Socio-Digital Co-Design Practices: A Case Study on Human-Computer Entanglements in Architecture

Cordula Kropp

Institute for Social Sciences, University of Stuttgart, Stuttgart, Germany

Yana Boeva

Institute for Social Sciences, University of Stuttgart, Stuttgart, Germany/yana.boeva@sowi.uni-stuttgart.de

Kathrin Braun

Institute for Social Sciences, University of Stuttgart, Stuttgart, Germany

Abstract

Studies of architectural design practices have shown that building projects take shape through the intricate interactions between human designers and various technological tools. In present-day's architectural practice, these interactions are increasingly being reconfigured by two major trends that are affecting the future of construction: digitalisation and the imperative to make building processes and the built environment sustainable. Against this backdrop, the paper presents insights from an ethnographic case study on socio-digital co-design practices in the planning and preconstruction phase of an ambitious building project. This research explores how digital tools reconfigure design practices and highlights the 'reverse salient' that has limited the realisation of the integrative potential of socio-digital design processes. Using a practice theory approach centred on 'socio-digital co-design', the study shows that digital tools reorganise, but do not take over, the coordination practices in early design necessary to achieve coherent results and sustainability outcomes.

Keywords: Design practices, digitalisation, co-design, sustainability, reverse salient, practice theory

Introduction

New buildings are not created in a void, but require a multitude of co-design processes shaped by the interaction of humans, technologies, standards and models. Today, digital tools for calculation, simulation and visualisation are playing an increasingly important role in these co-design processes. They allow actors to synthetise different options, calculate new ones, flag out and address coordination issues and more. Alongside digital potentials and logics, however, social perspectives continue to inform socio-digital co-design practices in architecture and thus get embedded in them. We understand socio-digital co-design practices as the realisation of human-technology entanglements and distributed agency that involve embodied enactments of skills, routines and aesthetic judgment in professional settings.

This work is licensed under a Creative Commons Attribution 4.0 International License

Planning a building typically involves complex networks of actors. Architectural firms collaborate with numerous companies in which professional teams of engineers, specialists and project managers plan, sketch, visualise, and calculate using their respective technical tools, sometimes separately, sometimes together. In addition, they are in regular contact with clients, project developers, investors, authorities and sometimes also a broader public, and they may even establish planning companies for larger projects. Later, additional construction, assembly and installation companies join in. Human participants in these interactions routinely draw on visual representations, two-dimensional plans and data, (three-dimensional) models and renderings of previous projects, and incorporate calculation software and models that represent their interactions and lend them coherence (Henderson, 1991; Houdart, 2008; Yaneva, 2009a; Yarrow, 2019). In the course of design, planning and construction processes which often take several years, not only participants and their relationships change, but also objectives, models and visualisations, construction materials, technologies and costs. The early design phase of building, therefore, can be described as a multi-layered and multi-staged sociotechnical system in which social and technical components dynamically interact and need to be related to each other.

The difficulties of coordinating these complex interactions are generally considered the main cause of time and cost overruns, efficiency problems, construction defects and sustainability deficiencies. Against this backdrop, there is a widespread view that data-based approaches and digital tools are key to improving coordination and integration (Miettinen and Paavola, 2014; Paavola and Miettinen, 2019). Governments, software companies and consultancies are promising that digitalisation will also contribute to solving the enormous sustainability problems in the construction sector by improving efficiency of material consumption, integrating information about CO_2-emissions and energy demand, providing more accurate, data-based estimates of object-specific requirements, interdependencies and opportunities and by improving data-based documentation for maintenance and reuse purposes (Braun and Kropp, 2023).

For digital design and construction to become a successfully stabilised system, all technical and social components would have to be mutually adjusted and, metaphorically speaking, aligned in the same direction towards a common goal. Research in science and technology studies (STS), however, has shown that the evolution of socio-technical systems, particularly large, open, and fragmented systems, is vulnerable to centrifugal forces driven by the divergent interests and agendas of those involved in their development (Callon, 1986; Hughes, 1983). These forces can only partially be controlled by closing interpretative flexibility and partially lead to context-specific unequal or even dissident advancements. As a result, the system's growth is uneven and incoherent, it remains instable and unable to realise its full innovative potential. Thomas Hughes (1983: 79-80) coined the concept of 'reverse salient' to describe the dynamics of uneven growth in complex sociotechnical systems where social, material, technical, historical and other components and subsystems interact with each other. It denotes components whose evolution is falling behind in relation to others, similar to a fallen back section of an advancing battle line or military front, thereby impeding joint advancement of the system. Once these reverse salients are identified as 'critical problems', they become amenable to creative critical problem-solving activity bringing the system back in line with its innovation objectives.

Whether the use of digital technologies will generally lead to the promised efficiency gains and make economies more sustainable remains controversial (Santarius et al., 2020). STS-informed case studies on digital technologies' use in architecture and construction have shown that expecting improved coordination simply from applying digital models is unrealistic because it ignores the fact that these models act as 'intermediary' (Paavola and Miettinen, 2019) or 'partisan' (Whyte and Harty, 2012) objects that both require and cause changes in design collaboration. Research on technological change in design and architecture has demonstrated that digital technologies have changed action repertoires, design intents, design options and distribution of agency in the design process over the past decades (Boeva and Kropp, 2024; Houdart, 2008; Paavola and Miettinen, 2019; Picon, 2010; Vertesi et al., 2019; Whyte and Harty, 2012; Yaneva and Guy, 2008). Therefore, we refer to design practices supported by digital tools as 'socio-digital co-design', meaning distributed interaction between designers, computational information, software and other digital tools. We use the term 'socio-digital' to describe a mode of socio-technical interaction where software and shared data link technical and social conditions and practices, resulting in socio-digital implications.

To assess digital and computational technologies' contribution to integrative sustainable design and construction, we argue, we need to better understand *how* they are used in architectural design practices. Therefore, we examine these practices through an ethnographic case study of the interplay between human actors and digital and computational tools and technologies in the planning of a future university building. For this research, we participated as silent observers in the regular meetings of a so-called planning group, consisting of architects, engineers, IT experts, and sometimes officials, industry partners and other professionals during the design and preconstruction phase of the building project. The building was devised as a showcase project to demonstrate the potential of *integrative* computational design and construction technologies to improve the sustainability and performance of architecture and construction.

Starting from a practice-theoretical understanding of socio-digitally enacted design practices informed by actor-network theory (ANT), we explored how digital tools, software and visualisations intervened in the design and planning of the building project. As digital tools are increasingly being integrated into planning practices and their arrangements, we were interested in the potential as well as the actual features of socio-digital co-design. In particular, our study aimed to examine *how* digital tools entangle the social and the digital in design projects, and how this impacts the sustainability imperative. While we have previously examined the techno-political implications of digital planning tools (Boeva et al., 2024; Braun et al., 2022), this ethnographic study focuses on their implications for design practices. The case study is organised in three vignettes to show how socio-digital co-design is enacted under specific regulatory, technological and economic conditions. The first vignette demonstrates how planning constraints, design intents and computational optimisation interact with and inform practices of socio-digital co-design in an iterative back and forth to create an initial viable building design. The second vignette highlights how the use of digital technologies enables and defines the integration of various social and technical actors of architectural design and their perspectives. The third vignette captures how the addition of another type of actor — the construction companies — substantiates the economic framing of socio-digital co-design.

