way it is (Lee and Lai, 1991), as well as the explicit documentation of alternative solutions (Wyke, Lund Jensen and Svidt, 2021).

Such design knowledge, including design intent, and design rationale can additionally, if accessible, increase design productivity, which can improve the overall quality of a product (or design) (Peña-Mora, Sriram and Logcher, 1993; Otey *et al.*, 2018; Wyke, Lund Jensen and Svidt, 2021), in addition to being a foundation for better decision making (Wyke, Lindhard and Larsen, 2023).

Only limited research has, however, been conducted focussing on the documentation of design intent and rationale on design projects in the Danish Architecture, Engineering, and Construction (AEC) industry, and no research has been identified in the process of writing this paper, attempting to quantify and analyse the level of development of such design models in the Danish AEC industry. It is, however, important to investigate the Level of Development (LOD) and discuss to which degree knowledge is shared in design models, in order to understand how to improve the knowledge exchange between actors in the interdisciplinary projects characterising the AEC industry. Development of knowledge, skills and competences needed for developing design models with high levels of reliability, geometry, and information, has additionally not received much attention in the existing body of scientific literature.

In the Danish AEC industry, LOD in design models is commonly defined as the combined state of the level of reliability (LOR), level of geometry (LOG) and the level of information (LOI). In this study, LOR is defined as, the reliability of the information provided for the building part and its properties. LOG is defined as, the building parts' geometric representations and the extent of secondary components/parts, whilst the LOI is defined as the building parts' properties contained in, linked to, or in some other way connected (DiKon *et al.*, 2019).

According to Tribelsky and Sacks (2010) slow and interrupted information flows can lead to significant waste on a project, which explains why design information is essential to manage efficiently in the AEC industry. In addition, it is imminent that it is the correct and agreed upon information which is exchanged and that it is accurate, and useable throughout the building's lifecycle, and in the building information management process (Penttilä, 2006; Succar, Sher and Aranda-mena, 2007).

Multiple advancements have been made at educational institutions, in order to develop curricular and non-curricular learning, which allow students to develop professional work knowledge, skills, and competences in interdisciplinary design and collaboration, before entering the AEC industry. One of such events is The Digital Days, which is a reoccurring annual learning event, focussed on interdisciplinary learning and utilisation of digital tools for AEC (Gnaur, Svidt and Thygesen, 2015). The event furthermore functions as a simulation of the industry the students will enter after graduating their education. At this event, the students work interdisciplinarily with a design project, in a "safe-to-fail" environment, allowing the students to experience "real world" problems and work-conditions of the industry before entering it (Wyke *et al.*, 2022). The Digital Days, additionally, facilitates a learning scenario resembling workplace learning, in which competences can be developed, preparing students for jobs already available in the industry, as well as jobs which do not yet exist (Römgens *et al.*, 2020), and experimentation of how to work interdisciplinarily when documenting, storing, and sharing knowledge.

In the currently available body of scientific literature, it has not yet been evaluated if development of knowledge, skills and competences on learning events, such as the Digital Days, is reflected in the design models, developed during such events, and no previous analyses have been conducted evaluating the correlations between the LOR, LOG, and LOI, and the competences of those developing design models (DiKon *et al.*, 2019), to the knowledge of this author.

This paper, therefore, answers the question: What is the current LOD in architectural design models at the Digital Days and which factors can be identified affecting the LOD, in terms of knowledge, skills and competences?

In the next section, the methodology applied for answering the research question is presented, whilst section three presents the results and discussion of the analysis. Section four, finally, presents the conclusion of the study together with the perspectives for further research.

Methodology

The methodologies utilised for this research can be divided into two categories, the data collection and the data analysis, which are presented after an introduction of the overall research design.

Research design

The data collection was conducted at the Digital Days learning event in Northern Denmark in 2019, 2021 and 2022, in which the 3D models developed by the participants were collected as well as other project relevant materials and information.

