Ref. Ares(2021)3583248 - 31/05/2021

PrismArch

Deliverable No D3.1

Report on cognitive issues in VR-aided design environments

Project Title:	PrismArch - Virtual reality aided design blending cross-disciplinary aspects of architecture in a multi-simulation environment
Contract No:	952002 - PrismArch
Instrument:	Innovation Action
Thematic Priority:	H2020 ICT-55-2020
Start of project:	1 November 2020
Duration:	24 months
Due date of deliverable:	31 May 2021
Actual submission date:	31 May 2021
Version:	1.0
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Project funded by the European Community under the H2020 Programme for Research and Innovation.

Deliverable title	Report of cognitive issues in VR-aided design environments
Deliverable number	D3.1
Deliverable version	Final
Contractual date of delivery	31 May 2021
Actual date of delivery	31 May 2021
Deliverable filename	PrismArch_D3.1_v1.0
Type of deliverable	Report
Dissemination level	PU
Number of pages	73
Workpackage	WP3
Task(s)	T3.1 and T3.2
Partner responsible	ETH
Author(s)	Martin Brösamle, Panos Mavros, Christoph Hölscher
Editor	
Reviewer(s)	Spiros Nikolopoulos (CERTH), Risa Tadauchi (ZHVR)

Abstract	A careful review of the requirements (cf. D1.1) is complemented by consulting with architects and engineers in exploratory interview sessions. A distributed cognition approach allows us to model design as a collaborative activity of an entire design team, including human actors as well as their physical and digital surroundings in the environment. UML-inspired sequence diagrams provide an abstract view on team activities in terms of who exchanges information using which media. Case studies on tracing as a design medium complete our study of established design practices in AEC industries. The analyses will guide the upcoming development and research activities in WP3and PrismArch as a whole.
Keywords	design practice, immersive virtual reality, design media, tracing paper, distributed cognition, sequence diagrams, cross-disciplinary collaboration

Deliverable history

Version	Date	Reason	Revised by
0.5	19/5/2021	Beta version: Released by ETH for internal review.	Martin Brösamle (ETH)
0.6	<31/5/2021	Beta version: Comments by internal reviewers.	ZHA, CERTH
0.7	31/5/2021	Beta version: Internal review comments addressed.	ETH
1.0	31/5/2021	submitted	Martin Brösamle (ETH)

List of abbreviations and Acronyms

Abbreviation	Meaning
AKT	*AKT II Limited (Project Partner)*
CERTH	*Ethniko Kentro Erevnas Kai Technologikis Anaptyxis (Project Partner)*
ETH	*Eidgenössische Technische Hochschule Zürich (Project Partner)*
SWECO	*SWECO UK Limited (Project Partner)*
ZHA	*Zaha Hadid Architects (Project Partner)*
AEC	Architecture, Engineering and Construction
AR	Augmented Reality
ARC	Architect
BIM	Building Information Modelling
CAD & CAM	Computer-Aided Design & Computer-Aided Manufacturing
ch.	Chapter
DE	Design Engineer
HMD	Head Mounted Display
ibid.	ibidem
MEP	Mechanical Engineering Plumbing (Engineer)
POV	Point of View
PWS	Personal Work Sphere
Req.	Requirement (reference to the numbering in Deliverable D1.1)
sct.	Section
SE	Senior Engineer
UG	User Group
UML	Unified Modeling Language
UX	User Experience
VR	Virtual Reality
WP	Work Package
[VILLA]	*Private Residential Villa (Case Study 1)*
[OPD]	*One Park Drive (Case Study 2)*
[OTM]	*One Thousand Museum (Case Study 3)*
[BYW]	*Bankside Yards West, alias Wood Wharf (Case Study 4)*

Executive Summary

PrismArch aims to develop a virtual environment for professionals from multiple design disciplines to collaborate on building projects in the AEC industries. The present deliverable D3.1 starts with a careful review of the requirements as they are provided by our design partners in Deliverable D1.1. We complement the picture by consulting with architects and engineers in exploratory interview sessions, who were involved in the project case studies. A cognitive account of design team *activities* is developed with a focus on information flows and involved physical and digital *design media.* Conceptually extending the boundary beyond individual thought, the distributed cognition approach allows us to model design as a collaborative activity of an entire design team, composed of human actors as well as their physical and digital surroundings in the environment. UML-inspired sequence diagrams provide an abstract view on team activities in terms of *who* exchanges information using *which media.* The approach fosters a comprehensive modeling of the task-specific information flows in a design team on a certain level of abstraction. At the same time, the properties of the media involved remain hidden due to the abstraction and cannot be studied. A case study on tracing paper therefore completes our study of established design practices. It reveals media-specific aspects of *how* an information should be presented so that the design medium can support human cognition in performing the respective design task at hand.

The decision to use a diagrammatic form for our analyses reflects the professional background of the project: It is common practice in design to present complex relationships in graphical representations; UML sequence diagrams are specified as a standard visual notation in the field of system development.

In view of the upcoming development and empirical testing of the PrismArch immersive design environment we ask, how a design workflow can be successfully implemented in virtual reality. The aforementioned analyses of established practices in today's AEC industries will guide our upcoming research activities as well as provide guidelines for driving the system's development in the next months.

If you were to design a virtual planet, ...

...would you give it time zones?

1 INTRODUCTION

PrismArch as a project aims to develop a virtual environment for professionals from multiple design disciplines to collaborate on projects in the architecture, engineering and construction (AEC) industries. `By employing advanced VR applications, designers can immersively perceive and interact with the current status of their creations and realize the consequences of their decisions [...] PrismArch aims to achieve a "prismatic blend" between aesthetics, simulation models and meta-information that can be presented in a contextualized and comprehensive manner in VR.' As an idea, 'prismatic composition' and 'prismatic de-composition' draws on the physical capabilities of an actual glass prism to decompose white light into the multiple colours it is initially composed of. Multiple disciplines appear as 'parallel worlds,' in which members of each field have their specific professional view or perspective. 'Architects and a variety of engineers coexist in an architectural project with distinct requirements and role' and 'only the "intersection", by means of close collaboration, of these "parallel worlds" that can bring an architectural project to fruition' (Description of Actions, 2019, pp. 1–2).

All design activity will take place in one unified immersive space. Related documents will be available in that space and all team activity can be coordinated there. In essence, bringing all design activity into one overarching data management system will lay the foundations for accessing the entirety of project-related data in a unified way. An important ingredient will be a compelling user experience design for making that data not only technically accessible but giving it an experiential quality, so that it becomes tangible to the senses of the user. This overarching vision, as developed by ZHA in their role as the artistic lead in this project, will drive the ongoing development of the PrismArch platform.

The interdisciplinary character of PrismArch is not only evident in its future application as a platform for collaboration between architectural and engineering design disciplines. The project itself equally constitutes a collaborative effort across teams and disciplines, who envision, design, co-author, implement, and test an architecture; namely the architecture of an immersive environment for design collaboration. The technical and experiential components of this future collaboration architecture need to be configured in such a way as to accommodate the design activities of each discipline, who are accustomed to their specific requirements and needs. Understanding this vision and following its inherent "virtue" or "logic" is a key ingredient in ETH's efforts to support the user experience development in a way that brings this vision to life. While the requirements follow directly from a careful analysis of how design is practiced by our design partners today, the project vision guides all project activities in a more subtle but also more holistic and fundamental way.

> **Architecture begins with an *idea*.**
>
> Good design solutions are not merely physically interesting but are driven by underlying ideas. [...] Without underlying ideas informing their buildings, architects are merely *space planners.* Space planning with decoration applied to "dress it up" is not architecture; architecture resides in the DNA of a building, in an embedded sensibility that infuses its whole.
>
> (Frederick, 2007, #14)

Naturally, there is a considerable amount of openness and underspecification at the time of writing this deliverable. The design intent as well as the investigations into the technical feasibility gained and still gain contours in workshops, meetings and discussions among all project partners. It is yet to be found out which visualisations, diagrams and metaphors will prove adequate carriers of a coordinated team effort. As is typical for early design stages, ideas need to be exchanged that are still vague or ambiguous. This is certainly true for traditional building design projects, as it is true for the development of the PrismArch platform. In terms of communicating ideas before they can be specified in a fully explicit manner, a number of metaphoric or analogical concepts emerged over the past months in internal communications. Concepts such as 'data space' or 'data sphere' are valuable in their capability to serve as placeholders for what they will become. When the 'data sphere' as a phrase entered the internal meetings it was presumably understood by some or even most project partners primarily in a metaphorical sense; a digital space in which documents reside in an organised manner. According to internal communications with our project partner ZHA 'the unified data sphere is a singular database for all content inside the PrismArch platform' (cf. sct. 6.2 for a detailed account on 'sphereing'). Over the past couple of months the *data sphere* has gained contours, as a concept that exists in data space where, in reference to time as a fourth dimension, we could claim it being four-dimensional, and as a (three-dimensional) sphere that may well be experienced by PrismArch's future users as such. The latter is suggested by a couple of sketches shared in internal presentations (ZHA, 2021, May). The episode nicely illustrates the openness regarding the interpretation of design concepts that is an integral part in early stages of a project. As for any design project, whether a concept becomes a tangible component of the user interface, so that it can be directly perceived by the interacting user, or whether it remains in the intellectual sphere, guiding users on a more cognitive level, needs to be carved out in an extensive exchange between the involved parties.

1.1 Approach

ETH considers it paramount that the overall approach to WP3 reflects the actual requirements and practices encountered in architectural and engineering design projects at industry level. Whereas the functional requirements formulate the *necessary* ingredients for this endeavour, the project vision goes beyond the pure functional requirements. We will therefore return to it on several occasions throughout the report.

Chapter 2 opens with an overview of key literature on topics such as design practice, team collaboration, and virtual reality. Chapter 3 provides a careful review of the requirements as they have been explicitly stated by our design partners from their "inside" perspectives as practitioners in their respective design fields (Deliverable D1.1). Chapter 4 complements Chapter 3 in that it collects material that ETH found relevant in relation to user activities in collaborative design. Various sources were consulted including the project documentation provided by our design partners as part of the project case studies (D1.1, ch. 3). A number of exploratory interview conversations with our design partners provide insights that go beyond what we could infer from reviewing the case study documentation (sct. 4.3). The requirements define the desired properties of the envisioned platform for its application in the AEC industries. A more cognitive perspective is introduced in Chapter 5 which provides an account to the requirements in terms of information flows, task environments and cognitive characteristics of various physical and digital design media. The user experience concepts that we propose in Chapter 6 are considered early sketches or proofs of concept how certain requirements could be reflected in the future user interface. Rather than defining the visual or experiential aspects in detail they instead exemplify minimal solutions which help study the requirements in depth. Similarly, Chapter 6 examines the current state of user experience design as they are currently being developed by our project design partners.

Overall, the present report provides an insight into established work practices in AEC industries from a cognitive point of view and reviews the user requirements under the same token. As part of our role to provide guidelines to 'drive the development' of the overall system (Description of Actions, RA3.3) we constantly strive for a strong overlap with our design as well as with our technical partners in conceptual terms as well as regarding professional vocabulary. Towards this end, diagrams provide us with a presentation medium that allows us to combine a high level of notational precision with more open-ended and flexible aspects such as composition and graphical style.

1.2 Evaluation and Empirical Work (T3.1 and T3.2)

To ensure that the empirical work for WP3 is not only based on the explicitly formulated requirements, but also reflects the overall vision of the project, ETH decided to develop the studies for T3.1 and T3.2 in close coordination with the architectural partners ZHA, AKT, and SWECO. At the same time, as the partner most concerned with human factors, we see our role in maintaining a critical perspective on proposed concepts as well as in empirically accompanying the upcoming development.