In the next section, we first situate the study in relation to previous studies on digitally supported architectural design practices informed by practice-theoretical approaches and ANT. We then briefly introduce the challenges posed to design and construction by climate change and resource depletion and sketch out the introduction of digital technologies and their affordances into architecture as an envisioned solution to these challenges. In the fourth and fifth section, we explain our methodological framework followed by our three-part reconstruction of the uses of digital technologies in socio-digital design practices. On this basis, we then discuss how, in this case study, definitional authority translated into socio-digital co-design. In the final section, we draw a preliminary conclusion about increasingly digital design processes, describing the interweaving of social and technical perspectives and highlighting the role of unequal access to 3D models and computational explorations as a 'reverse salient' that causes critical problems for the definition of shared innovation objectives.

A practice-theoretical and ANT perspective on human-computer entanglements in architecture

Approaches from actor-network theory and practice theory have highlighted the part that technologies, artefacts and materialities play in enacting sociotechnical arrangements without, however, treating technological tools and other artefacts as allegedly neutral, stable determining factors (Latour, 2005; Reckwitz, 2002; Schatzki, 2002). These works emphasise that, in these heterogeneous contexts, agency emerges from the fabric of *sociotechnical practices* interwoven in organisational principles (Kalthoff et al., 2016: 20) and that technologies and other objects intervene in these practises depending on the respective 'assemblages' (Latour, 2005). Accordingly, to understand the design practices of various actors as being embedded in material arrangements (Orlikowski, 2007; Schatzki, 2010), linked by a series of technological mediations (Latour and Yaneva, 2008), and determined by routinised performances (Reckwitz, 2002) is to see the different elements of these constellations as interrelated and the intentions and capacities for action as interdependently shifting. From this perspective, our investigation looks at the promises of digitally *supported* coordination of designs, design phases, tasks and interests. We ask, how computational technologies are *entwined* with design and planning activities, how they *afford* it and possibly *coordinate* or *steer* it towards a more robust integration of sustainability goals.

Previous studies have explored architectural practice from an ANT perspective to show the "different actor-networks that underpin buildings and the complex negotiations" (Yaneva and Guy, 2008: 1; also, Blok, 2013; Georg, 2015; Houdart, 2008; Picon, 2010; Yaneva 2008, 2009a). Latour and Yaneva have argued for investigating design and construction processes as "moving project[s]" in a "series of transformations" (Latour and Yaneva, 2008: 80) through which the social and the material are linked and modified step by step. In their view, doing ethnographic research along these lines is the only way to get at both the practices of co-production of spatial relations distributed among people and things and by which people, material and the built environment are set in relation to each other and the discarded spaces of possibility. In her ethnographic studies of an architectural firm and a building's renovation process, Yaneva (2008; 2009a) showed this co-evolutive sociotechnical back-and-forth between model and design, meetings and drawing techniques, archives, and various groups of people. In her case study on the architectural firm, only architects who had mastered various practices of perspectival, technical and digital drawing had agency. Yaneva (2009b) and Gieryn (2002) looked at the design and use of university buildings with a similar focus on sociotechnical networks and emphasised the limited connection between the design processes (*design in the making*) and the final building in use (*design made*). Houdart's (2008) ethnographic study of a Japanese architectural office highlighted that virtual perspective drawings and their production are an assemblage of digital practices ("copying", "cutting", "pasting images"), hand-drawn sketches, and architectural sensibilities, often only verbally articulated. In a historical perspective, Picon (2010) traced the role of digital design proposals and object libraries in determining the architectural construction of social reality in different technological periods. In a case study of sustainable urban development in Denmark, Georg (2015) employed the ANT-concept of 'translation' to investigate the significance of a digital tool for sustainability assessment as a mediator and translator in processes of urban development design. This study shows how the digital tool influenced and mediated the planning processes between the various planners. Above all, it shows that the overarching socio-economic constellations or 'assemblages' in which professionals in architectural competitions operate had a much greater impact on the outcome of the planning processes than the tools and technologies they were using (Georg, 2015: 339). Other sociological case studies (Whyte and Harty, 2012; Kropp and Boeva, 2021) have used the concept of 'translation' to work out how digital planning tools constitute and reconfigure definitional power in collaborative design processes. Each of these studies conceives of planning and the built environment not as expressions or results of architectural design ideas, urban planning constraints, political orientations or digital technologies, but as elements of a complex practice that is as much social as it is technical, and in which planners' agency depends on multiple translations needed to create a common ground for the contribution of other professionals, technologies, materialities, and models.

Besides digital technologies, a significant role is played by professional, including administrative, know-how regarding procedures, norms, and technical possibilities. Theories of practice do not ignore intentions, but focus on how these are embedded in doings, entangled with the tools of knowledge production, and consider them as interconnected components in "routinized body/knowledge/things-patterns" (Reckwitz, 2002: 258). In practice, computers and software are not isolated instruments but always enmeshed in spatio-temporally specific socio-material arrangements that are ordered according to rules (Schatzki, 2002; Orlikowski, 2007). From these socio-material arrangements, a relational and situated socio-digital co-design agency emerges as a capacity to act, in which neither digital tools support humans, nor humans choose the most appropriate technology at will, but which depends on successful associations of all agents involved. Will this socio-digital co-design "question the previous interactions through which these processes of generating and materialising form and space have taken place since the Renaissance" (Knippers and Menges, 2021: 23) in favour of sustainability?

Sustainable development and digital transition as new challenges facing architectural practices

Across the world, architecture and construction are facing the challenge of becoming sustainable and resource efficient. In order for construction to still meet the 1.5-degree target, changes in energy and material consumption as well as legal and regulatory framework are required at national and international level. Additionally, the sector is confronted with an accumulation of crises, from a productivity crisis and a skills and material crisis to the overarching environmental and climate crisis. Whilst opinions differ about the extent, causes and effects of these crises, the general assumption is that the future of construction will and must be digital or else the sector will be unable to overcome these crises, particularly with regard to sustainability (Braun and Kropp, 2023). In fact, all major programmes for making construction more sustainable strongly rely on technical solutions, digital assessment tools and technological innovation. The European Commission (2022) has already proclaimed a "twin transition" that would link digital and sustainable transformation, with construction to act as a model sector for the New Green Deal.

In short, design and building practices emerge within social, cultural, technical and economic horizons in which architectural design intentions, building technologies, forms of housing, property relations and ways of knowing, ordering and living in the world mutually shape and co-produce each other. Against this backdrop, in design and construction as anywhere else, sustainability-oriented objectives must be 'translated' into concrete targets and strategies in order to become effective (Schroeder, 2018). Instruments used for this purpose influence building knowledge and practice, which, however, often goes unnoticed, as do the sociotechnical assemblages in which decisions are made. Yet, it is precisely these sociotechnical assemblages in and through which planning and building practices take place and sustainability is "thought" that determine outcomes (Georg, 2015; Blok, 2013).

The digital transition with its attendant promise to disruptively enhance the built environment by means of integrative planning tools, is often mistaken for a linear and uniform process. However, this discourse conceals very different paths, visions and assemblages which will result in correspondingly different outcomes (Braun and Kropp, 2023). Moreover, the use of software for design and planning is not entirely new but has been only very slowly changing architectural practice over several decades. It is, therefore, fair to ask why digital tools have not significantly improved the coordination and sustainability of construction projects yet.