Since 2019 the Digital Days has been held three times. In 2019 as a physical event, in 2021 as an online event, due to the Covid-19 pandemic and in 2022 as a hybrid event, with most participants engaged in the event physically, and with some taking part in the event online using Microsoft Teams. The event was also planned for 2020 but was cancelled due to the Covid-19 pandemic.

Each project team, at the event, consisted of various disciplines with approx. eight participants on each team in 2019, 22 in 2021 and 20 in 2022. A list of teams and number of participating students in 2019, 2021 and 2022, is shown in table 1.

Table 1 Number of participants at the evaluated Digital Days event, divided by teams and year.

Participants in	**2019**	**2021**	**2022**
Team 1	6	23	21
Team 2	8	23	22
Team 3	7	23	21
Team 4	7	23	22
Team 5	6	23	21
Team 6	7	23	21
Team 7	7	23	21
Team 8	6	22	17
Team 9	8	22	18
Team 10	7	22	
Team 11	12	20	
Team 12	10	22	
Team 13	11	21	
Team 14		19	
∑	102	290	184

A majority of the participants in 2019 were from the bachelor programme of architectural technology and construction management (ATCM), which has been the programme in which the event has been anchored since its introduction in 2009. However, in 2021 and 2022 approximately half the participants were from other educational programs than ATCM.

In 2019 the projects, the students worked on, during the three-day event, were based on the semester project at the ATCM bachelor programme, whilst the projects in 2021 and 2022 were event-based projects with no direct connection to any of the participating educational programmes. Hence, it was made possible in the analysis of the design models from the different years, to identify the difference between design models rooted in curricular activities, such as in 2019, and a unique event-based assignment, as were the case in 2021 and 2022. As the events were also different with respect to how they were conducted from year to year, it was furthermore made possible to analyse if design models were affected in terms of LOD based on the event being a physical, an online or a hybrid event.

At the Digital Days in 2019 the participants worked with a design project with an initiating level of development (LOD), based on the work of students at the ATCM programme at one of the participating institutions based on the same assignment, whilst the model used in 2021 and 2022, was a building design in a very low LOD.

In all iterations of the event, the participants were, handed a list of criteria for evaluation of their projects, two weeks before the event started, of which one of the criteria were that models should be classified using the BIM7AA specification (DiKon *et al.,* 2019). The participants then initiated the design process when the event officially began, working on designing their building to a quality suitable for the initial design phase and the level of design development as specified in the Danish AEC industry (FRI og Danske ARK, 2012).

The design reached through modelling the design in 3D and through utilising 3D-based analyses, was subsequently uploaded to an online tender platform, after which it was evaluated by an appointed committee for the event. This procedure was chosen to allow the participants to experience the practice of project handover, as it is done in the Danish AEC industry. The upload to the tender platform contained all documents and files developed throughout the event, thus providing the authors of this paper with the Autodesk Revit models, which were utilised in the data analysis.

Data collection

The data collection was divided into two steps. Firstly, a collection of relevant scientific literature, and secondly, the collection of data from the case-event.

Literature collection

The literature collection for this research was based on a key-word search in the Scopus database, focussing on knowledge management, design and pre-planning, engineering education and problem-based learning. The literature was, finally, analysed and implemented in the research, guiding the analysis of the collected data from the case-event, as well as the discussion of the results.

Quantitative data collection

The data collection was conducted over a four-year period, using an online repository to store the design models from the event from year to year, copied from the tender platform which was used for project handover at the event. A list of participants (in a person unidentifiable format, describing only disciplines and roles of the participants during the event) was also stored in the repository, as well as the case-descriptions and requirements for each iteration of the event.