Supplementary to the documentation of 'current limitations of AEC software tools' and 'functional requirements' delivered as part of D1.1, ETH consulted with architectural and engineering designers from the project partners in interview-type conversations. According to Deliverable D1.1, a large variety of design tasks rely on physical media and digital tools. The interviews focus on a micro level analysis of activities and information flows across several members in a design team, as well as on how physical and digital media are involved in the process. This fine-grained analysis allows us to describe design activities on a cognitive task level. As part of the cognitive task analysis, we use *sequence diagrams* to provide a condensed view of team activities and information flows in design collaboration. In particular, activities taking place in parallel become legible as such through a graphical representation that allows the human vision to access activities not only in a narrative/sequential way. Instead, parallel *life lines* allow humans to access the codified activities based on individual actors and involved media (sct. 5.1). Beyond that, we not only study which task-related information is provided by sketches, CAD software, design documents and so on. We seek to develop a qualitative understanding of how the information can be presented most effectively, especially in relation to the specific requirements in the application domain at hand (cf. sct. 2.1, below).

The design process episodes as well as the cognitive task analysis in Chapters 3 and 4 are a prerequisite to defining specific user activities, i.e. tasks and materials, to be used in the upcoming empirical studies. In particular, T3.1 foresees studies based on 'exposing designers to various degrees of visual detail and available architectural information', in turn requiring us to define the type and mode of visual presentation in coordination with the design task at hand. Describing in detail what we know and what needs further investigation provides a stepping stone to answer questions such as

> how much and what type of information can be presented in a VR environment without losing spatial cognition and navigability, with emphasis given in complex digital architectural constructions (e.g., buildings). Moreover, it aims to analyse how these constructions are mentally represented by users in terms of orientation and navigation. Finally, it will identify interface features capable to help architects and engineers to rapidly understand the spatial characteristics of design variations.'
>
> (Description of Actions, RA3.1)

Second, in order to investigate the cognitive load associated with being immersed, as well as working in, virtual environments (T3.2), ETH plans to 'compile tests containing design analysis tasks that require participants to switch perspective between their own primary design focus and the implications and tradeoffs of their design decisions on other stakeholders.' Here, the cognitive task analysis informs the development of design tasks as well as ensures their ecological validity with respect to the application domain.

1.3 User Experience (UX)

Towards user experience developments, RA3.2 'aims to identify and record the essential interface features that will allow architectural designers and engineers to control the various aspects of the VR environment.' In a similar vein, RA3.3. 'aims to provide rules and criteria that will drive the development of the VR environment. Apart from increasing PrismArch's usability, these guidelines will accelerate the platform development process by foreseeing essential UX characteristics and thus reduce re-iterations in the development procedure' (Description of Actions, 2019, RA3.x). While there are general guidelines for evaluating the *Ergonomics of human-system interaction* (ISO/TR 16982:2002), more specific approaches are necessary to approach complex application domains such as the AEC industries (cf. Albers & Still, 2010, ch. 1; cf. also sct. 2.1, below). Furthermore, our project-internal reviewers point out that 'there is no standardized 3D UI as of yet. PC users have been using WIMP (Windows, Icons, Menus, Point and Click) interaction style for decades as all Softwares existing inside the ecosystem apply the same UI strategies which helps users to operate applications without extensive training. The same applies to the smartphone ecosystem' (ZHA, internal communication).

As a method, the sequence diagrams foster a way of describing design processes by abstracting away from media-specific aspects, which are otherwise an integral part in descriptions of architectural design and engineering tasks. The resulting description by means of information flows and parallel activities within entire design teams serves as a stepping stone for identifying and structuring the UX requirements. We invite readers primarily interested in the application aspects and/or the user experience issues to proceed directly to Chapter 6 of the present deliverable: It documents our efforts to develop a concept of (1) which information and navigational choices users have in certain situations and (2) how the user's could be presented with these information and control aspects in a coherent way. As part of the conceptual work we make an attempt to provide tangible materials such as storyboards and mock-ups. We would like to make it clear, however, that they are not meant to define final solutions in the sense of a matured aesthetic concept. Instead of precisely defining *how* things should look, they rather serve as guidelines about *what* information to provide to the user for a particular task and how it could be structured. They exemplify possible solutions that *should* fulfill a minimal set of requirements and therefore serve as test cases and proofs of concept for the collected user requirements. After all, tangible examples are capable of driving ideation and further developments much more effectively than abstract descriptions and guidelines alone.

2 THEORETICAL BACKGROUND

2.1 Design Practice

Being written from a cognitive science point of view the present report tends to focus on knowledge, information-flows and so forth. It is crucial to be aware, however, that this perspective has its limitations. Design needs to be considered a cultural practice established over two or more millenia.

> From a practice-based perspective, knowledge is not so much something that can be codified, but something that can be representedre-presented, in ways that are to varying degrees ambiguous, contingent, and partial.
>
> [...] images fix a communicative intent, thereby enabling meaning to be distributed across space and time to others.

(Whyte et al., 2016)

Recalling Maurice Merleau-Ponty's *Phenomenology of Perception* our internal reviewers suggest that 'we could define design as the inversion of cultural incorporating or inscribing practices. Hand sketches and actions immediately related to design work would then become reenactments of incorporated memories.' New spaces are made from the designers' cultural knowledge - 'abstract and embodied' (ZHA, internal communication).

The impact of physical and other media on creative ideation is broadly acknowledged in the design disciplines, who consider design media a foundational element in their professional workflows. Murphy (2005) describes design practice as a process of 'collaborative imagining' in which gestures, talk, and graphic representations contribute to 'a social, jointly-produced activity in which the objects of thought are created and manipulated in the shared space of face-to-face interaction'. With regard to individual sketching activities, Goldschmidt (1991) uses the term 'interactive imagery,' pointing out that 'sketching [...] is not merely an act of representation of a preformulated image' but rather 'more often than not, a search for such an image.' Specifically, she describes this process as a 'continuous production of displays pregnant with clues, for the purpose of visually reasoning not about something previously perceived, but about something to be composed, the yet nonexistent entity which is being designed.' Based on an ethnographic field study, Comy and Whyte (2018) put an emphasis on 'making rather than sensemaking,' bringing 'into view the visual artefacts that practitioners use in giving form to what is "not yet" – drawings, models and sketches.' They provide an account of how 'visual artefacts become enrolled in practices of imagining, testing, stabilizing and reifying.'

Given the forming influence that physical and digital media have on architectural and engineering design activities such as idea generation, problem (re-) formulation, or individual insight, we do not consider the involved representational media neutral substrates. Rather, we understand design media as full-fledged actors in their own right, which are forming the ways in which information is transmitted and perceived on an individual and collective basis. Physical and digital media are an integral part of our individual experience, thus having an influence on the way we perceive and engage with "presented" information, ultimately shaping our external cognition as a system of insight. Speaking from a distributed cognition point of view (Rogers & Ellis, 1994; Hutchins, 1995a, 1995b), design media are integral parts of the cognitive system that consists of human actors as well as their physical and digital surroundings in the environment in which design takes place. The underlying rationale of the distributed cognition theory considers cognitive processes not to reside exclusively in the individual human (mind/brain) but, instead, to conceptualise them be distributed across entire teams including the involved media and information systems, tools, instruments, notations, which complement individual human thought.

Collaboration Across Disciplines

Design is an inherently social activity, where multiple actors interact and exchange, and therefore social interaction inside virtual worlds is relevant. Extending the design-specific scope, the contribution of physical and digital media to professional practice can be understood on an even broader basis. Carlile (2002) stresses that cross-disciplinary communication often relies on physical and digital media that facilitate a 'mutual understanding through communities of interaction.' This work further clarifies that beyond the *tacit* nature of knowledge (Polanyi, 1966) `knowledge and knowing cannot be separated from an individual's engagement in the "practicing" of their practice.' According to Barley et al. (2012) 'objects allow individuals to work together, even in the absence of shared understanding.' In reference to a study by Henderson (1999), Barley et al. continue to point out that multi-disciplinary teams may use drawings to `coordinate their efforts even though they did not fully grasp the complex ways in which others attached meaning to the [same] drawings.' Here, we find the concept of *boundary objects* (Star and Griesemer, 1998) as particularly apt to describe media or that help interface between different domains and individuals. They define *boundary objects* as

> 'scientific objects which both inhabit several intersecting social worlds [...] and satisfy the informational requirements of each of them. Boundary objects are objects which are both plastic enough to adapt to local needs and the constraints of several parties employing them, yet robust enough to maintain a common identity across sites.'

While this describes the situation well on a macroscopic level, Carlile (2002) points out that the 'characteristics of "effective" boundary objects' is not trivial to determine. 'For example, a CAD model can be an effective boundary object at one stage, but can falter when taken to another setting where a key functional group cannot represent their knowledge or alter the current knowledge with a CAD model.' In a similar vein, Ewenstein and Whyte (2009) conclude that 'emphasis has been placed on the role that the objects play rather than on the nature of the objects themselves. [...] The internal characteristics of boundary objects such as their representational capacity are discussed on a general level, but they are not explained.'

Towards this end, the cognitive task analysis provides a micro-level analysis of established design activities. Cognitive task characteristics are described on a level of detail that reveals how particular pieces of (visual) content contribute to performing certain tasks. In view of the upcoming development of a platform for collaborative design that heavily relies on immersive virtual reality technologies it will be an important question how to design the environment in which PrismArch's users will be immersed in and interact with.

Visual Design Media

Visual representations can be considered intermediate project outcomes that not only stabilise the commitments that have been made up to a certain stage. 'These are objects which embody what is not yet known, and provide a motivation for the creation of new knowledge' (Scarbrough et al., 2014; cf. also Rheinberger, 1997; Knorr Cetina, 1997, 1999). Comy & Whyte (2018) describe a design meeting in which architectural sketches 'embodied, instead of avoided, uncertainty about the past and future.' They identify four distinct processes that shape architectural design projects on a macroscopic level:

- Imagining, where designers identify and explore different design alternatives
- Testing, where designers pursue each design alternative
- Stabilizing, where design directions are agreed and refined
- Reifying, where a chosen design direction is elaborated and refined

Comy and Whyte (2018) developed this taxonomy of design processes based on the analysis of an architectural project which was completed in the first years of the millenium, and thus primarily relied on 'traditional' design media such as tracing paper, printed drawings and CAD software. Nevertheless, this taxonomy allows us to clearly conceptualise different and distinct phases of an architectural project, how designers operate and communicate by handling different media. In a sense, these four stages of imagining, testing, stabilizing and reifying, are fundamental to design, and will be part of any design project regardless of the media available to the designer. Thus, a future VR-enabled system should also consider how it enables each of those processes. In relation to the cognitive task analyses provided in Chapter 5, this taxonomy provides a more macroscopic account on different cognitive tasks.

2.2 Virtual Reality as a Design Environment

Intuitively, space is experienced as a continuum. However, from the point of view of spatial perception and cognition, spaces can be distinguished according to the 'perceptual scale' – in other words according to how a space can be perceived (Montello, 1993). Montello (1993) provides a taxonomy of four scales of space: figural, vista, environmental and geographic space. Figural space can be perceived in its totality with small movement of the eyes; thus it is the space of figures, maps, print media, and recently screens. Vista space extends beyond the body of the observer, such as a room or a large atrium, and can be perceived without any movement. In contrast, environmental space, i.e. the space of buildings and cities, cannot be experienced from a single vantage point; instead the person has to move from one space to another and integrate spatial information across multiple scenes, or 'vistas'. Finally, geographic space, such as the space of countries and continents cannot be directly experienced, and is therefore experienced through other media, such as maps. Deliverable T6.1 develops an interaction model that will allow users to 'dynamically navigate and review project data and design objects inside VR by recording snapshots of world coordinates' (ZHA, internal communication).