However, most architectural firms managed without design software until into the 1990s and, if they used computers at all, did so mainly for invoicing and word processing while only today, computers, scanners, printers and plotters count as standard equipment (Picon, 2010: 8). There was a long lead-up to the introduction of digital planning tools in which the implementation of what were at first information-based and later data-based management strategies was linked to cybernetic concepts of control in the military sector and production processes in globally operating corporations (Picon, 2010; Cardoso Llach, 2015). First came applications for computer-aided design (CAD), then calculation software for computing material requirements and prices, and ICT-applications for coordination and communication, and finally algorithmic tools for parametric design (Cardoso Llach, 2015; Vrachliotis, 2012). Research in STS and architectural history has shown how design practices, organisational patterns and professional identities by and by started to change in response to these tools and arrangements. Initially, the most significant changes were in design, while fabrication and construction remained influenced by trade practices and craftsmanship. In the second phase, development was focused on digital 3D models, building information modelling (BIM), and sensor and robot technologies. Today, we are witnessing a 'second digital turn' in architectural design (Carpo, 2017), raising expectations of data-based linking of all elements and phases in the design, construction and maintenance of buildings. In addition, the 'second digital turn' opens up prospects of novel built worlds by means of increased computer performance, machine learning and construction robotics and inspires sociotechnical visions of better, digital built worlds (Braun and Kropp, 2023). Sometimes, the visions centre on the digital, data-based modelling, coordination and control of the construction value chain, sometimes on the automation of (pre-) construction processes analogous to automotive manufacturing; sometimes on constructing iconic buildings with parametric design technologies, and sometimes on 'greening' building systems by using more efficient procedures, new calculation techniques and digital material catalogues for recycling and reuse (Braun and Kropp, 2023).

But the different horizons of digitalisation are not just a backdrop to the prevailing relationships among actors in the building sector and the respective processes and goals. Rather, they change the latter and are themselves being changed in a reciprocal way. Uses of 3D digital building information models (short BIM), which are increasingly replacing paper blueprints and cardboard models, are shifting the ways how architecture and construction professionals cooperate by reconfiguring planning and coordination processes (Whyte and Harty, 2012; Paavola and Miettinen, 2019; Kropp and Boeva, 2021; Yarrow, 2019). And algorithms aiming to optimise the use of space or light and energy conditions have the potential to re-define, in the course of machine learning, agency and design contributions but also the built environment and options for action (Boeva et al., 2022; Kropp et al., 2022).

However, it is only by being used that any of these digital technologies acquire their significance, especially in routinised practices as part of infrastructures that are taken for granted (Boeva and Kropp, 2024). Their use must therefore be analysed in the context of distributed practices, in which actors take up standards, calculations and techniques of drawing and building and realise their designs with the help of countless instruments and models (Latour and Yaneva, 2008). At this confluence of factors, design practices depend on the skilful orchestration of possibilities and power relations that cannot be considered in isolation from materialities, economies and technologies, as the following case study shows.

Methods

All architectural planning, even that of conventional buildings, is the result of an interplay of many people, things and techniques. To better understand this interplay, we joined the ongoing planning process of a German building during the design and preconstruction stage. The project is a showcase project with the explicit objective of demonstrating how computational design and construction technologies can improve the sustainability performance of building. The study is based on observations logged during two stages: (1) the approximately bi-weekly meetings of the planning group that took place from August 2021 to July 2022 (*design stage*), augmented with qualitative interviews; and (2) the weekly meetings of the planning group with three different construction companies and, on occasions, the client that took place from November 2022 to February 2023 (*preconstruction planning stage*).

All authors took turns participating as observers in the meetings. Due to the Covid 19 pandemic, some meetings were held as virtual conferences while others took place in a hybrid format in the various offices of the participants. Typically, these meetings involved about ten physically present persons and a few digitally connected participants, the former sitting across from a large monitor that alternated between showing 2D-cross-sections, the current agenda, 3D-detail views, the virtually present members of the planning group, and calculations and simulations from at least six different software applications. Although meetings are often considered by professionals as uneventful, in reality, “they are central to the process by which designs acquire more details and greater focus, through a range of interlinked processes” (Yarrow, 2019: 176), as we illustrate in our case study.

This type of silent observation, where the social scientists are present in the meetings but do not actively engage in the ongoing discussion, draws on Goffman’s approach to exploring the organising principles of social practices in an open-ended way, asking “What is it that’s going on here?” (Goffman, 1974: 25), a method that is also used in design ethnography. It integrates various data collection techniques in which notes on researchers’ sensory perceptions in unfamiliar realities play just as significant a role as the evaluation of meeting minutes, in-depth interviews, supplementary documents, situational arrangements and photos. Once the design and preconstruction planning phases were completed, we had at our disposal forty-six protocols of meetings, four in-depth interviews of approximately one hour each with active planners, ten documents from all project stages and numerous photos of intermediate planning stages.

Socio-digital co-designing in action – a case study

Our ethnographic investigation of the complex planning process is at once focused and data-intensive demanding that data be exploratorily objectified in a (re)constructed second-order account (Müller, 2021: 88) – which is what we did through the three vignettes below. In the first vignette, we introduce key moments in building design with a focus on the tension between planning constraints and design freedom. In the second, we take a closer look at the use of digital planning tools, and in third, we trace the relevance of needs and constraints that construction companies bring into socio-digital co-design in the preconstruction stage.

Co-design between design intentions, planning constraints, and digital integration

A building project rarely starts with an idea that is then converted into ground plans, building forms, material selections and structural calculations. In general, before the actual design planning begins, a set procedure of basic evaluation and preliminary planning identifies where the building can be located. Like any new building, our project had to be situated in an already built environment, which is ordered according to a land use plan at the municipal level and “precisely by parcel” (architect) at the level of individual plots in the development plan. Furthermore, there was a masterplan for the densification of the entire area, in which the location of new buildings, the provision of parking spaces and the handling of existing trees were already roughly defined. These specifications entailed numerous planning stipulations bearing on building height and use, clearances, open spaces and traffic areas, specifications regarding façade design, and the development policies of urban planners. In addition, a “users requirement definition” prescribed by the state building law was “duly” drawn up by a subcontractor; it specified the structural-organisational input variables and the functional programme of the building as a basis for determining a suitable site and eligible space allocation plan “accurate down to the number of wall sockets”, as one of the architects lamented. Feasibility studies were conducted examining the intended site, the potential means of realising the building and the economic parameters in various scenarios, already using Excel spreadsheets that converted user needs into numbers and digital design software converting future options into design horizons; these were backed up with cost–performance analyses and recommendations. Based on these results, only two building sites with their respective potentials to meet the demands of the functional space allocation plan, that is, the arrangement of the various office, laboratory, recreational, operational and circulation areas were still up for discussion, and they both specified either a more or less rectangular or a more or less square building outline. Moreover, the planned timber structure could only comply with fire regulations if the number of storeys was restricted to a specific building class: "And just like that you fall back to the (pause) long, rectangular block of a building", as another interviewed architect summarised the rather disillusioning preliminary design results.

Up to this moment one and a half years in ground plans had repeatedly been plotted to precise scale and presented. Whether they were presented digitally or printed out, since these plans lacked a discernible building shape, they did not have much to say to the future users to whom they were presented, even as the architects were already drawing inferences about the "building cubature", a loose reference to the building's geometry. In the subsequent twelve months of design planning, we were often unable to discern from the visual models and cross-sections the merits or problems of the individual design stages, which, however, sometimes galvanised our planning colleagues, who dealt with them successively in a series of micro-decisions.

Thus, the "building block", its site, height, orientation, and space allocation plan were already in place when design planning commenced. That said, there were still many decisions to make. While the views on the screens gained in detail and presentations divided the building into functions and areas, there was talk of development objectives and intentions, needs for meeting individual area requirements were solicited, staircases were discussed with regard to various uses, trees and shrubs spring up alongside cross-sections, photos and plans of other buildings in other regions of the world illustrated what is possible or to be avoided, digitally visualised interior views suggested lightness and sunsets, Excel spreadsheets served as a reminder of the users requirement definition, and square metre specifications and models became a basis for discussing perspectives, options and implications. As the co-design practices continued, ever new visualisations of design options appeared in the form of partial digital models. Ideas and drafts were commented upon, digitally supplemented with freehand drawings, altered, discarded, or later improved. While some significant decisions crystallised early on in this iterative process, others long remained open questions.