Data analysis

The data analysis consisted of a quantitative ranking of the architectural 3D (.RVT format) model, from each project group on the case-event divided by year. The ranking of the models was focused on four specific components in the models in similar locations in each model. Those components were: the exterior wall, the 1st floor deck, the 1st floor window and the building roof. The components were chosen due to their commonality in all buildings. Each component was then ranked based on the BIM 7AA specification (DiKon *et al.,* 2019), on a scale from 0 through 4, with respect to LOR of a building component, LOG and the LOI. A rank of 0 was equivalent to not fulfilling the generic LOR, LOG or LOI, whilst a rank of 4 was equivalent to reaching a final production and classification level of the component.

The ranking was performed by a building informatics expert with a background in ATCM and design modelling, which was audited through sampling of 10 per cent of the rankings, by another building informatics expert. The first auditing of the ranking revealed a 2,7 per cent ranking discrepancy, which was then rectified through discussion between the person who originally ranked the components and the auditor. When a discrepancy was revealed based on the sampling, an additional sampling of 10 per cent of the rankings was performed. When auditing revealed no discrepancy between the original ranking and the auditing, the ranking and quality control process was completed.

After ranking the models, a factor correlation analysis was performed using MATLAB R2022a. Because data was found not to be normally distributed, the Spearman's ρ test was applied.

Correlations were interpreted in accordance with Dancey and Reidy (2004), entailing that:

- 0.00- 0.19 no relationship
- 0.20-0.29 weak relationship
- 0.30-0.39 moderate relationship
- 0.40-0.69 strong relationship
- 0.70-1.00 very strong relationship

Results and discussion

The analyses of the collected data showed that the average LOD from project to project and year to year, did not vary

Table 2 Correlation analysis between number of participants, project m² and LOD of the design model objects. Strong and very strong correlations are marked with bold.

	No. Participants	Project m²	LOD: External walls	LOD: Floors	LOD: Windows	LOD: Roofs
No. Participants	1	**-.82**	.06	.15	**-.65**	-.30
Project m²		1	-.02	-.24	**.59**	.21
LOD: External walls			1	**.57**	-.02	**.40**
LOD: Floors				1	.09	.15
LOD: Windows					1	.25
LOD: Roofs						1

significantly, even though the design projects varied notably from 2019 to 2021 and 2022. This is an interesting result, based on the fact, that 2019's event was conducted as a physical event, whilst 2021 was purely an online event, and 2022 was a hybrid event.

Overall, the LOD of the models from year to year was mediocre, with an average of 1.53 on a scale from 0 through 4, with the average LOD across the analysed objects being 1.74 in 2019, 1.46 in 2021 and 1.40 in 2022. This could indicate either, a general lack of interest in participating in the design process, or a lack of skills and competences. Interestingly, a lack of knowledge did not seem to be the case, when evaluating the models from a qualitative perspective, as most models actually showed an understanding of how to e.g., classify a design objective in Autodesk Revit, with models having implemented the framework for structuring object classification, yet without having it filled in. Correlation, with respect to the LOD from year to year, was furthermore, insignificant with no or weak correlations, except between floors and external walls and roofs where large correlations were found. This finding shows that well-defined geometry and information on one object on a project, did not entail a well-defined geometry or information for other objects in the same project, as shown in table 2. However, between some areas weak correlation were observed.

Only two areas in the analysis of correlation between factors showed a strong or very strong negative correlation between elements. The two correlations were number of project participants and the m² area of the project model, and number of project participants and window LOD. The first correlation can be explained through the project in 2019 being bigger than the projects in 2021 and 2022, whilst the number of team participants were significantly higher in 2021 and 2022, compared to 2019. For the second correlation, however, there does not seem to be an obvious explanation for the causality between factors.

Looking at the analysis on an object level, windows in 2019 were ranked significantly higher in terms of LOD, compared to 2021, and 2022, and especially the LOR was ranked higher in 2019. This can be explained by the fact that most of the projects, in that year, imported their windows as BIM objects from a vendor platform. As the LOI in 2019 had an average of 1.62, whilst the two other years had a LOI of 1.0, it was furthermore highlighted, that the missing link with respect to e.g., windows, is to be found in the effort made by the designers, in terms of not only downloading and implementing an object, but also classifying the object, as well as adding supplementary information about the intent and/ or rationale.