This distinction is useful when thinking about the cognitive processes that take place during an architectural or urban design session. The architects inspects a site (environmental space), then transforms it using drawings into a figural space – where sketching and ideation take place – while imagining how the space will look like from the end-users perspective, i.e. in vista space. Despite the fact that we all inhabit and routinely use all four scales of space, translation from one scale to another can be effortful – this challenge is not unique to architecture. Consider how it feels to have to relate a city map with one's own viewpoint, in order to navigate, or how difficult it can be to appreciate how a space will be experienced, used and feel simply by looking at its floor plans – especially for laypersons. In response, some augmented reality applications for geographic / urban space such as Google Street View, combine a first person perspective with a top view.

Virtual reality promises to bridge this cognitive cost of 'moving' from figural to environmental space – a drawing on a screen (i.e., in figural space) can be experienced from within (i.e. in vista space) with the click of a button; a team of designers and/or clients can indeed move directly from one room to another, going seamlessly from the figural of a drawing to the environmental space of the building. Second, VR enables a transition between abstract spatial forms (e.g. geometric primitives) to highly detailed/textured representations. In some fields, such as GIS and urban planning this is formally described as levels of detail (LOD), although definitions vary (Biljecki et al., 2021). Moving across different levels of abstraction, from the simple volumes to textured surfaces or even occupied spaces, can help guide users' attention to different elements of the environment, or facilitate enhanced sense of presence, spatial properties, dimensions etc.

On one hand, the capacity to translate between scales of space and between different levels of detail, is an essential strength and rationale for integrating VR into the design process. For architects who are trained to do such conversions using their imagination, a precise spatial representation can help anchor one's own intuitions – how small or large is a space etc; yet for non-trained users, such as clients, this can greatly facilitate the experience of unbuilt space. On the other hand, interface design should carefully consider the cognitive effort associated with linking a 2D drawing (e.g. floor plan) with a 3D view of the same space. In this respect, linking multiple media requires additional cognitive effort for making the link between mental and external representations (Kirsh, 2010). A VR system shall therefore aim to support users from different backgrounds in this process. For instance, simultaneously showing the position and bearing on a top-view within an immersive 3D view can help establish where the user is and keep track of their movement in the virtual space. Besides providing a design environment for architects and engineers, PrismArch will also be used as a platform for presenting architectural design projects to clients, contractors, and interested visitors who might or might not have a comparable level of experience in navigating and interpreting spatial content in immersed environments. Supporting non-expert users in maintaining oriented should be considered when modeling the user interaction for 'public users' (cf. D1.1, Req. #1).

Navigation in Virtual Environments

> An early model of navigation in VR was developed by Steve Benford and Lenart Fahlén that is still relevant today (Benford and Fahlén, 1993). They identified that interaction takes place between people and/or objects through a medium. Every avatar and object in the VE has an aura surrounding them that defines the extent of their presence. When the auras of two objects/avatars come into contact they are able to interact. They also recognized that awareness of others is critical to interaction in VR.
>
> (Benyon, 2004, p. 41)

Compared to "conventional" real-world environments, navigation in VR raises a number of challenges that users have to overcome. When a person is moving through space in the real-world, she receives information (sensorial input) about this movement from different sources. Visual perception provides information about visual (optic) flow, body-based senses provide kinesthetic and proprioceptive feedback (about the movement of one's own parts) and vestibular input about the acceleration and rotation of one's head. The integration of information from multiple sources (senses) contributes to the ability to self-localise and keep track of movement within an environment.

During the last decades, Virtual Reality has been used extensively in the fields of Cognitive Science and Environmental Psychology, to investigate the cognitive processes underlying human navigation (for recent reviews, Kuliga et al., 2015; Diersch and Wolbers, 2019). Typically, in such empirical studies, volunteer participants from diverse demographic backgrounds (i.e. not design /experts) are asked to navigate in a virtual reality, either using a desktop-based interface or using an immersive head-mounted display (HMD). Comparative studies between navigation in the real or in a virtual replica of the same building, suggest that people's strategies and wayfinding performance does not differ between real and virtual environments (Kuliga et al., 2019). Other studies have shown similar results of comparable task performance in real and virtual office spaces (e.g. Heydarian et al., 2015).

As already identified by Weisman (1981) there are four main factors that make navigation (or wayfinding) difficult in buildings:

A. lack of architectural differentiation (many spaces look similar)
B. lack of visual access (difficult to see from one space to another, and how spaces are connected)
C. lack of signage
D. layout complexity

Indeed, large complex buildings typically combine all the above features to assist wayfinding, e.g. atria to allow visual access within and between floors, strategically placed signage and maps. etc. Spatial cognition research has also demonstrated that users (i.e. person navigating in the building) rely on such views and cues to navigate effectively. When these are not intuitive, usability and navigation 'break-down' – people become lost or take long detours trying to find simple destinations (Hölscher et al 2006; Kuliga et al 2019).

While it is critical for architects to consider how their designs perform with respect to these four factors, these are also relevant in the context of an immersive design interface such as PrismArch. During the early stage design phases, architectural drawings (2D and 3D) primarily contain architectural forms, rather than architectural details (materials, textures) that would facilitate navigation. Similarly, at such design phases there may be no signage present.

Navigation within immersive VR environments poses three major challenges: how to move through space without physical movement (translation without locomotion), how to provide adequate perceptual cues to the user about the movement (speed, distance). Further, users often report incidents of motion-sickness as a direct result of trying to move through a virtual space. Various technical solutions have been proposed to this problem: continuous translation using the press of a button, teleportation, where the user can point to a distal location and appear directly there, without the experience of moving through the intermediate space, and intermittent movement, where the user moves in a succession of small intervals. In addition, some of these methods rely on pressing buttons on a keyboard or joystick, while others require physical movement, such as 'walking-in-place' with the intention to reduce the experience of motion-sickness. These three major methods of VR movement provide different visual cues to the person with regard to the movement. Nevertheless, researchers have shown that movement methods that do not consist of continuous translation do not disrupt the acquisition of spatial information (e.g. Li et al., 2021), while providing the benefit of reduced incidence of motion-sickness.

A separate, yet critical problem arises when more than one person navigates in the same virtual environment – that of coordinated movement. The issue known as *spatial desynchronisation*, occurs when one of the two people move in one direction while the other stays in the same or moves in another direction. In real-world it is easy to perceive and direct the other person using voice, vision and tactile communication. However, in VR people may be physically next to each other, or thousands of kilometers away. A solution proposed by Weissker et al. (2020) is that of Multi-Ray Jumping. VR participants groups are allocated into the roles of one 'navigator' and one or more 'passenger(s)'. The navigator can move freely (point-and-teleport); in contrast, when a passenger initiates movement using their joystick, initiated, the UI not only 'teleports' them next to the navigator but also mediates their oncoming trajectory using a curve towards their future position to facilitate spatial updating and lower cognitive load (Weissker et al., 2020).

3 USER REQUIREMENTS FROM A COGNITIVE PERSPECTIVE

The present chapter reviews the report on *Limitations of AEC software tools, VR user/functional requirements* provided by our project partners (Deliverable D1.1) and assesses key requirements in cognitive terms. Reviewing the descriptions of *Architectural, Engineering and Construction Industry* as well as the user requirements (D1.1, ch. 2 and 4, respectively) substantiates our understanding of (a) project data and how it is disseminated across design disciplines as well as (b) how the visual qualities of various presentation media shape the way in which designers can engage with their building projects. Besides occasional general observations, a detailed investigation of the project case-studies (D1.1., ch. 3) is postponed and will be provided by Chapter 4 of this report, together with the interview consultations with our project partners.

3.1 Visual Presentation and Design Media

When reviewing D1.1. and the project documentation provided alongside the case studies, one of the first things we observed was the rich diversity of the visual material. The key role of visual media is equally true for collaborative design workflows in meetings and workshops as well as in the individual work of architects and engineers.

> Diagrammatic Drawings are used throughout the life of a project, especially in the initial stages -to represent engineering plans and sections details and conceptual options without detailed information. These drawings are presented to clients in an early stage of design development and these are also helpful to communicate with the rest of the design team to discuss advancement in the design. A selection of those is often attached as appendices in the design reports.
>
> (D1.1., p. 32)

As already pointed out in Chapter 2, we consider visual representations to be intermediate project outcomes that not only stabilise the commitments that have been made at a certain stage. They also serve as condensed, *stabilised* representations of the project information that has been accumulated so far.

> Visualizations are evolved through practice, multiply, become increasingly collated and enriched in more reified and hybrid forms, become linked together, and circulate across localities and stakeholders, including the supply chain involved in fabrication, assembly, and on-site work, and the external sponsors such as clients, insurance companies, and public authorities.
>
> (Whyte et al., 2016)

Within its specific scope, a particular plan or drawing provides a consolidated view of all design-relevant aspects. As such it is a starting point from which the subsequent design development can evolve. We also highlighted earlier that it is a key capability of visual representations to acknowledge rather than hide 'uncertainty about the past and future' (Comy and Whyte, 2018).

Designers choose tools according to task-specific requirements, media-specific characteristics, and their individual styles and preferences.

> Designers' work involves exploring design options, and they tend to gravitate to tools that allow them to achieve their aim fluidly and within the shortest time. The tools that are used in an early concept stage vary and can be multi-media, can be a hand sketch, digital 2D/3D sketch or cardboard physical models.
>
> *(D1.1, p. 51)*

To be successful as a design platform, PrismArch should therefore support individual styles on an interactive as well as on a workflow level. Regarding the latter, allowing for a thorough integration with a decent spectrum of traditional digital and physical media ecosystems is more than desirable.

> PrismArch platform should be aware of the fact that the project inspiration parameters can vary and the terms should be flexible and these might include cultural, experiential, personal, environmental, economic, technical or mathematical terms.
>
> (D1.1, p. 97)

Tracing Paper

By studying tracing paper as a case study we develop a broader account of the design-typical vision-centric workflows. The recurring theme or concept of the *visual overlay* subsumes their capability to

> overlay the information [from multiple sources] to obtain the full picture of the design constraints [... so that] all the available information can be seen and reviewed together.
>
> (D1.1, p 105)

A wide range of design disciplines and related design activities rely on this characteristic, which is probably best understood in terms of its tight integration between visual information presentation and other cognitive activities such as imagining new information or recombining existing pieces of information. This becomes particularly evident in the wide applications of tracing paper in collaborative and individual design, where it allows to put 'into relation present and past information' (Comy & Whyte, 2018, p. 1065; cf. also sct. 4.SEL). An important component of early-stage design work is to stabilise information from various sources by 'consolidating [...] a cascade into increasingly stable or fixed images' (Whyte et al., 2016), accumulating and integrating it into a coherent visual representation such as the site constraints diagram (AKT, 2021, Jan, slide 7; cf. also sct. 4.2).

Architectural and engineering design disciplines put a strong emphasis on visual presentation modes and the application of tracing paper allows the gradual accumulation and recombination of visual information within one view, provided by a two-dimensional visible medium.

Tracing paper is a routine yet fundamental medium that is essential for the design process. Through its nature, tracing paper allows copying information from an underlying layer. Yet it also allows to *blur* the details of the underlying drawing, yet permits to recognize – and (re)trace – key spatial forms. This *strategic opacity* allows designers to selectively transfer spatial objects from a drawing, in order to highlight, explore, and manipulate geometric information. During a design session, for instance, a tracing paper is placed on the site plan, an initial access plan is drawn, another layer is then superimposed with an initial idea, which is then distorted and refined with subsequent layers (cf. sct. 4.SEL). This practice has been transposed in CAD and other software (e.g., Photoshop, After Effects) where users superimpose information across multiple layers. This cumulative process, where layers of information and ideas are superimposed is an essential component of the design process – it is a way of thinking about space. As noted by Do et al (2000), such diagrams serve multiple functions: concept generation, problem visualisation and problem solving, representation of real-world objects so that they can be 'manipulated and reasoned with,' perception and translation of ideas (Do et al., 2000; cf. also Goldschmidt, 1991).