An illustration of how conflicts were negotiated between demands for sustainability, climate adaptation, user comfort, architectural ambition, and administrative regulations is provided by the problem of room temperature. The regulations stipulate a maximum room temperature of 25.5 to 28 degrees [Celsius], which may exceptionally be exceeded up to 30 degrees for 50 hours per year. But the planners were more ambitious:

> Architect A: We don't just want to comply with the standard, we want comfort. The user workshop concluded that 'room comfort' is a top priority.
>
> Architect B: We have to take into account that it will become even warmer and more humid in the next decades.

For the sake of environmental sustainability, the building had been planned as a lightweight construction in order to reduce the consumption of building materials. But lightweight construction has a temperature problem, as one of the building physicists involved pointed out: "There is always this problem when we build without thermal mass. The solutions for lightweight construction are often very specific". A wide array of such specific possible solutions was then discussed, including central ceiling fans. But these were rejected; they were felt to be too contrary the design intent, as architect A commented: "We don't want to hang a forest of fans over a large open area; it's contrary to the idea of this space." Fan-equipped drones were discussed as an alternative, along with different options for adding thermal mass to the building, for example, by means of loam in the ceiling, granite slabs, a loam parapet, or a concrete table. Finally, an agreement was reached to pursue various options, especially the use of loam.

Further additions, such as partitions, balustrades, façade posts and emergency staircases were debated as necessary responses to user demands and building permit requirements. "Conflicts" like interfering tension bands and steel girders, which were often first discovered in the presentations and models, had to be resolved: "Have you checked what's there under the support head?" New assessments based on material requirements, calculations and problematic joints reacted to recalcitrant intermediate results that refused to comply with design intentions, echoing Schön's characterisation of design as a "conversation with the materials of a situation" (Schön, 1983: 78). Designers take a step in the design process that brings about changes, such that the situation "talks back" (Schön, 1983: 79), triggering a response, a "reflection-in-action", on the part of the designers.

Special attention is garnered by the roof, a free-floating "shell roof" with an enormous surface area formed "of seven double-curved partial shells that span the short distance" without obstructive interior supports. The structure can neither be named nor its merit grasped without recourse to technical terminology. The team supplemented this distinctive architectural feature with solar panels that cover the entire area to ensure that future energy demands are met with renewable energy, making the new building — among many other innovative solutions — into one more showpiece of the award-winning design team. The photorealistic renderings of the roof from within recall a tent ceiling grown from wooden tissue; those of the exterior resemble a giant armoured worm. The roof is the result neither of an individual act of imagination nor of a technical calculation. It came to be – with reference to an undulating, prestressed concrete shell roof that is listed and well-known in building design theory – from countless variations generated by parametric modelling. The latter permitted the designers to draw on their previous experience with free-span roofs and plan the building not directly according to its geometry but by controlling individual parameters in interrelationships. Right from the initial studies for the roof, feedback was obtained through structural simulations. These simulations allowed considerations of architectural aesthetics, structural performance and digital fabrication capabilities to be aligned in such a way that highly efficient structural forms could be achieved through intensive computational co-design, so that the material requirements for the roof — even if bio-based — could be reduced maximally and the material properties and their variability could be optimally utilised for the design. The computational approaches taken here reflect the research objectives of the design team and go far beyond design routines typically used today. Many months passed between the first,

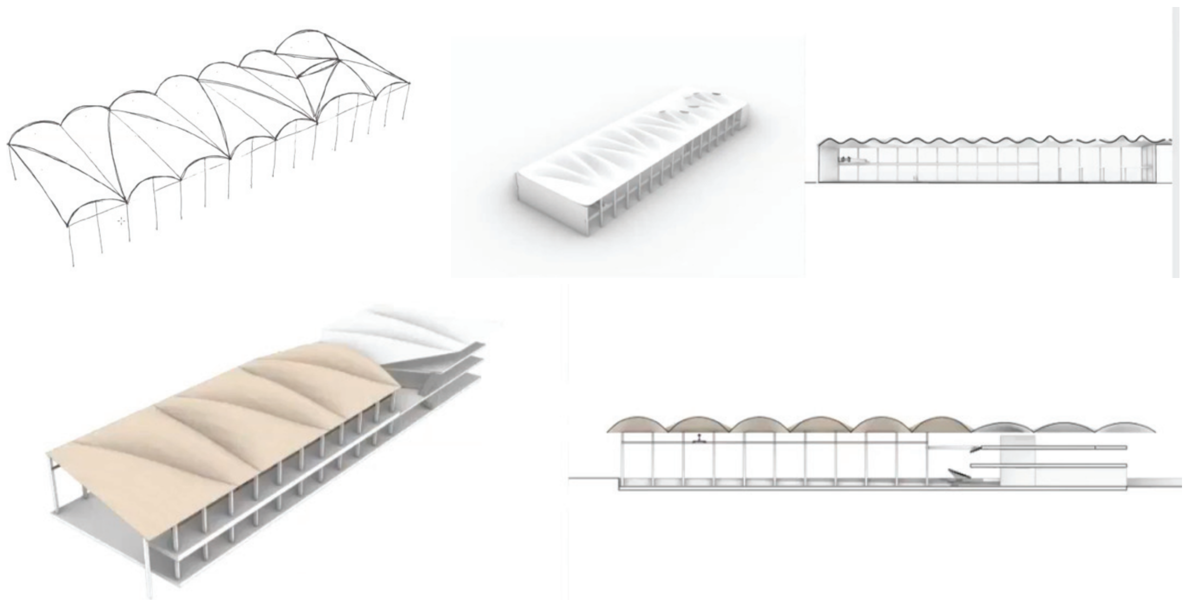

Figure 1. Hand sketch and parametric explorations for design planning. Permission to reproduce granted by: ICD/ITKE, University of Stuttgart.

hand-drawn sketch (Fig. 1), which only roughly conveyed the design intention and the design that was submitted at the end of the design stage, during which the parametric model was configured and intermediate models were produced in hundreds of varying iterations.

The model was operated by a computational design expert who, while balancing the expectations of the lead architects with his own design intent, produced new versions and visualised them, compared them, brought them into discussion and edited them further. Another expert took up these results and computed, through many loops of agent-based modelling, the optimal segmentation of the roof shells "as seen from the perspective of the wooden coffers", he explains, "so they [i.e. the coffers] decide how they want to be arranged in the space: by size, for example, or to be as planar as possible." Without these computational methods, the expert said, it would be impossible to generate a form-fitting cover for a double-curved surface without gaps. Computational design tools, here, afford agency to the roof shells, inviting the shells to communicate their arrangement requirements to the planners and the planners to comply with them.

In our observations, the building project emerged from a complex, but consensual combination of mutually influential models, conceptual designs, ambitious designers, specifications, construction methods, material requirements, and external and internal desires — of users as well as of wooden coffers — all digitally represented in software, presentations, video conferences, documentation, data, and spreadsheets. The digital applications also provided information about material requirements and costs and allowed for comparisons with specifications and with internal and external objectives, such as those relating to building operations. These specifications did not include sustainability requirements. To the extent that these were taken into account at all, it was only on the deliberate initiative of the planners. The episodes discussed in this vignette make it clear that only socio-digital co-design practices in an iterative back and forth between building standards, professional expertise, data generation, computational optimisation and calculated evaluation could translate the tension between planning constraints and design freedom into an initial viable design. In retrospect, our analysis shows that, with the help of this internal socio-digital co-design, the planning group was largely successful in translating the externally defined regulations and economic conditions, set out in Excel spreadsheets, into a first consensual architectural design. Let us now take a closer look at this socio-digital integration and coordination.