Another element of the design process which can be identified, looking both quantitatively and qualitatively on the data (and models) is the sense of ownership the participants reflected upon the models in 2019, compared to 2021 and 2022. This is evident looking at the information, the objects were supplied with, regarding energy performance parameters and fire ratings. A type of design knowledge, which is not present in a design model if no attempts are made to implement them by a designer, either through modelling the various layers of a wall, floor or roof, or through manually typing such data onto an object, using the "edit type" function in Autodesk Revit.

In 2019, most projects were equipped with objects with energy performance parameters, such as U-value available, especially when it came to wall and roof objects. This was not the case for projects in 2021 and 2022, which had barely any of such information available. It is notable in this regard, that the projects of 2021 and 2022, were not founded in the curricular projects of any of the participants. Hence, it can be argued that the ownership of a design (model) is bigger, if the design (model) is useable for the participants and can benefit the them later in their curricular activities, which presents an argument for founding the project the students work on at the Digital Days in curricular activities, in order to increase engagement from the participants, leading to more reliable and better geometrically modelled and informative design models.

This way of only documenting knowledge in a design model, due to how it can benefit the designer, and not those whom the model is later shared with, is in line with

Table 3 Correlation between LOR, LOG, and LOI. Strong and very strong correlations are marked with bold.

		Exterior wall			1st floor deck			Window			Roof		
		LOR	LOG	LOI	LOR	LOG	LOI	LOR	LOG	LOI	LOR	LOG	LOI
Exterior wall	LOR	1	**.79**	**.66**	.37	.36	**.41**	.02	.03	.05	.39	.12	**.46**
	LOG		1	**.47**	.32	.37	**.42**	-.11	-.06	.06	.31	-.05	.38
	LOI			1	**.63**	**.53**	**.64**	-.07	-.05	.14	.21	.04	.34
1st floor deck	LOR				1	**.92**	**.87**	.01	.17	.19	.14	-.23	.27
	LOG					1	**.81**	.00	.17	.13	.07	-.29	.21
	LOI						1	-.18	.00	.10	.16	-.21	.25
Window	LOR							1	**.78**	**.65**	.17	.09	.33
	LOG								1	**.57**	.22	.04	.35
	LOI									1	.17	.10	.34
Roof	LOR										1	.57	**.89**
	LOG											1	**.50**
	LOI												1

existing research, in which Brandt *et al.* (2008), argues that making knowledge explicit can lead to employees weakening their positions as indispensable knowledge holders, hence facilitation their own replacements in an organisation. Documentation of design decisions or rationale is, furthermore, often seen as an unacceptable overhead by designers (Lee, 1997), as benefits are typically to be found later in the design process (Brandt *et al.*, 2008), withholding designers in sharing their knowledge, with later model users, as it will mostly benefit others.

Knowledge sharing through a model, is nonetheless not limited to benefitting users of a model when the model is handed over. Benefits are also available whilst modelling, and when communicating with other project participants, based on what is modelled, utilising the design model as a knowledge repository, explaining what has been done, what should be done, as well as why. A model that allows the design rationale to be explicitly stated are, additionally, more easily manipulated or changeable, which, summarised by Peña-Mora *et al.* (1993), leads to a more intelligent use of knowledge and resources, as reasons or justifications which are lost during the initial design stages can result in the need to define solutions over and over again, resulting in increased project costs and more importantly, in project delays. Design knowledge, such as rationale is, however, often only documented on design projects on handwritten notes, post-its or in the memory of the designer (Wyke, Lund Jensen and Svidt, 2021), making it hard to exchange explicitly, due to its informal nature and lack of being computer-readable.