In reference to the theoretical framework of distributed cognition one could understand tracing paper as providing a (material, external, physical, analogue) representation for spatial information. Comparable to Hutchins' approach (1995b) to 'apply the cognitive science frame to the cockpit as a cognitive system' we can consider the entire design team including the design media and in particular tracing paper a distributed system that processes information which, in turn, we can analyse according to cognitive principles. 'How are the speeds represented in the cockpit?' How is the (spatial) information represented that informs the design activities in question? 'How are these representations transformed, processed, and coordinated with other representations in the descent, approach, and landing?' How can tracing paper be processed and coordinated with other representations? We mentioned previously how tracing paper plays a key role in design practice for its capability to visually coordinate, recombine, accumulate etc. spatial information from various sources and bring this information into one view (cf. also the *Instance Query User Interface*, T6.1). On a more long-term scale, Comy and Whyte (2018) portray

> how visual artefacts become enrolled in recursive practices of imagining, testing, stabilizing and reifying, whereby they enable making the transition to a realizable course of action. This transition [...] is performed as visual artefacts are assembled and evolved to envision an increasingly stable, holistic and persuasive view of the future.

Hutchins (2005) provides a cognitive account of 'a general and ancient human cognitive phenomenon, the association of conceptual structure with material structure.' Section 5.2 provides a more thorough account of the cognitive characteristics of tracing paper and other visuals in their application as design media.

Spatial Alignment and Visual Inspection: Layering

One of the key lessons that can be learned from the tracing paper case study is its capability to spatially align two or more different sources or layers of spatial information. A similar technique is provided in CAD systems where three-dimensional content can be separated into *layers.* Spatial elements can be assigned to different layers, independent of they extend in and are arranged in 3d space. The layering allows the user of the CAD software to selectively hide/show elements or to allow/block them being edited. Typical applications range from assigning materials and other properties based on layers so as to efficiently edit elements of similar type or properties. The technique is further used to show specific aspects selectively for presentation purposes. For instance a designer might want to show functional requirements together with the key circulation components for a presentation to the client while hiding structural elements for this presentation. Comparable to tracing paper, layers allow the recombination of spatially aligned content for visual inspection. While these requirements are derived from how "conventional" design media are used in practice today, future approaches such as *sphereing* (currently under development as part of PrismArch, cf. T6.1) will have to achieve an equivalent functionality in immersive VR and other future design environments.

Perspectives, Views, Markups and Overlays

More broadly, the issue of visual coordination between multiple media in three-dimensional space will be of great importance when studying the cognitive characteristics of the *Toggle Camera Perspective Tool* (D1.1, Req. #7) and the *Commenting + Mark-up Tool* (Req. #11).

Depending on the spatial location of a user in space the perspective changes. Which three-dimensional content can be seen by a user and how the spatial elements appear in the visual field depends on the position of the user (or the virtual eye) in space. Preserving the exact visual impression over time requires the user (or the virtual eye) to return to exactly the same location.

Req. #7 foresees 'user camera perspective shortcuts for reviewing the loaded 3D assets from fixed points of view: as default, TOP, SIDE and PERSPECTIVE, ' allowing users 'to view the project from several key perspectives repeatedly without having to travel to them each time.'

> Comment and markup tools seem to be used by disciplines throughout all project phases and these are therefore commonly included in most of the available AEC tools.
>
> (D1.1, p. 51)

'Markups and comments are attached to the object content. The spawned markups and comments are automatically resized according to the user distance and users can show and hide the comments' (Req. #11). The functionality relies on precisely aligning two-dimensional and/or three-dimensional elements spatially. Users create comments or markup in precise visual coordination with two- or three-dimensional content that already exists. Req. #11 refers to the Toggle Camera Tool when stating that users should be given the opportunity to 'add comments and mark-ups from a fixed viewpoint'. Again related is the functionality subsumed under the Clipping Plane Tool (Req. #14) which, in a slightly different way, allows to stabilise a view onto a, typically but not necessarily flat, planar cutting surface.

How spatial content is presented visually can greatly influence how a design task unfolds from a cognitive perspective. Furthermore, overlays are of particular importance for *Visually Inspecting Spatial Data.* We will return to these two points in Section 5.2.

3.2 Design Workflow

Data and Document Management

First and foremost, our project partners highlight an overall requirement applying to all design projects: To manage risks that can emerge throughout all project phases in a cost-effective and health and safety compliant manner.

> [...] risks can be introduced at any stages of the project development including the construction stage and after project handover. Incidents often involve the actual physical site conditions that are uncovered after works begin on site, and these are often investigated and reported by project contractors.
>
> (D1.1, p. 104)

With respect to information management in design projects this implies that emerging new information needs to be disseminated efficiently between project partners and be brought to the awareness of involved stakeholders. The ISO Standard No. 19650 defines tools and processes for effective information management (International Standard Organisation, 2018). D1.1 stresses that 'risk is introduced every time information is translated or exchanged between parties during the design stages'. It also became clear early on in conversations with our partners that keeping track of the status of information is essential, including authorship, confidentiality and approval status (e.g. sketch, draft, final, approved by...), actuality, revision/versioning.

Beyond the actual development stages of a project, maintenance and monitoring activities rely on an adequate data basis 'upon the handover of the information to the building operation managers.'

Access Control Across Teams and Disciplines

Depending on which 'party' an information 'belongs to', it

> cannot not be unilaterally or immediately available to all PrismArch users, but accessed according to the users' project role and access privilege. For instance, it is necessary to withhold structural and MEP calculations from contractors, so that the contractor can verify their capability through doing their own calculations, and accept the liability for the construction. This is also used as another check for the engineers' calculations.

Early on in our research, studying scenarios such as the one described by Episode I1ZMa highlighted to us how important it would be to address such confidentiality concerns, especially for a project that promotes the fluent co-presence of digital information across organisations and design professions. Meeting remotely, presenting and exchanging potentially sensitive content via a digital meeting platform requires the careful consideration of the future users' demand for an unconditional trust in the data security and privacy capabilities of the system. Based on this scenario, Sequence 1 in Section 5.1 analyses the activities related to presenting, sharing and collaboratively working on documents in design teams with a particular focus on access privileges and team structure. Concerning the checking of engineering calculations described in the last sentence of the above quote we would like to point the reader to the next subsection. A particular challenge lies in finding a good solution for (a) not hindering a fluent interaction between multiple immersed users on the one hand and (b) giving users adequate means of monitoring and controlling information access privileges on the other.

How information is protected, temporarily shared in a meeting, or permanently disseminated to a particular colleague, team, or group of colleagues and stakeholders is not only a matter of data security features of the underlying digital infrastructure. Equal care should be taken that the users can intuitively develop an adequate understanding of the platform data-management capabilities. A key component will be to provide tangible metaphors alongside rich (visual) feedback on possible actions and their consequences. The *sphereing* concept proposed by our project partner ZHA represents a promising candidate for a tangible interface in this respect (sct. 6.2).

Design Options, Data Integrity, Versioning

To a large extent, designers are occupied with activities around

> producing design options, evaluating and amending the options, and coordinating programmes and circulations [... in order] to form the project-brief collaboratively with the clients and to propose the best possible solutions that match the clients' requirements.
>
> (D1.1, p. 55)

Combining the above with the

> Golden Thread principle, whereby concise records of every decision will be required, as well as the criteria for the decision and any conditions that influenced it,

(D1.1, p. 106)

introduces a requirement for remaining data integrity and versioning of design options at all times.

> The PrismArch platform should automatically generate a record of the project, including the full file version history, a record of internal and external meetings, decisions, approvals, submissions, and the detailed reason for any changes introduced along the way, either during design or construction.
>
> (D1.1, p. 106)

Conceptual ideas around the versioning of design options have been discussed throughout the project timeline in internal meetings as well as in official reports. Primarily reflected in the ideas expressed by our architectural partners that 'each data element should have a representation of the author signature and timestamp' that would serve as a 'unique label/tag that works as an identifier' (D1.1, p. 112; cf. also Req. #3, Query tool).

Project-internal consultations concluded that the version control system Git™ together with cloud-based collaborative platforms GitHub™ and GitLab™ provide a large set of functionalities that meet the above requirements. Revolving around the notion of a *history of transactions*, each version of a project can be seen as a node in a network of transaction histories. Section 6.2 provides a model of the user activities and information flows within collaborative design teams. Relating this analysis to Git's transaction history approach the study provides valuable insights on how to communicate and visualise versioning aspects to future PrismArch users.

Beyond the actual technical requirements concerned with the system's design providing data integrity, we would also point to the social and psychological factor, in how far users trust or can verify whether data are valid, for instance by (visual) double-checking procedures (cf. sct. 5.2).

3.3 The challenges of Virtual Reality

The collection of user requirements points to a variety of activities, interactions, and processes that need to occur in a "conventional" meeting setup or design environment. These include sharing and showing materials, making gestures for emphasis or to point to specific (design) objects, sketching, manipulating objects and more. These interactions (with other people or design materials) can be considered an integral part of design and communication. However, it is not always obvious how to "translate" (or emulate) these in an immersive virtual reality setup.

For instance, two important challenges of a design sessions in VR that were identified in D.1, among others, are:

- the difficulty to take notes / write text / voice recognition
- the selection and manipulation of objects

Design and collaboration in VR raises further challenges that pertain to spatial cognition. These include how to maintain a sense of orientation and direction within a complex building, how to navigate from one space to another. In order to navigate inside complex real-world buildings, we routinely keep track of our movement, direction and destination, using vision and body-based senses e.g. walking speed), visual cues in the surrounding environment as well as distal cues (e.g. the view outside a window). Often, this information is insufficient, and buildings are equipped with additional cues to help users, such as signage or wayfinding maps is necessary to support navigation and avoid being lost. This is especially the case of large complex buildings that one is unfamiliar with (Hölscher et al., 2006; Kuliga et al., 2019). Yet, such navigation aids are usually refined and added once the project nears completion. Further, environmental cues (such as outside views) are not usually implemented in early-stage 3D / VR models. This raises the challenge of how to assist the users of PrismArch to navigate, in the literal sense of wayfinding, in large and complex settings during the various stages of design. For example, imagine a design review where a team of designers and stakeholders wish to navigate inside a large public building (library, stadium, shopping centre). What information should be provided to them to ensure they can efficiently visit all the spaces of the design review? Potential solutions could include:

- virtual compass
- map of the floor a user is on
- 3D view of the environment
- distal landmarks (i.e. outside the project itself)
- predefined routes to visit for the review

Visibility Control

The users can toggle on / off features of the design project (e.g. walls) in order to establish a sense of orientation (cf. also). Previous research in spatial cognition in VR has shown that by making some walls semi transparent and providing distal landmarks (e.g. a neighboring building) can help users maintain their sense of orientation while navigating complex buildings in VR. This point is related to layers (cf. above) and 'render modes' (D1.1, Req. #8) which allow users to control the way three-dimensional content is displayed in general (cf. also sct. 6.1). Contrary to the layer-wise visibility control, that strongly relies on a predefined organisation of the content based on typologies or on other ways of grouping the content, making a section can be considered a spatial way of "opening a view" into parts of a model that would otherwise be obstructed (cf. Req. #14, D1.1).