Co-design between software and coordination

National and international governmental actors, policy-makers, professional associations and business consultancies are pushing the use of digital 3D models using building information modelling, in short, BIM (Braun et al., 2022; Leviäkangas et al., 2017). Countless documents and position papers by industry actors have promoted the use of BIM models, promising increases in speed, productivity, quality and, above all, coordination, and many governments have mandated the use of BIM for public building projects (Braun et al., 2022; Braun and Kropp, 2023). At the centre of BIM is an object-oriented 3D model linked to a database, which is supposed to make the planning and construction processes, along with all relevant information, accessible to those involved. Ideally, geometric, technical, material, economic, ecological and use-specific parameters are all included. One promise of BIM is to integrate all building component data into the 3D models in the form of shared specifications and material datasheets in order to better achieve sustainability goals by reducing design mismatches, material consumption and waste. Yet, precise details and their model representation require decisions early-on that can constrain the distributed socio-digital co-design, as we observed and show in this vignette. As we will explain, such a coordinating and all-encompassing 3D BIM model was not available in the design process under study here.

Although BIM models do require inputting all planning data, the more than twenty organisations involved in the design process in our case study made only unequal use of the model for the various – operational, scheduling and technical – purposes. An architectural firm operated the model and regularly extracted some views and information for external parties in the form of PDFs. This firm did not use Revit, the world's most widely used BIM software, marketed by the US-based company Autodesk. Instead, the 3D models were created with the comparable product ArchiCAD, marketed by the German software company Nemetschek, a BIM pioneer.[1] The software choice followed from the architectural firm's tradition, which had been using BIM models for almost five years — "mostly for specific parts or phases" (architect), and not as a generalised intermediary object. "We use ArchiCAD because we work with Macs," one of them pointed out. This architect, in dialogue with a colleague from the planning group, added that everything is built up geometrically in ArchiCAD. In other words, everything is drawn "the way designers are used to". The Autodesk programmes, on the other hand, were originally a tool "for infrastructure planners who don't draw but insert objects, a motorway, for example. […] for us, it opens up a whole new way of working." The colleague went on: "Now it is no longer a matter of thinking, what do I want there, how should it be? But rather, is this what I want? […] and you always have to consider: Is that really the way I want it? Standards are permanently at issue. You have to consider what they mean, what else would be possible." This explanation by the architect demonstrates how digital driven and social, that is, professional logics merge into socio-digital co-design practices.

Both agreed that BIM software comes with a risk of standardisation due to stored object libraries. For a long time, for instance, the roof mentioned above could not be represented in the BIM model because there was no corresponding pre-defined element. "Now we've put something in there" (architects): The roof geometry was "loaded" via the interface of a freeform surface 3D modelling software (Rhino3D) "when we got it", ultimately as an IFC-file, a non-proprietary standard that facilitates data exchange in design and construction processes. This file format is also used to deliver the PDF files to contributing planners and building authorities, "who also need some way to access the information" — a quote that highlights how those without design software (access) are significantly cut off from the design process. As it grew, the BIM model thus gathered information 'under one roof' while imports and exports facilitated changes and review, but the integration was neither strictly cooperative nor dialogical. Yaneva (2009a) showed for analogous models a scaled knowledge production: Smaller models remained undefined in many respects, while large models had a greater impact on decision-making because they were "meticulous and enriched with more data and concrete details" (Yaneva, 2009a: 145) in order to attract more observers to the construction project and to augment it with more information. Today, this function is taken over by BIM models. BIM coordinators, a new professional profile, are to assume a decisive role in the management of building projects.

BIM models and the way they do integration thus involve exchange processes, uneven actor relationships, and introduce new hierarchies in design teams. The architects in our study viewed them with suspicion and did not use them as a standard intermediary model, but rather sought to "keep them at a distance", as they told us. The 3D building model was only fed data once a preliminary consensus was reached. Though it can display a planning history, it does so selectively – and thus reveals the "partisan nature" of models "bridging boundaries between some groups while creating and sustaining others" (Whyte and Harty, 2012: 201). In short, the 3D BIM model was not at the centre of the co-design process, let alone organising it.

Instead, in our case study, the group used additional software for coordination. Microsoft Teams provided for the involvement of physically absent team members for shifting quickly between views, planning stages, models and even the agenda of the respective meeting. In addition, plans were stored in a Miroboard so that those attending the meetings could quickly draw in their ideas for others to see and understand them. A dialogue from this design phase illustrates how this digitally mediated interaction worked:

> Planner A: "Come on, don't plan in elements. More like a ship: a full deck! We cut in there with scissors and push this down and then it's the stairs."
>
> Planner B: "I'll give it a try (draws around in the sketch). Make it parallel to the glass wall."

The presentation software PowerPoint was used to prepare the agenda and to display renderings and models, some supplemented with explanations. These images took up a lot of meeting time because consensuses were recorded in them. The planners used Rhino Renderer, a visualisation tool that, with the help of numerous plug-ins, provides working views of interiors and exteriors, of sections and technical problem areas, and even views of the greenery outside the window, by day or night. It was likewise present at the meetings and received praise for its suggestive views, but could be operated by only one expert on the team. This expert prepared renderings — preferably always from the same angle, to enable comparisons with whatever elements were at issue — but this was not all. During meetings, he was constantly prompted to rotate the view, switch to street perspective or view the building from above, go up and down the stairs, zoom in, or display the former solution one more time. Rhino3D and Rhino Renderer are not architecture-specific software applications; they are also used in the development of other products, from ships to jewellery design. With their help, designs can be "cloned", views "pimped", partial plans "replaced". The question of the role played by their suggestive visualisations for the various participants in socio-digital co-design — gleaming staircases, shimmering roofs, lush green spaces in sunshine and at sunset — can only be answered by further research (cf. Christmann et al., 2020).

Moreover, additional specialised digital technologies were running in the background. SoFiSTic, for example, was involved in the structural design; Grasshopper, a visual programming language, allowed for the simplified coding of optimisations in Rhino3D. There were other programmable plug-ins for everything from ecological assessment to scripts that would empower the wooden coffers to make positioning decisions. These tools enhanced architects' means of exploration but also came with their own selectivities and requirements. Their preliminary results served in a visualised form as the basis for coordination among members of the planning group. Under the conditions of digital interconnectedness, the building project thus became a virtual product across various renderings. Cardboard and wooden models, more labour-intensive variants of materialisation, were being displaced due to the digital ease with which multiple design variations were generated. In socio-digital co-design, we were told, there is no such thing as a single design creator. In fact, the various software tools make it possible to integrate the various architectural and technical concerns and to coordinate joints and troubleshooting between the various professionals involved. However, the tools included some previous designs and excluded others, and they were not equally accessible to all parties. We now want to see how external, economic issues are added to the internal co-design.

Co-design between calculations, standards and materials

The complexity of building design and construction requires more than the coordination of human and non-human designers through digital models and software. One approach to organise this is preconstruction planning, which takes place before contractors' bidding and actual construction. Preconstruction planning combines costing and calculations, constructability reviews, risk assessments, regulatory compliance, and project planning and management, and is typically offered as a service by large general contractors and construction managers. Therefore, preconstruction planning not only advises building design regarding its technical and economic feasibility but also co-designs it between costs, standards and construction companies' interests and needs, as we will illustrate in this vignette.

As a showcase project for computational design and construction, our case study's building-in-the-making included a five-month-long phase of preconstruction planning. It involved multiple and occasionally intersecting stakeholders: three construction companies, each responsible for one of the building systems and sections, several computational design and construction experts, the planning group for overall project coordination, the lead architects, and the project's client. The additional preconstruction planning stage was also a response to the widespread reluctance to implement design and construction innovations in new buildings and to concerns about cost explosion. Therefore, the idea was that the construction companies would step in, provide an initial price range with an upper and lower price limit and then use the preconstruction planning to optimise their calculation, ideally towards the lower one.