Lee (1997) and Burge and Brown (2008), additionally, describe how formalised knowledge is costly, and if too costly, will outweigh its benefits, arguing for a need for a structured method for producing design rationale. Yet, in the context of the Digital Days, where cost is not an issue, the lack of design knowledge capturing and exchange, seem to be stemming from lack of participatory motivation or lack of skills or competences, with respect to how to document it. Lack of knowledge of how to document design knowledge can, additionally, be a reason for why it is not done by participants at the Digital Days, as well as in the industry. As highlighted by the analyses of design objects in the models from the Digital Days, a propensity to focus on making a model look good in terms of geometry seems to prompt the way the design models are developed, rather than the need for information and knowledge which is required from the model, if the design were to be built. As also argued by Burge and Brown (2008), design rationale, (or design knowledge) is only useful if the developers or designers use it. However, in order to use it, the designer must be aware that knowledge can be documented and how to do it and understand in which circumstances it can benefit the designer, as well as current and future collaborating project participants.

Analysing the correlation between LOR, LOG, and LOI further, it is obvious that most of the LOD correlations on the analysed projects were insignificant or weak, and that the modelling processes the participants had utilised was not based on a formalised modelling strategy.

Interestingly, a correlation between the LOI of the 1st floor decks and the LOR, LOG, and LOI of exterior walls, was observed to be strong or very strong. A correlation which can be explained through understanding the modelling process, which is similar for modelling of walls and decks in Autodesk Revit. The LOR and LOG additionally showed a high correlation with respect to the LOI.

Focussing on exterior walls, the analysis showed that the LOR had high impact on LOG and LOI, which makes sense, as well-informed geometric objects must be more prone to scoring high in terms of LOR, than non-informed geometric objects. The correlation of LOR, LOG and LOI for the exterior walls is, additionally, observable for 1st floor decks, windows, and roofs, as shown in table 3.

The insignificance in correlation between the analysed factors is an interesting result, as the LOD seems to be close to random in most regards, further indicating the project teams did not have a formal plan for design modelling. Another reason for this could, nonetheless, be that the event did not run for long enough, forcing the participants to prioritise other parts of the project assignment, rather than 3D and information modelling. This last explanation, however, seems rather unlikely, due to the consistency in the lack of correlation between factors, rendering a lack of modelling discipline or planning, the most likely explanation. This is also in line with research by Alducin-Quintero *et al.* (2012), who describe how use- and reuse of building information on a project can be hard to undertake, when building information is developed based on a poor modelling strategy.

Conclusion

Through analysing models from three iterations of the Digital Days, which is an annual interdisciplinary learning event in Denmark, the question: *What is the current Level of Development (LOD) in architectural design models at the Digital Days and which factors can be identified affecting the LOD, in terms of knowledge, skills and competences,* was answered.

The analysis showed that design modelling can be hard to manage on interdisciplinary projects, and that motivation and engagement by the designers is essential in order to achieve a high LOD, consisting of design objects with a high level of reliability, geometry, and information.

The analysis showed no correlation between the three aspects of the LOD in the design models in either year, even though the event was conducted differently and that the number of participants in each project team changed in 2021 and 2022, compared to 2019.

Observing the models both quantitatively and qualitatively showed that design models at the Digital Days had a low LOD, which did not seem to stem from lack of knowledge, with respect to defining reliability, geometry, or information. The analysis did, likewise, not document a lack of skills in this regard, as most models had well defined objects. However, not consistently from object to object in the same model. As also shown in the analysis, it was close to random if a model had well defined exterior walls, windows, or both, and having well defined exterior walls, was no guarantee for other objects being defined at all.

Hence, limited competence levels in design planning based on a formalised modelling strategy seem to be the reason for the low LOD in the design model. This calls for an increased focus on this aspect in future repetitions of the event, in order to provide the students with the competences needed for documenting design information consistently in design models. A competence which is also needed when they enter the AEC industry, which is simulated during the Digital Days.

Knowledge, skills, and competences of students is, however, not limited to design modelling. Future research should, therefore, focus on which competences students need, to be ready to enter the AEC industry after graduating their education, and how short-term learning events, like the Digital Days can facilitate such development of competences.

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