Co-presence and Immersion

Benyon's quote (2004, p. 41) at the outset of the section on *Navigation in Virtual Environments* introduces the notion of *co-presence*, referring to the capacity of three-dimensional physical environments to let people immerse in space and experience the people and objects around them to "be there." Co-presence and immersion are the properties that make an environment "spatial" in the sense that the aforementioned activities can happen in a "natural and intuitive" way. Having an entire design team immersed in one three-dimensional space while at the same time allowing each member to maintain their specialised professional view on this space represents the key user experience design challenge of this project. This will require the system to (1) provide users with a sense of spatial immersion and co-presence that adequately reflects the team configuration, task requirements, and underlying data model, (2) allow them to understand and control their interactions with the team and the content through the system, and (3) enable them to perform the tasks at hand in a fluent and efficient way in relation to the overall design workflow. For instance, in a traditional meeting setup it is immediately clear for a "user" that leaving a note on a large plan on the table will result in this note being "public" to the other members of the meeting. By contrast, a note taken down in a small book this user brought along for her or himself will remain “private.” The user's freedom of choice whether to make a note public or private should not be affected by relocating the meeting to a virtual space. However, interacting with a virtual system will affect the way such options are presented to the user and therefore the way users act to achieve the desired outcome. Topics related to migrating design activities into immersive virtual environments will be revisited in more detail throughout the course of the present document (5.1, Sequence 1 and 2; sct. 6.1 and 6.3). On a larger scope, an integrated digital workflow opens opportunities that go beyond the actual development, including the virtual use of the created datasets and designs in post construction phases, as virtual twins and in virtual archives, their exploitation as research data, as virtual filmsets, tourism, etc.

From a requirements POV, enabling users to fluently interact with the immersive environment in a way that is meaningful to them will be critical to making the unified design space a place where future AEC projects are developed.

4 DESIGN EPISODES CATALOGUE

Complementary to the more descriptive presentation of the user requirements in the previous Chapter 3, we now turn to design processes at a more fine-grained descriptional level, with particular emphasis on design *events and activities.* An episodic, narrative aspect that is the constituting criterion for the material collected in this catalogue. We focus on episodic reports that we consider representative of architectural, structural and MEP engineering practices. The catalogue thus provides a stable basis against which UX concepts, guidelines, and experimental procedures can be tested. Some of the sequences also serve as raw material for a more thorough cognitive task analysis (ch. 5).

Sources for such activity sequences or process episodes can be (1) existing literature, (2) scenarios developed by or in collaboration with our project partners, which are documented in project deliverables or in internal presentations as well as (3) consultations with our architectural and engineering design partners in interview-like sessions. The following sections make reference to the respective sources. Links to related sections and additional sources will be provided in braces *[ ]* where applicable. The collected episodes are of various degrees of detail, depending on how they are reported in the source material.

4.1 Source: Existing Literature

We present a typical episode based on a narrative report from an ethnographic field study by Comy and Whyte (2018):

> In response to the strategic brief, the architects invited their engineering consultants at CS. A few days after the project kick-off, they held a design meeting to discuss future options for the carpark. This was attended by four participants: the lead architect, the founder architect (Ted Cullinan), a service engineer and a structural engineer. As they engaged in conversation around the strategic brief, the two architects captured their thoughts through a felt-tip pen sketch on tracing paper laid over a site plan. The sketch of the carpark was produced through consultation of pre-existing artefacts: not just the site plan laid under the tracing paper, but also a draft of Stage A/B report (which included the architects' response to the strategic brief). This report contained results of an environmental assessment of the site, and was consulted for information on existing features (e.g. listed trees). Another pre-existing artefact that gave shape to the architects' sketch was a site development plan, …
>
> ...which illustrated proposed extensions on the east and west sides of the existing Herbarium. It suggested relocating the carpark from the riverside to the rear of the existing Herbarium, and incorporating the existing staff carpark to provide 256 parking spaces. This document had been prepared two years earlier by another architectural studio, and was included in the strategic brief for consultation by CS architects.
>
> ...architects incorporated present constraints into the sketch (e.g. listed buildings, trees and walls) and considered suggestions from strategies formulated beforehand (site development plan). Yet, the site development plan became contested as the architects' sketch revealed inconsistencies with existing features of the site. The lead architect explained that the vehicle access option suggested in the site development plan ignored significant trees and encroached onto a listed wall. Furthermore, the architects and engineers doubted that the carpark could fit 256 parking spaces, and noted a lack of information on the strategy underlying the site development plan.
>
> [...]
>
> architects' sketch [...] became reworked, retraced and annotated with calculations of capacity requirements for the car park.
>
> [...]

As architects and engineers engaged with sketches, they took notes on their notepads: questions about as-yet-unknown information, or hunches about potentially viable options.

(Comy & Whyte, 2018, pp. 1065-1069)

[cf. sct. 5.1]

4.2 Source: Scenarios Developed as Part of Project Deliverables

Design Reviews

Internal design reviews include project technical and design director, senior engineer and design engineers with occasional guidelines from principals. Design reviews can happen in a meeting room with a TV screen with an A1/A0 printed document, projected BIM models and or physical models. Meeting minutes are to be recorded during the reviews and hand sketches and verbal communications are the core driver of the discussion.

(D1.1, p. 28)

Remote co-design

Each member worked individually using their own work environment (software, PC spec, folder structure etc) to produce several massing options.

(D1.1, p. 55)

[VILLA]

[cf. Episode I1ZMa, Appendix A; Sequence 1, sct. 5.1]

Massing

In order to propose a few geometry options that reflect the clients' requirements and present the visual and aesthetic qualities of the building, architects typically carry out massing studies using 3D modelling tools prior to sharing these ideas with engineering disciplines.

(D1.1, p. 98).

[cf. previous and following subsection: Remote co-design, Structural Concept; cf. also Akin & Mustapha, 2003]

Structural Concept

In this stage the project director and the senior engineers are interfacing with the client and the design team, understanding the brief, the constraints and the ambitions in terms of materiality and sustainability, and assessing the targets in terms of performance and cost. In this initial phase of the project the early CAD drawings, site material, investigations, photographic surveys, digital surveys etc are reviewed to understand both the existing conditions and the Architectural intent. In this instance, we have supported the Client and the architectural team in developing the first massing ideas.

(D1.1, pp. 62)

The history of the site and its surrounding area has been assessed using extracts from John Rocque's 1746 Map of London, historical Ordnance Survey (OS) maps from 1851 to the present day and other reliable information. AKT II have obtained existing drawings of Ludgate House from Sir Robert McAlpine Archives which give an indication of the structural scheme of the building that is arranged on lower ground, ground and eleven upper floors.

After collating all the relevant information from the site, a site-specific constraints diagram is prepared (Figure 3.2.b.1). This document allows the team to coordinate with the rest of the

> design team, issues such as potential clashes with services, impact on proposed structural system, on massing and interferences.
>
> [...]
>
> The existing Geotechnical report has been received by the client, then this information is reviewed and used to extract the parameters needed for the design of the foundation system and the retaining structure[...]
>
> (D1.1, pp. 80)

[cf. Episode I2ANa, Appendix A].

Structural Modeling Workflow

> Preparation of different structural modelling FEM (Finite Element Modeling), element design. Several 3D FEM models have been prepared by the senior engineer and his team to provide the wider team with fundamental considerations such as behaviour of the tower against lateral forces, impact of load takedown on foundation system, informing structural grids and typologies of structures. The work is done on instruction of the project design director and technical director that have defined the most appropriate structural typologies.
>
> (D1.1, p. 63)

[cf. Episodes I2ANa, I5AAa-b, Appendix A]

Changes in later Design Stages

> Since the final model was changed, submitted drawings also needed adjustments in response to the changes. This specific case study did not implement the BIM system, yet even if the system was implemented, the 3D model adjustments had to happen inside the 3D model with lower design resolutions. This means that the project needed to be downgraded to make changes and they would need to access the multiple software again to essentially create a new BIM 3D model.
>
> (D1.1, p. 100)

[cf. Episodes I2ANa, I5AAa, I5AAb, Appendix A]

T6.1, Task A.Struct.3: Lead Designer_Structure creates...structural model...

This episode of collaborative activities was initially presented by AKT in an internal meeting (AKT, 2021, May), before it matured into one of the user scenarios for the deliverable T6.1 (ch. 3, A.Struct.3) in preparation. It exemplifies the collaborative workflow between a Design Engineer (DE), a Senior Engineer (SE), an Architect (ARC), and an MEP Engineer (MEP). The workflow example nicely demonstrates how documents are handed over between and within design offices, and how the status of information changes whenever information is transferred, approved, etc. The status is reflected in the tag that belongs to each document instance.

> 11. LD_S makes a copy of the current architectural 3D model. In this new model, they create an abstracted global FEA model of the building: manually building mesh and line elements that represent columns, beams, walls and floor slabs. LD_S assigns a new PAST and names it 'StructuralModel_v1_GeomInputs'. This new model is assigned SL1, and saved inside the PAW.
>
> 12. Using a software connector, LD_S exports this geometric model to a structural analysis package. Inside this package, LD_S applies cross sections, materials, supports, loads and load cases to create a complete FEA model. LD_S assigns a new PAST and

names it ‘StructuralModel_v1_FEAinputs’. This new model is assigned SL2, and saved inside the PAW.

13. LD_S runs a structural analysis on the FEA model. The results are directly exported to a PA-compatible data file, and uploaded into the PAW. LD_S assigns a new PAST and names it ‘StructuralModel_v1_Outputs’. This new model is assigned SL2, and saved inside the PAW. LD_S creates a PAMS to discuss the results with PD_S.

14. PD_S and LD_S meet in the arranged PAMS. The results from the structural analysis are presented as a series of structural stick models, with various structural analysis datasets (deflection, utilisation, max force, etc) overlaid on them via colour-coding and labelling. PD_S reviews the model and is happy with the chosen design variant. They approve all of the SL1 content created by LD_S, and these assets are upgraded to SL2. LD_S’s tasks are resolved and disappear from the PrimArch dashboard.

[cf. sct. 6.2]

4.3 Source: Interview Consultations with Design Partners

Our design partners’ internal research on their work practices produced an extensive body of project documentation on four *Project Case Studies* (D1.1, ch. 3) and related events or ‘incidents’. Despite the great level of detail provided by the material, a majority of the process knowledge is only implicitly given by the drawings, plans, sketches and renderings given as part of the material. For instance, it may be trivial for an engineer to *infer* based on a site constraints diagram, which steps were necessary to produce it. Yet, from a non-engineering perspective it is evident that the diagram itself does *not make explicit* all the activities and types of information sources required to compile such a diagram (AKT, 2021, Jan, slide 7).

In order to gain a more holistic understanding ETH discussed some of the materials in depth with engineers and designers who were actually involved in the projects underlying the case studies. While we had initially planned to conduct a questionnaire-based study asking participants to comment on selected items from the visual materials in the case study documentation, an interactive, interview-like conversational format turned out to be more suitable to capture the complexities underlying the production of design drawings and other materials.

Each session was organised as open or semi-structured individual conversations or consultations between a researcher and an architectural or engineering designer. Due to the CoViD-19 pandemic situation these conversations took place on the video-conferencing platform zoom™, which was also used for recording the sessions. The sessions focused on

1. the role of different digital and /physical media as well as technical design tools (paper, CAD, VR, AR) in the design practice
2. how these media have been adopted and used in the projects.

Visual material from the documentation of these case studies helped establish a meaningful conversation and facilitated directing the conversation towards aspects that are relevant from a future user's perspective.

The collected selective transcripts describe sequences of events and activities based on verbal reports by our interview partners. In most cases, they are related to existing design projects or case studies. If possible, the episode will have a reference to the discussed case studies.

Transcripts (in Appendix A)

The actual transcripts of the interview conversations are located in Appendix A.

5 COGNITIVE TASK ANALYSIS

The cognitive task analysis follows the rationale to provide a formalised account of key components of the cognitive processes in individual and collaborative design. They are a preparatory step for the upcoming activities in WP3, effectively driving the systems design as well as our future empirical testing of the systems prototypes (cf. Description of Actions, RA3.3 and RA3.1) as part of the upcoming activities in WP3 (cf. sct. 6.4).