In order to give an initial offer, each company received a functional specification reference for their respective building system based on the "design freeze" of the previous design stage. While typically, a design freeze in product design, where the term originates, refers to an approved final design, its translation to architecture marks the end of a design planning stage. Hence, a design freeze in this case means further changes can be made to the design if needed or that changes are only made after specific decisions. The building's design was being revised, even if it was minor details, while the construction companies worked with an already outdated design. The functional specifications, however, were considered to be detailed and precise enough to draw out information for cost estimations as well as construction planning. Yet, it was precisely these potential uncertainties that influenced the calculation according to the construction companies' needs and interests.

For the first month, each company met with the respective computational design experts in a series of workshops to gain an understanding of the design and construction innovations developed with the computational approach. In reverse, computational designers gained insight into construction realities. The intensive workshops resulted in further optimised computational design and construction models to meet construction companies' experience, operations, materials, and standards. For instance, during one of the workshops for the timber roof, one computational design expert presented the segmentation of wooden coffers described in the first vignette. The construction company's task was to verify the roof segmentation's constructability by providing practical knowledge, fabrication details, and different quantities based on the available standard materials and their size specifications. Through the constructability check and material specifications, the overall material use should be diminished, and thus, the price estimate be closer to the lower threshold. However, as part of typical practices of valuation, the observed practices of "probing" the novel computational design processes included qualitative dimensions of "tasting" — in the sense of liking it — next to quantitative aspects of "testing" — in the sense of its feasibility (Hutter and Farías, 2017: 9f.). As any probing exposes novelties "to the judgment of acknowledged arbiters" and of "those who have gone through enough experience to make reliable comparison with earlier events" (Hutter and Farías, 2017: 9f.), it cannot be separated from either the physical perception of the design being tasted or the standards being tested. As Pinch (1993) observed, testing is about making connections between actual and imagined performance – and as Yaneva (2009a: 144) shows, this leads to judging the new against parameters that are already known. In the course of this process, some of the internally successful translations are abandoned in order to return to the established standards.

The preconstruction aimed to enable cooperation and knowledge exchange between the construction companies and computational design and construction researchers to co-produce construction specifications for bidding and fabrication and, ultimately deliver an updated cost estimation closer to the client's expectations. Yet, what seemed to be a collaborative and constructive exchange among professionals was, in the first place, a strategy for the client to save costs and for the construction companies to legitimise their expertise and established construction practices and standards. The computational optimisation of the roof's design reduced the amount of material needed by twenty percent. However, due to calculation constraints such as assembly and installation costs, this did not translate into a commensurate cost reduction and therefore fell short of the client's expectations. During a meeting, the disappointment about the lower-than-expected savings became apparent, when the seemingly exhausted and overworked planning coordinator voiced their regret that "200.000 saved Euros are not the goal we have set." The discrepancy in the interpretations of the preconstruction planning goal was partly due to the different sociotechnical approaches to calculating 'optimisation' and cost reduction. From a sustainability perspective, the material and thus environmental savings achieved through computational optimisation were first translated into an economic sustainability that then fell short of the prevailing construction market logic. In other words, the novel design and fabrication approach and its sustainability potential were forfeited by arguments about higher or uncertain labour and production facility costs on the side of the construction companies.

What we began to observe in the remainder of the preconstruction planning became a strategy of assembling and visualising elements. During and between the meetings, construction companies and designers exchanged, coordinated, and presented their results again in arrangements with multiple non-human digital actors such as Miroboards, PDFs of functional specifications, Excel spreadsheets with calculations, PowerPoint presentations, computational design, 3D modelling software, and occasionally forgotten to be updated servers and materials. Both sides strategically enrolled these technologies to provide as much argumentative ammunition as possible to make their case. For example, the font and size of a table in a presentation of optimisation results and costs were either scaled down to near illegibility or coloured in green to highlight an improvement.

The struggles resulted in delays in the updated calculation and addition of new aspects, such as budgetary and technical risks involved in integrating a robotic fabrication setup into the companies' existent facilities. Risk is a virulent concept within language and practices of contemporary building design and construction. Risks are invoked to legitimise costs by translating uncertainties and liability issues into calculation or to stay within the standards manufacturers and clients are familiar with. A considerable uncertainty, from the construction company's point of view, was the new glue for the coffers, which still needed to be certified and approved for the market. The absence of details about the glue's behaviour, which the designers had to provide, allowed the company to work with lump sums or cost estimates based on standard material they had experience with. The novelty of building materials and components compared to standard ones, as well as the lack of experience in utilising them, were considered as a cost factor. Towards the end of one meeting, the stakeholders joked wryly that they could as well replace all timber ceilings with conventional ones for the sake of saving money — which would of course have absurdised the whole point of the project. This little scene shows that the team was well aware that they were at risk to sacrifice sustainability for economic efficiency. Other construction companies also lacked experience with the innovations developed by the computational designers and incorporated them as imprecisely defined costs in their calculations, such as certification fees for robotic fabrication or lump sums for its setup.

In our case study, while computational and material optimisation was considered to have the potential for cost and resource optimisation, and thus contribute to the larger sustainability imperative of the project, interests, market standards, and conventions of practice — of construction companies and clients — co-designed the building mostly from an economic perspective, which is often absent in digital design models. The discrepancies between expectations, responsibilities and precise specifications were regularly used as a rationale to legitimise or challenge proposed costs. In his observations of designer and contractor interactions, Yarrow reconfirms that: "Where architects are concerned to highlight problems in the building, contractors are concerned to find shortcomings and inconsistencies in the plan. […] Money is made by exploiting the gap between what is specified and what will be needed" (Yarrow, 2019: 200). Indeed, one of the companies' managers commented that without precise specifications for one of the building walls, they had to calculate to the maximum in order to be on the safe side.

Discussion: The place of power in socio-digital co-design practices

At the early design stage, expertise, authorship, decision-making power and assertiveness are variably distributed among members of the planning group. During preconstruction planning, responsibilities are expanded to include the construction companies but also the client. Differences certainly reflect organisational structures and individual responsibilities. We noticed that the decision-makers in all meetings primarily ask questions and make remarks on presented developments. Conversely, the experts provide details, variations, views, costs for individual elements, or search for solutions until the next meeting. They are constantly looking back and forth from their own laptops to the presentation monitor while participating in the discussion and recording last-minute adjustments and wishes, whereas the lead architects focus on the face-to-face planning interaction. At this point, they comment, explain, ask questions, or go up to the large monitor to point out conflicts or remaining open positions in the current planning. Yarrow's ethnographic study of an architectural office similarly reveals that lead architects "spend much of their time circulating among the others, [who are] perched on desks, gesturing at screens, or sketching over plans" (Yarrow, 2019: 28-29). Sometimes one of the lead architects in our study used his tablet to draw in alternatives in green colour, which then team members elaborate further. In response to the question of why the decision-makers do not bring any hardware, he answers: "Because we are concentrating on the matter at hand" — suggesting to us that at some points, the close socio-digital connection is consciously interrupted. Similarly, the construction companies in the preconstruction planning rarely used computers in the meetings. Still, they provided calculations and numbers in advance or verbally for the planning company to document. How are we to interpret this occasional return to analogous exchange without digital support? Although distributed sociotechnical co-design during the design set-up phase contributed to translating different actor expectations into a viable design, this way was abandoned at particular decisive external interfaces. We can identify a reverse salient in the sense of Hughes (1983: 79ff.) here insofar as digital design models were available, in principle, but they were not structured coherently nor could they be used for dialogue and co-design practices. Therefore, their unequal availability impeded the achievement of the shared objective.