Following the distributed cognition approach by (Hutchins, Rogers and others), the cognitive system comprises all components that contribute to solving the task at hand. In our case, we consider entire design teams and their design tools and media a cognitive system. Choosing the right level of abstraction will be crucial for deriving a meaningful analysis. Subsequent refinements may shed light on processes that were omitted in the abstraction of the present analysis.

The narrative material collected in the *Design Episodes Catalogue* (ch. 4) serves as input.

5.1 Sequence Analysis

The sequence analyses presented in this section are inspired by UML 2.0 sequence diagrams, a type of diagram that 'focuses on the Message interchange between a number of Lifelines' (OMG™/UML, 2017, 17.8, p595). Their essential characteristics allow the modeling of the interactions between multiple actors and their parallel activities in one unified diagrammatic representation.

The technique suits the media-heavy, highly collaborative activities to be modeled in an architectural design context. The sequence diagrams abstract away from all media-specific aspects which emphasise a different set of aspects compared to the predominant focus on design drawings, visual practices. Ultimately, this constitutes an intermediate representation for extracting requirements from more specific and "context-heavy" material. In particular, the sequence-based approach fosters an explicit diagrammatic representation of the functional requirements. Beyond identifying involved parties and their interactions, the approach encourages the researchers to complete the picture by becoming more concrete. Identifying specifying which information is exchanged between the actors is a stepping-stone for a comprehensive task description from a cognitive point of view.

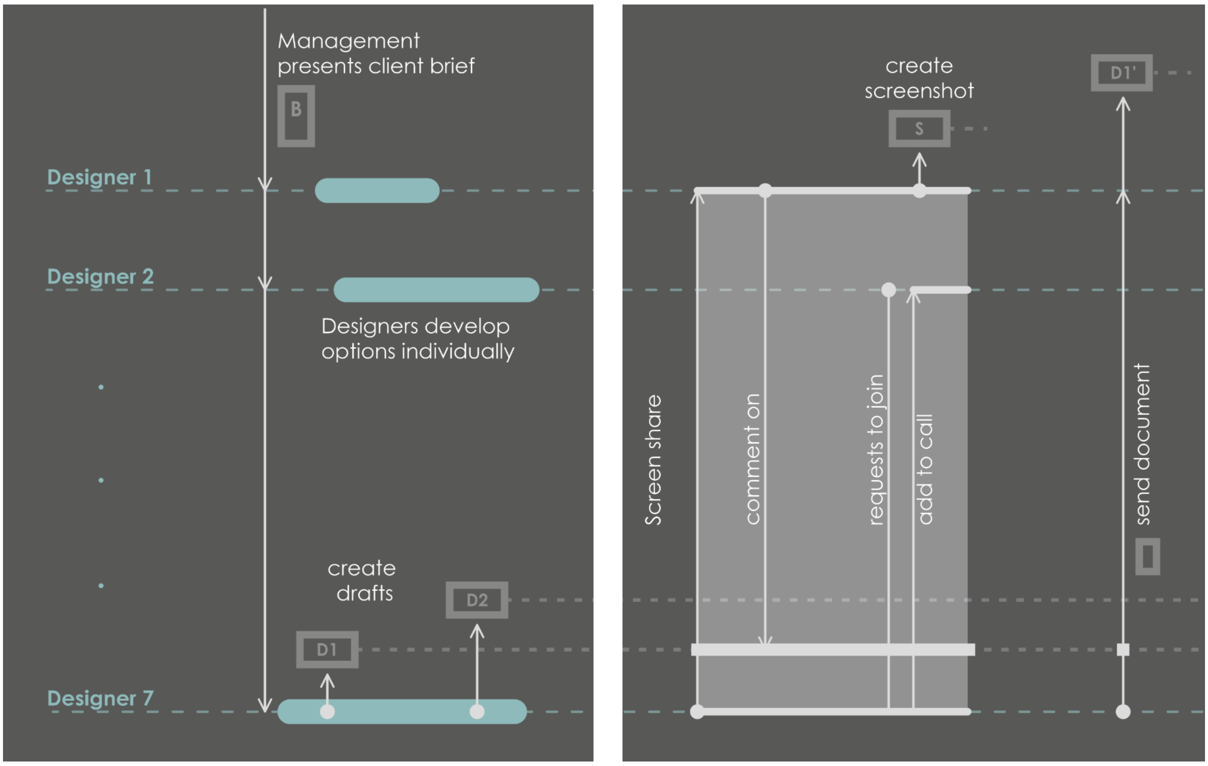
Concerning the development of a UX concept, their abstract nature, in turn, captures the bits that need to be specified for the future system. The design media and their visual qualities are to be designed for the new immersive environment, driven by and in compliance with the abstract descriptions provided by the sequence diagrams. The situation is comparable to what Wei, Delugach and Wang (2019) describe as a 'model with semantic holes [which] provides insights of the system to the modelers and invites them to complete the model by filling in the holes with missing requirements or correcting inconsistent requirements acquired from other models', design process episodes, in our case.

Notation

The approach taken here uses the *lifelines* to represent human as well as non-human *actors*, i.e., users, technical systems components, as well as physical and digital media and documents. In the diagrams these are depicted as horizontal dashed lines, with the actors' name or caption attached to the left. Alternatively, an icon can be used. We consider persistent *documents* and *design media* an integral part of the overall team collaboration, as mediators between team members. Documents and media are, hence, represented as lifelines/actors as well, i.e., as a text framed by a thick rectangular line of the same colour.

Sequence 1: Remote co-design

This sequence is based on an episode described by our project partner ZHA as part of the requirements analysis (D1.1), complemented by an individual conversation with one of the designers who were involved in the project (ch. 4, I1ZMa).



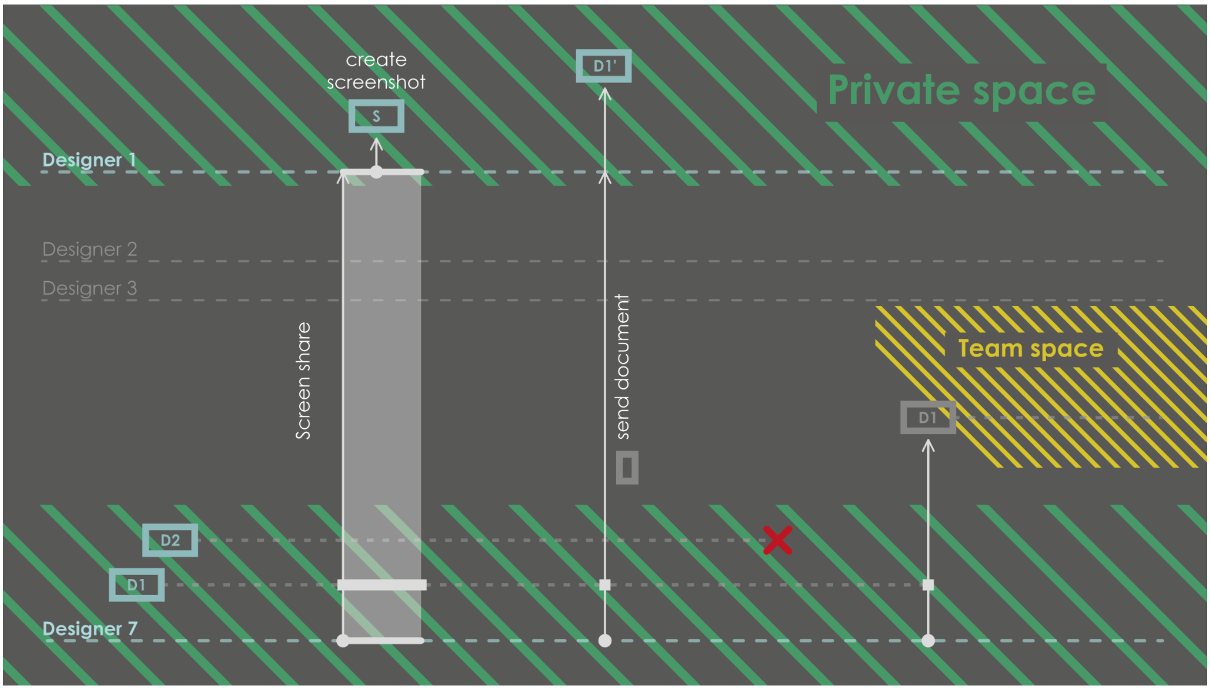


Figure 1: Sequence Analysis based on Episode I1ZMa, provided as three images (a, b, c).

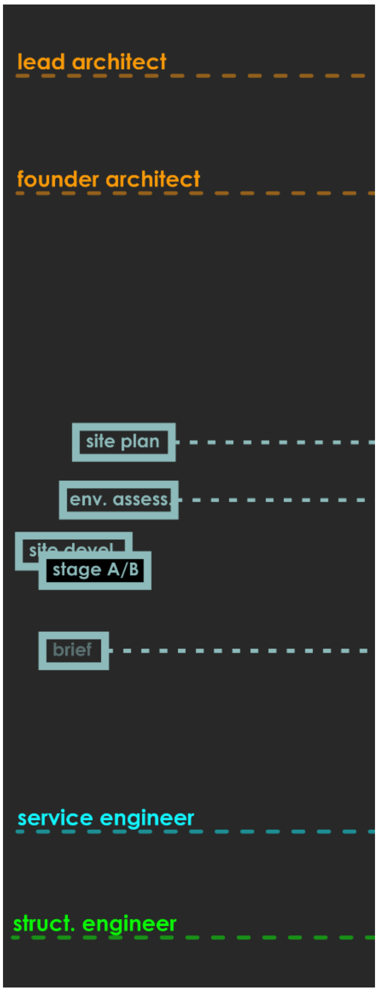
Figure 1 provides a condensed version of the sequence analysis diagram developed for studying Episode I1ZMa. (a) The management presents the client brief to the design team. As a next step, designers work individually to develop design options in parallel. (b) Designs are presented to other team members via video-conferencing platforms in combination with screen share as well as other document sharing mechanisms. (c) Depending on the medium which is used for presentation and how documents are exchanged (screen share, team-wide document repository) team members grant to their peers different levels of temporal or permanent access to content that was created individually. Overlays show an early sketch for how spaces or levels of individual privacy and access rights could be structured for the future system.

Two aspects are revealed: First, designers use a variety of different media and modes of data exchange when presenting their work to their colleagues in a two-way conversation, to their team internally, to a senior for approval. Each medium and method of sharing has implications of how permanent the data is shared and how designers can interact with the content during the presentation. For instance, a screen share allows for manipulating the view and even commenting on the presented material by means of overlay drawing tools. The presenter will remain the single owner of the shared material after the presentation, although image content may be copied by the meeting members via screen shot. Sending a file, by contrast, gives the receiver permanent access to the data model.

Second, studying scenarios such as the one in Episode I1ZM highlight how important it is for a design platform to address confidentiality concerns prevalent in architectural and engineering contexts (cf. sct. 3.2).

Sequence 2: Architectural Designers meet with Structural and Services Engineers

Analysing this episode provided in Section 4.1 from a field observation by Comy & Whyte (2018) reveals (1) how access to documents should be restricted based on the team structure, (2) how access may be granted temporarily to other users as part of a meeting situation, and (3) how tracing paper as a medium for collaborative design activity can be modeled as a document that is shared across all members of the meeting. The three aspects above are strictly media-agnostic and it will, hence, be straight-forward to transfer them to other media, i.e. immersive virtual environments (cf. sct 6.3). Beyond, tracing paper has the media-specific capability to allow for (4) sketching on a semi-translucent medium in visual/spatial alignment with an existing *reference* medium without affecting the reference permanently. A detailed study of how to achieve similar or equivalent properties in a three-dimensional immersive virtual environment will be discussed in Section 6.1.