The new building in our case study can only be planned within the iteration of socio-digital co-design practices. However, the capacity to act is distributed unevenly across the planning team: The generation of alternatives and their presentation as design options rested on the power and skills of individuals. All decisions in the design team were made by consensus. The gradual process of reaching consensus was driven by functional, architectural and administrative perspectives, which were mainly contributed verbally. Those persons who were responsible for the overall project success avoided the use of digital tools. They communicated their wishes in the form of hand drawings, partly in digital media, and making decisions in such a way as to consciously distance their creations from those provided by digital objects.

A powerful influence is also exerted by administrative and economic guidelines, which in this case mainly served to foster compliance with maximum square meters and costs, comparability with similar projects and safety specifications. Represented by authorised persons, these guidelines, which were quoted in every meeting, influenced calculations and visualisations. They played a major role in decision-making situations since the design team was always careful to comply with the guidelines so as not to jeopardise the project.

In our study, as in Georg's (2015) on the role of digital sustainability assessment tools in multi-actor urban design planning, sustainability requirements were not anchored in the overarching institutional arrangements, unlike clearances, maximum surface square meters, and investment amounts. This meant, that it did not constitute a planning requirement. Therefore, it had to be constantly defined and defended by the planners themselves. To be sure, the building project's countless design options were processed and reduced by standards, guidelines, technical and regulatory requirements as well as architectural routines and digital options. Yet while spatial and economic factors constantly appeared on the agenda in the course of the socio-digital practices, consideration of sustainability aspects such as resource and energy consumption depended entirely on the situational definition and ambitions of the designers or the client, and thus were much more dependent on social representation than on technical representation.

The detailed examination of the case study in three vignettes demonstrates that the socio-digital co-design practices in the preliminary design phase, with multiple socio-digital entanglements, significantly supported the necessary work of translation, which was required to create common ground by integrating the various issues and expectations into a viable design. However, this was not achieved simply by a digital tool such as the BIM model taking over the coordination, but by successfully linking several distinctive socio-digital practices. Sustainability was not a necessary objective, but an additional one and was seen more as a challenge, for example with regard to the thermal and structural restrictions imposed by the use of bio-based materials. At the early design phase, the efforts of integrative computational co-design for a sustainable building were intensified and the observation made it increasingly clear to us that the constant back and forth between individual planning tools, their results and their integration into one project (design) is extremely challenging. There is no digital planning centre, no 'neutral' intermediary boundary object, but decision-making authority is primarily established and defended verbally. Those digital objects which are promoted for better coordination, especially BIM, were enrolled by deliberation, as their implicit ordering authority over the design process was suspected of causing premature commitments and decisions. Different from large architectural firms with their established and settling BIM-based coordination models, however, many project structures like the one we observed include multiple and diverse actors, lack experience with such socio-digital approaches and the needed time to reorganize accordingly. At the prefabrication stage, the critical problems associated with the unequal distribution of distributed socio-digital co-design tools became abundantly obvious: The complex, painstakingly put-together design was now trialled and tested from perspectives that were previously insufficiently involved and had no souverain access to the co-design practices during the evaluation.

From the perspective of Callon's (1986) model of translation, the translations achieved through socio-digital co-design thus lacked shared moments of problematisation, interessement and enrolment in order to be successfully mobilised for the final building. The circularity made possible by socio-digital co-design, through which later building materials and construction details can already be taken into account in the design stage (Knippers et al., 2021), is not flanked by an institutionally secured participation of the relevant stakeholders. Instead, administrative processes define sequential participation, for which the necessary co-design tools are not equally available. Yet, that the critical problems can be identified doesn't mean they are easy to solve.

Conclusion

The interweaving of the social and the digital emerged clearly in this case study. We have shown that design intentions and their implementation only took shape through interaction with models, comments, calculations and visualisations. At the same time, we saw that the degrees to which socio-digital co-design agency penetrated the situated design interactions varied greatly. As a result, socio-digital co-design practices took place against a backdrop of uneven involvement of different actors; representatives of authorities and contractors could only react on the basis of viewer documents rather than proactively engage in co-design. Their internal socio-digital agency had not developed coherently enough to meaningfully contribute to defining shared objectives, and ultimately these actors slipped into the role of veto players. The uneven socio-digital development within the interdependent subsystems and, in particular, the restricted access for some stakeholders to actively contribute to socio-digital co-design practices, proved to be a reverse salient that limited the performance and output of the overarching system.

And yet, on a less observable level, the building project was co-determined by the planners' far-reaching claims and aspirations. These were partly specified in steering the course of socio-digital co-design through their selection of processes, and partly defended by verbal comments. Their aim was to make the building project a showcase for their research, demonstrating both potential and practicality of computational, integrative and sustainable building methods (Knippers et al., 2021). Making architecture and construction sustainable through building differently is the whole point. This surplus of meaning, as the case study illustrated, was partly negotiated, changed and shaped through socio-digital co-design practices, eventually abandoned by some actors for different reasons. Design and decision, visualisation and calculation, material and culture – architectural practice emerges from co-design practices within which intentions and know-how, specifications and possibilities, materials and technologies coalesce object-specifically in virtual worlds. Yet, agency is not restricted to human actors, as the case of the roof shells has shown. It arises from the entanglement of digital and human design capacities and must be linked to organisational principles and to the collaborative project.

In this process, a future building as anticipated realisation of the design project comes into being and must later stand the test of realisation. Discussing ethnographic studies by Schön (1983) and Yaneva (2009a), Ammon (2017) has asked whether design practices can be understood as scientific experiments. With regard to practices that are explorative, but also co-productive of novelty, she answers in the negative, for several reasons. One of them is that experiments are tested in reality as their "counterpart" (Ammon, 2017: 511), whereas, in design processes, *possible* realities are projectively interrelated and coordinated but there are no (technical) means for evaluation by an external other. Put simply, design ontologically lacks the standard of an external truth: "truth does not help in the case of designing" (Ammon, 2017: 513). Digital data and 3D models do not change this, nor do conventional calculations and analogue models. The selection of specific design options from the spectrum of infinite possibilities is ultimately determined only by the mobilised requirements of the concrete situation; the result depends in principle on the planning group's "arbitrary" judgement in this situation (Ammon, 2017: 514). In our case study, the building project seems to be restricted to realise only those selected aspects, that can be judged against established parameters, while others are in danger of falling by the wayside. Sustainability, in the end, remains dependent on strong spokespersons, while economic goals are enforced with power, even retrospectively in planning.

We do not see our analysis as conclusive when it comes to discussing the potential of socio-digital co-design practices. Rather, it should be considered in the context of the case studies discussed above, which also found that the use of digital tools does not automatically lead to improved integration. Our in-depth research suggests that the reason for this finding lies in the uneven engagement of the relevant stakeholders in the socio-digital co-design practices due to uneven access to related digital technologies and skills from which socio-digital agency emerges. As previous studies on design and innovation but also prominent project examples demonstrate, which actor-constellations work well and how so, in relation to the digital tools, depend on projects' ambitions, social preferences and organisational structure. Any analysis would require looking closely and carefully at the context of distributed design practices and under consideration of materialities, economies, technologies, and the power relations behind them. Thus, a conclusive answer to the evolving digital and sustainable transformation of design and construction practice is far from reach.

Acknowledgements

The authors thank all participating researchers and members of the design team for their openness and valuable commentaries.

This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618.

References

Ammon S (2017) Why Designing Is Not Experimenting: Design Methods, Epistemic Praxis and Strategies of Knowledge Acquisition in Architecture. *Philosophy & Technology* 30(4): 495–520.

Blok A (2013) Urban Green Assemblages: An ANT View on Sustainable City Building Projects. *Science & Technology Studies* 26(1): 5–24.