In response to the **strategic brief**, the architects invited their engineering consultants at CS.

A few days after the project kick-off, they held a design meeting to discuss future options for the car-park. This was attended by four participants: the **lead architect**, the **founder architect** (Ted Cullinan), a **service engineer** and a **structural engineer**.

As they engaged in conversation around the strategic brief, the two architects captured their thoughts through a felt-tip pen **sketch on tracing paper laid over a site plan**.

The **sketch of the carpark** was produced through consultation of pre-existing artefacts:

not just the **site plan** laid under the tracing paper,

but also a **draft of Stage A/B report** (which included the architects' response to the strategic brief). This report

contained results of an **environmental assessment of the site**, and was consulted for information on **existing features** (e.g. listed trees).

Another pre-existing artefact that gave shape to the architects' sketch was a **site development plan**, ...

Figure 2a: Sequence Analysis, Step 1: Identify Actors. The narrative is given on the right hand side (Comy & Whyte, 2018). Colours were added so as to visually link key actors, documents, and media described in the original source to ETHs sequence diagram.

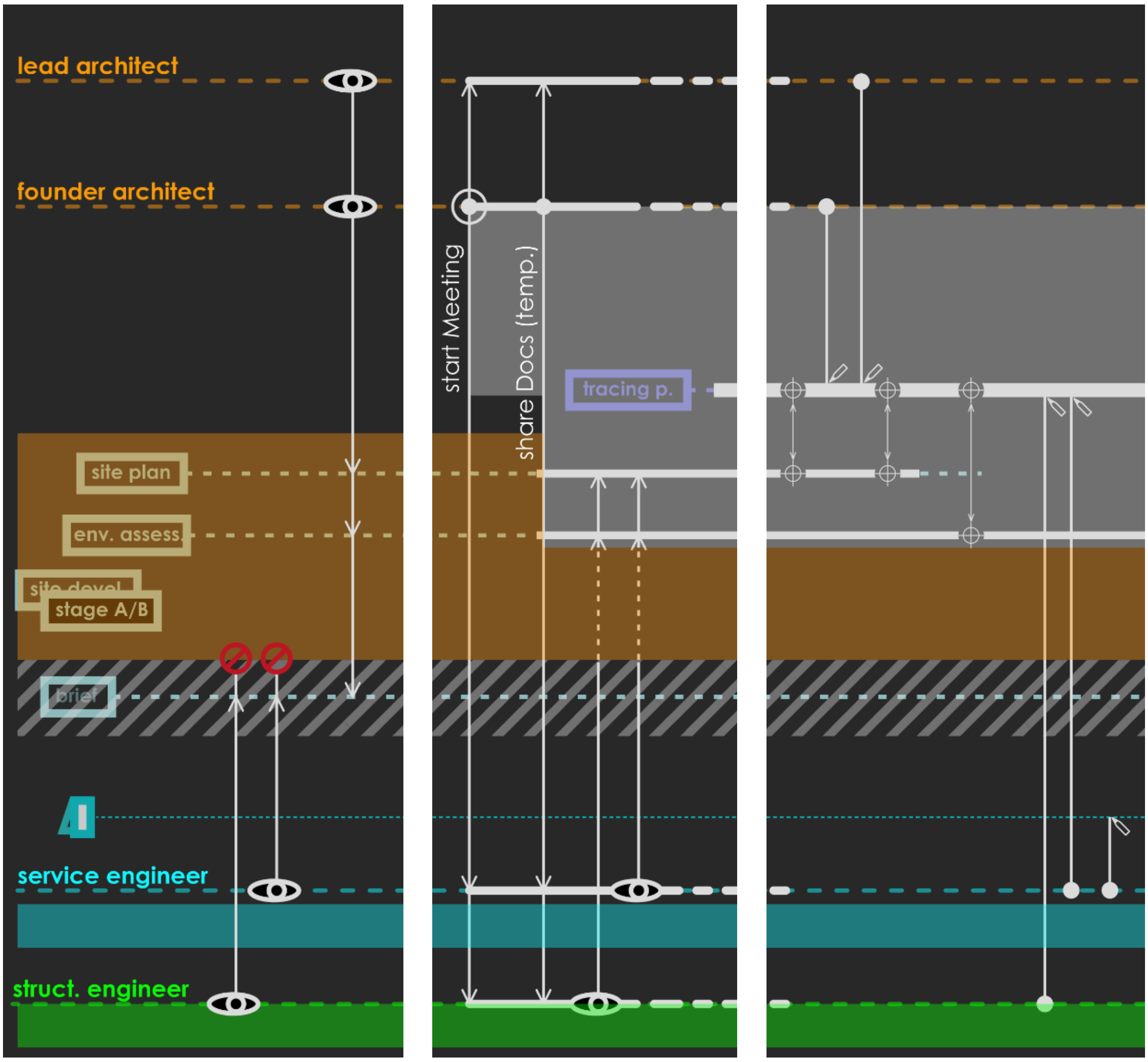


Figure 2b: Sequence Analysis, Team Document Access. Orange, cyan, and green overlays represent the document spaces with their team-specific access restrictions. White (light gray) represents a temporary document space established during the meeting, white (light gray) hatches represent project-wide access to the design brief.

Figure 2b describes different situations regarding document access and media interaction throughout the meeting. (a) Before the meeting, the service and structural engineers do not have access to the documents in the architects' team space. (b) After initiating the meeting, the founder architect grants access to the site plan and the environmental assessment; reflected by the white meeting space overlay extending so as to enclose the two temporarily shared documents. Tracing paper appears as an additional document that is created during the meeting. (c) All meeting participants have access to the tracing paper which can be spatially aligned with other media/documents; symbolised by the arrow-connected registration marks.

Beyond its functional role (allowing multiple meeting participants to annotate and sketch simultaneously), tracing paper as a visual/spatial design medium is studied in Section 5.2.

Sequence 3: Early Stage Exchange Between Engineering Consultants

This sequence shows an extensive exchange of information in an early project phase between various involved engineering consultants as documented in the project case study

One Park Drive (D1.1, sct. 3.1.b). Rather than a sophisticated parallel activity and interaction between multiple actors, as was the case for the previous activity sequences, this example puts more emphasis on the accumulation and structuring of information from various sources. Whyte et al. (2016) describe a similar effort around a major coordinating document as a 'cascade of representations that led to this composite document.' While this abstract view on the information flows and their directionality reveals the key pieces of information to be accumulated, other aspects remain unspecified or unresolved: How information is structured and presented to the designers is largely omitted; folded into media-agnostic arrows which do not reveal any of the visual qualities or the mediality of the exchanged data. Comparable to the tracing paper example that was presented in the previous section the abstract description of information flows between actors is a *necessary* component in gaining an understanding of the team-wide processes but it is by no means *sufficient* to capture design in all its tangible and media-specific dimensions. The following Section 5.2 substantiates our view on the information flows by discussing the tangible aspects and media-specific characteristics that help designers process and exchange the information in practice.

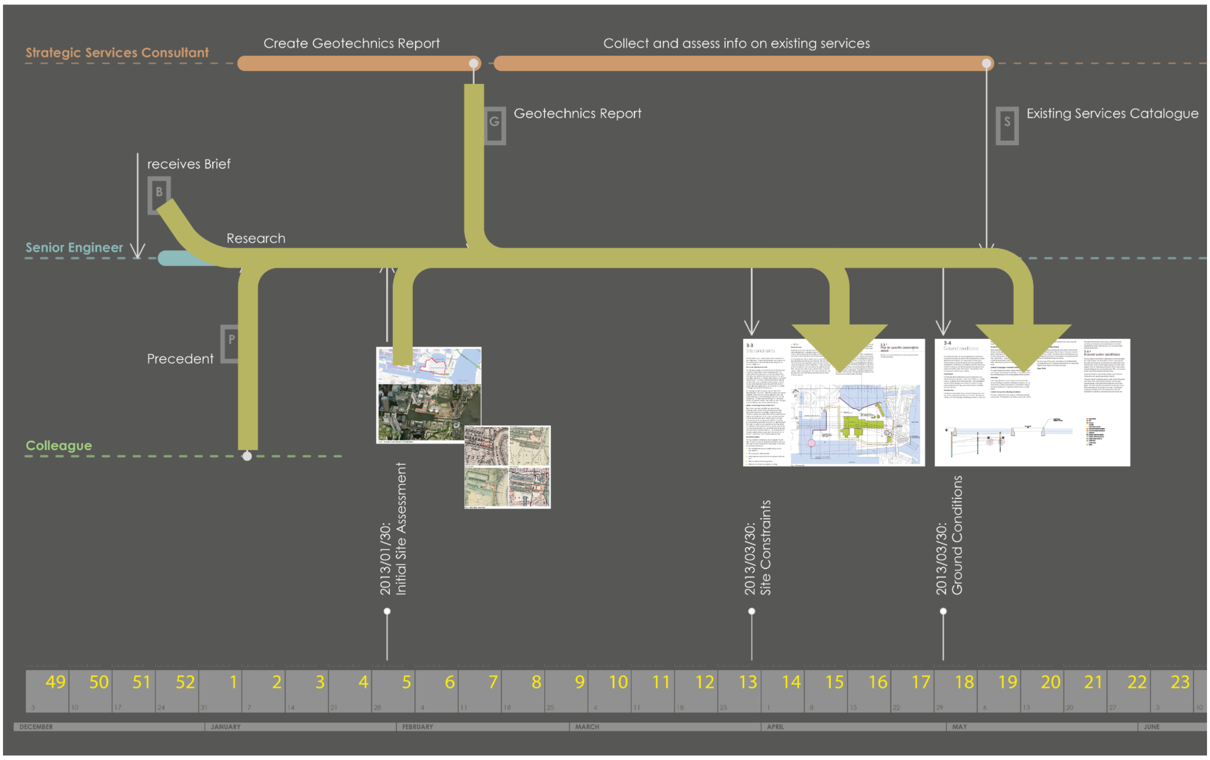


Figure 3: Sequence Analysis, Compiling the site constraints and ground conditions information for One Park Drive (D1.1, sct. 3.1.b).

5.2 Cognitive Characteristics of Design Media

The present section reports on case studies that we analysed qualitatively in order to substantiate our understanding of the tangible qualities provided by different design tools and media such as tracing paper. A second subsection studies some of the strategies designers use in conjunction with different modes of presenting spatial information in design media. For instance, design media help stabilise large accumulations of complex datasets, such as the ones typically compiled into conclusive reports towards the completion of each design stage (D1.1, p62), e.g. as a result of the site analysis in stage 1 (AKT, 2021, Jan, slide 7).

Tracing Paper

As we have argued in Section 3.1 tracing paper exemplifies a number of desirable properties for design media which this section will describe with a cognitive approach in mind. Its capabilities to visually align spatial content allow designers to transfer spatial content with relatively little cognitive effort. One spatial arrangement serves as a *reference* or *source* with a temporal drawing surface overlayed on top, that serves as a *target*. Both media represent planar, two-dimensional, continuous euclidean spaces, which are practically identified by means of the visual alignment. An application in design practice is well documented by *sequence 1* in this chapter. Several modes of operation are possible: (a) Successively overlaying one target tracing paper with several *sources* of the same scale allows designers to *accumulate* spatial information from all sources into the same target by tracing it with a pen on the target paper. (b) By retracing specific aspects from a source on multiple tracing papers may *selectively extract* spatial information from the source. (c) Overlaying different combinations of the tracing papers will later allow to *re-combine* the information in arbitrary ways. (d) Finally, *combining* and *re-combining* tracing papers (b, c) in conceptual sketching provides designers with a tool for *generating* and visually exploring un-imagined combinations of visual content, in turn stimulating their visual imagery and ideation, recalling Goldschmidt's 'interactive imagery' (1991) as discussed in Section 2.1.