Boeva Y, Braun K and Kropp, C (2024) Platformization in the built environment: The political techno-economy of Building Information Modeling. *Science as Culture* 33(2): 146–173.

Boeva Y and Kropp C (2024) Buildings in the algorithmic regime: Infrastructuring processes in computational design. In: Jarke J, Prietl B, Egbert S, Boeva B, Heuer H and Arnold A (eds) *Algorithmic regimes: Methods, interactions, and politics.* Amsterdam: Amsterdam University Press, pp. 141–162.

Boeva Y, Wortmann T, Kropp C, et al. (2022) Architectural Computing and Design Optimization for Healthful Ecotopian Built Environments? In: Kanaani M (ed) *The Routledge Companion to Ecological Design Thinking*. 1st ed. New York: Routledge, pp. 367–379.

Braun K, Kropp C and Boeva Y (2022) Constructing platform capitalism: inspecting the political techno-economy of Building Information Modelling. *Architectural Research Quarterly* 26(3): 267–278.

Braun K and Kropp C (2023) Building a better world? Competing promises, visions, and imaginaries-in-the-making of the digitalization of architecture and construction. *Futures* 154: 103262.

Callon M (1986) Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay. In: Law J (ed) *Power, Action and Belief: A New Sociology of Knowledge?.* New York: Routledge, pp. 196-223.

Cardoso Llach D (2015) *Builders of the Vision: Software and the Imagination of Design*. New York: Routledge.

Carpo M (2017) *The Second Digital Turn*. Design Beyond Intelligence. Cambridge: MIT Press.

Christmann G, Singh A, Stollmann J, et al. (2020) Visual Communication in Urban Design and Planning: The Impact of Mediatisation(s) on the Construction of Urban Futures. *Urban Planning* 5(2): 1–9.

European Commission (2022) Towards a green & digital future: Key requirements for successful twin transitions in the European Union. Publications Office. Available at: https://data.europa.eu/doi/10.2760/977331 (accessed July 23, 2024).

Georg S (2015) Building sustainable cities: tools for developing new building practices? *Global Networks* 15(3): 325–342.

Gieryn TF (2002) What buildings do. *Theory and Society* 31(1): 35–74.

Goffman E (1974) *Frame Analysis: An Essay on the Organization of Experience*. Cambridge: Harvard University Press.

Henderson K (1991) Flexible Sketches and Inflexible Data Bases: Visual Communication, Conscription Devices, and Boundary Objects in Design Engineering. *Science, Technology, & Human Values* 16(4): 448–473.

Houdart S (2008) Copying, Cutting and Pasting Social Spheres: Computer Designers' Participation in Architectural Projects. *Science & Technology Studies* 21(1): 47–63.

Hughes TP (1983) *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: Johns Hopkins University Press.

Hutter M and Farías I (2017) Sourcing newness: ways of inducing indeterminacy. *Journal of Cultural Economy* 10(5): 434–449.

Kalthoff H, Cress T and Röhl T (2016) Einleitung: Materialität in Kultur und Gesellschaft. In: Kalthoff H, Cress T and Röhl T (eds) *Materialität. Herausforderungen für die Sozial- und Kulturwissenschaften*. Paderborn: Wilhelm Fink, pp. 11–41.

Knippers J, Kropp C, Menges A, et al. (2021) Integratives computerbasiertes Planen und Bauen: Architektur digital neu denken. *Bautechnik* 98(3): 194–207.

Knippers J and Menges A (2021) Rethinking Architecture Digitally. In: Knippers J and Menges A (eds) *Architecture Research Building. ICD/ITKE 2010-2020*. Basel: Birkhäuser, pp. 22–23.

Kropp C and Boeva Y (2021) Die Übersetzung des Bauwissens und ihre versteckten Konflikte. *Gesellschaft unter Spannung. Verhandlungen des 40. Kongresses der Deutschen Gesellschaft für Soziologie 2020*.

Kropp C, Braun K and Boeva Y (2022) Echo Chambers of Urban Design: Platformization in Architecture and Planning. In: Strüver A and Bauriedl S (eds) *Urban Studies*. 1st ed. Bielefeld: transcript Verlag, pp. 237–258.

Latour B (2005) *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford University Press.

Latour B and Yaneva A (2008) Give Me a Gun and I Will Make All Buildings Move. An ANT's View of Architecture. In: Geiser, R (ed) *Explorations in Architecture: Teaching, Design, Research*. Basel: Birkhäuser, pp. 80–89.

Leviäkangas P, Mok Paik S and Moon S (2017) Keeping up with the pace of digitization: The case of the Australian construction industry. *Technology in Society* 50: 33–43.

Miettinen R and Paavola S (2014) Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. *Automation in Construction* 43: 84–91.

Müller F (2021) *Design Ethnography: Epistemology and Methodology*. SpringerBriefs in Anthropology. Cham: Springer International Publishing.

Orlikowski WJ (2007) Sociomaterial Practices: Exploring Technology at Work. *Organization Studies* 28(9): 1435–1448.

Paavola S and Miettinen R (2019) Dynamics of Design Collaboration: BIM Models as Intermediary Digital Objects. *Computer Supported Cooperative Work (CSCW)* 28(1–2): 1–23.

Picon A (2010) *Digital Culture in Architecture: An Introduction for the Design Professions*. Basel: Birkhäuser.

Pinch T (1993) 'Testing - One, Two, Three ... Testing!': Toward a Sociology of Testing. *Science, Technology, & Human Values* 18(1): 25–41.

Reckwitz A (2002) Toward a Theory of Social Practices: A Development in Culturalist Theorizing. *European Journal of Social Theory* 5(2): 243–263.

Santarius T, Pohl J and Lange S (2020) Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing? *Sustainability* 12(18): 7496.

Schatzki T (2002) *The Site of the Social: A Philosophical Account of the Constitution of Social Life and Change*. University Park: Pennsylvania State University Press.

Schatzki T (2010) Materiality and Social Life. *Nature and Culture* 5(2): 123–149.

Schön DA (1983) *The Reflective Practitioner: How Professionals Think in Action*. New York: Basic Books.

Schroeder T (2018) Giving Meaning to the Concept of Sustainability in Architectural Design Practices: Setting Out the Analytical Framework of Translation. *Sustainability* 10(6): 1710.

Vertesi J, Ribes D, DiSalvo C, et al. (eds) (2019) *DigitalSTS: A Field Guide for Science & Technology Studies*. Princeton: Princeton University Press.

Vrachliotis G (2012) *Geregelte Verhältnisse: Architektur und technisches Denken in der Epoche der Kybernetik*. Vienna: Springer Vienna.

Whyte J and Harty C (2012). Socio-Material Practices of Design Coordination: Objects as Plastic and Partisan. In: Leonardi PM, Nardi BA and Kallinikos J (eds) *Materiality and Organizing: Social Interaction in a Technological World*. Oxford: Oxford University Press, pp. 196-216.

Yaneva A (2008) How Buildings 'Surprise': The Renovation of the Alte Aula in Vienna. *Science & Technology Studies* 21(1): 8–28.

Yaneva A (2009a) *Made by the Office for Metropolitan Architecture: An Ethnography of Design*. Rotterdam: 010 Publishers.

Yaneva A (2009b) Making the Social Hold: Towards an Actor-Network Theory of Design. *Design and Culture* 1(3): 273–288.

Yaneva A and Guy S (2008) Understanding Architecture, Accounting Society. *Science & Technology Studies* 21(1): 3–7.

Yarrow T (2019) *Architects: Portraits of a Practice*. Ithaca: Cornell University Press.

Notes

1 Initially developed by Hungarian company Graphisoft, ArchiCAD and the company were acquired by Nemetschek in 2006. Nemetschek markets different BIM software along their in-house developed product Allplan.