On a micro-level, the use of tracing paper is probably best described as an example of conceptual blending with material anchoring: Humans 'anchor their mental processes on external features or processes' in that they 'establish a coordination between what goes on inside their heads and what goes on outside' (Kirsh, 2010). Based on Fauconnier's conceptual blends, Hutchins (2005) elaborates on 'thinking strategies that involve the interaction of mental structure and material structure.' Fauconnier (1997; cited after Hutchins, 2005) describes *conceptual blends* as operating on two 'input mental spaces to yield a third space, the blend. Partial structure from the input spaces is projected into the blended space, which has emergent structure of its own.' (1) The 'projections from the inputs' produce a 'composition', in turn making 'new relations available that did not exist in the separate inputs'. (2) 'Knowledge of background frames, cognitive and cultural models' i.e. cognitive models as well as cultural "background knowledge," things we know about the inputs, 'allows the composite structure to be viewed as part of a larger self-contained structure in the blend. The pattern in the blend triggered by the inherited structures is "completed"into the larger, emergent structure.' (3) 'The structure in the blend can then be elaborated. [...] It consists of cognitive work performed within the blend, according to its own emergent logic.' Rephrased in Hutchins terms:

> The key thing here is the way in which two or more spaces are blended together. Various elements of the input spaces are selectively mapped to the blended space. In the blended space, new inferences are possible. In fact, some new inferences become automatic.

And he further clarifies by giving the example of a queue:

> This cultural practice creates a spatial memory for the order of arrival of clients. The participants use their own bodies and the locations of their bodies in space to encode order relations. The gestalt principle of linearity makes the line configuration perceptually salient. Our perceptual systems have a natural bias to find line-like structure. But seeing a line is not sufficient to make a queue. Not all lines are queues. Soldiers standing at attention in formation form a line, but not a

> queue. In order to see a line as a queue, one must project conceptual structure onto the line. The conceptual structure is the notion of sequential order. [...] Conceptually blending the physical structure of the line with an imagined directional trajector turns the line into a queue.

In Hutchins' account, the tracing paper, pen and the reference media can be regarded as cases of 'material anchors', allowing us to perform complex cognitive operations such as (a) accumulation, (b) recombination, (c) extraction, (d) generation. The applications of tracing paper in design, hence, allows us to 'manipulate the physical device itself because it is not possible to imagine it accurately enough to be of use.'

Visually Inspecting Spatial Data: Double-Checking, Versioning, Data Sources

Under this somewhat unwieldy title, this section applies the insights from the tracing paper case to a broader scope. How spatial content is presented visually can greatly influence how a design task unfolds from a cognitive perspective. For instance, two (or more) design options can be presented (a) in *parallel* as separate plans or images arranged in a *distributed* layout, next to each other. In this case, users have to make comparisons by constantly redirecting their visual focus between corresponding locations in each option. Speaking in terms of material anchors, for making a comparison between versions users need to anchor and mentally coordinate both external representations at corresponding locations. Alternatively, options could be presented (b) as an *overlay* of the options, *cumulated* in the same spatial frame. Corresponding locations align in one spatial reference for all options. Comparisons between options with largely identical layouts with smaller or isolated changes will be easy to comprehend with this approach, e.g. different options derived by modifying a common predecessor). For larger changes the overlay is likely to produce a cluttered view, in turn, recommending the parallel, distributed presentation. (c) Instead of overlaying the options, the cumulated layout could be split into narrow stripes or *slices* which each present some details of one version, while the overall layout is preserved in the frame (cf. also). Finally, interactive approaches could allow users to (d) flip through the options at their own pace in a slide-show-type of presentation or (e) use a pointing device to interactively move the split between different slices.

In developing the above example, the focus was on the visual inspection of design options. Beyond, there are a number of design activities that require the careful comparison of spatial content for subtle changes. Most importantly, requirements analysis stressed the need for *Design Options, Data Integrity, Versioning* (sct. 3.2). Whether as part of inspecting versions of the same "file" or dataset, or as part of integrating content from heterogeneous sources, the way it is presented to the user greatly affects how well differences can be spotted. An example of layering different dimensions of project assets is given in Situation A no. 18 in connection with reviewing different design versions as a slide-show no. 25 (Deliverable T6.1, sct. 2.1). Furthermore, the cross disciplinary aspect of combining and re-combing project assets is exemplified in Situation A no. 31, (Deliverable T6.1, sct. 3.1).

As an example we refer to episode I3ZOe (Appendix A): Alongside with the 2d design drawings provided by the facade engineer for validating the layouts for the GRC panels, the architect 'requested the 3d model back' that the facade contractor used to produce the 2d design drawings. 'So we could overlay that model with our model.' The architect describes the task as being 'almost like clash detection' (I3ZOe, 1a, 1b, ibid.). A different approach in the same project was to take 2d plans and 'layer them up level by level in a 3d environment

[...] open the 3d model which we also had in microstation' in order to 'see if there's any areas where they weren't aligning' (I3ZOe, 2a, 2c, ibid.).

Episode I2ANa (Appendix A) documents a different case which, nevertheless, follows the same underlying rationale. Drawings and visual representations in general can play a role in explaining conceptual thinking, for instance in providing a visual narrative to engineering calculations. This will allow colleagues and other consultants to visually validate the underlying calculations by following the step-by-step visual presentation.

A second example is informed by internal project communication with AKT as well as based on sequence *I5AAb* in Section 4.3. Coordinating an architectural model with, say, a non-trivial finite element model (FEM) in a fluent workflow is among the open issues in AEC industries.

In general, developing confidence in a design is an iterative process which depends on several factors including the technical platforms on the one hand, but also how human cognition is being onboarded in terms of presenting information in a way that suits the task.

> A design like this, it has its complexity, it is even with the best sort of 3d visuals it's hard to really get your head around how some of these connections work [...] So when we did these 3d prints - it was something that helped everybody - especially [...] where the structure is very complex [...]'
>
> (Appendix A, I4ZCb, 4, 4a)

Similarly, Shih et al. (2017) report that designers prefer to keep switching back and forth between sketches and CAD modelling. To conclude, the value of coordinating multiple representations of the same design needs to be considered when virtualising design environments. Possibly, or ideally, these representations are based on different models and employ different modeling techniques; Humans will then need to engage with them in order to coordinate and *anchor* these representations through a coherent distributed cognitive process. Farías (2009) reminds us that the key productive forces in intellectual and creative activities may be exactly the 'breaks and discontinuities' emerging from working with manifold digital and physical media. On the other hand, linking multiple media requires additional cognitive effort for making the link between mental and external representations (Kirsh, 2010). Research questions D. and E. address these issues (ch. 7). Along these lines, the prospect of integrating task-relevant information into a holistic view has the potential to fundamentally transform the cognitive DNA of today's design practices.

6 USER EXPERIENCE DEVELOPMENT

This section presents conceptual sketches of key user experience elements as they were proposed and discussed in ongoing project meetings by our partners and ourselves. In reference to the requirements in Section 3, the design episodes in Section 4, and the cognitive task analysis in Section 5 we will then assess the proposed options for implementing an immersive virtual design environment. As a key contribution this will provide an understanding of how immersive environments as a design medium alter existing design practices as encountered in the field today.

We have stressed in the previous Chapter 5 that the sequence-analyses abstract from the media-specific characteristics and, hence, their application to the new implementation is more or less straight-forward. The sequence models will therefore serve as test cases for user interaction scenarios – comparable to integration tests in software development, but on a high level of abstraction that considers a multidisciplinary design team as a test case.

Other sections discuss specific topics such as the subsection on *Revisiting Tracing Paper* in Section 6.1. In these media-specific cases, a translation from the old media (e.g. hand sketches or tracing-paper) into the new medium immersive virtual reality is required. We need to carefully consider the role each medium and component plays in the work practices as they are currently established in the analysed domain.

6.1 Outlining a Navigation Concept

Allowing users to orientate and navigate not only depends on providing a map or introducing users to the structure of a spatial configuration. In order to orientate themselves, users need to use cues, landmarks and other features of the environment which help them make a connection between what they know and what they perceive (cf. ch. 2). Orientation can be seen as *anchoring* their internal, conceptual understanding with the external structure of an environment, and maintaining that connection while moving around. The activity of navigating then relies on sufficiently precise knowledge about the environment so as to make informed decisions on how to reach a desired location.

Material anchors frame an understanding of design activities from a distributed cognition POV (sct. 5.2; Hutchins, 2005). Our cognitive task analysis in Chapter 5 instantiates that logic by studying the entire design team as a cognitive system, including the information flows between people as well as the involved media. In order to accommodate individual human cognition in a task-environment that allows for an optimal workflow, it needs to be structured in a way so as to provide task-relevant information without overwhelming users with visual clutter or unrelated information. In terms of navigation this has implications for how PrismArch's virtual world should be structured, which spaces will exist in it in order to provide an optimal task environment for the various design activities to be performed. In the first place, this structuring is clearly defined based on cognitive and functional requirements. For instance, if a team needs to discuss a number of design options they need a meeting space that provides a certain configuration of people and information. It is certainly crucial to curate the information as well as the possible ways to interact with this information in such a way that users (1) maintain orientation, (2) are able to navigate in that meeting space. While the former usually refers to people finding their way in three-dimensional "built" space the concept of navigation can have a broader meaning. For user interfaces, navigation means to allow users to choose from the available controls in a structured manner. We can transfer/apply the two points to the meeting space example in a broader sense. This gives a glimpse on what are the choices we can and need to make in order to achieve a well-designed virtual task environment for design collaboration.

Anchoring Conceptual and Spatial Reference Frames

The diagram in Figure 4 was developed as part of the conceptual work by ETH in order to provide a navigational structure that incorporates and arranges the various functionalities based on a task-centred grouping. The sequential arrangement reflects the subsequent decisions a user needs to make in order to onboard the PrismArch platform and finally immerse in a particular design project at the desired location. Our visual presentation of the navigation sequence in Figure 4 is by no means indicative of how the actual visual concept will ultimately look like. In this respect, we would like to refer to the *PrismArch Platform Onboarding Sequence* as that is presented as part of the conceptual design work by ZHA (2021, May).

With respect to navigation, each space corresponds to a conceptual frame, i.e. it corresponds to a set of underlying concepts that help the user understand (frame) a set of related possible user actions. Each of the three depicted spaces accommodates the specific functions related to a certain level of control. From a navigation POV it makes sense to align those conceptual frames with experiential spaces users can navigate.

A user who enters PrismArch World (PAW) will first have to provide credentials in order to pass access control. The user has not yet chosen a project. The first space she or he will encounter therefore accommodates all topics related to *Access Control.* This not only refers to the individual login itself but also administrative activities such as controlling the access privileges of other PrismArch users, team configuration aspects across all projects etc. Obviously all activities are only available in so far as sufficient access privileges were granted to her or his account. All higher level user and team -related actions such as setting up new projects, making arrangements for new project teams and their required data repositories on a team management level. When choosing a project and entering *Project Space* the focus closes up on the chosen project. Teams that are working on this project, their members, project documents and how these relate to different teams and responsibilities become visible here. This is also a good place to arrange meetings, choose individual members to participate and make a general choice of which items to present. The meeting itself will then take place in an environment that provides confidentiality according to the required level, and which allows participants to curate and present design content in an adequate way. At this point, *Architectural Space* comes into play: 3d content needs to be arranged and presented, clients and visitors need to be navigated through the virtual environment, individual private notes can be taken, markup can be made and so on and so forth. It is here where the full interactional and informational complexity of PrismArch as a unified immersive design environment becomes most prominent.

In their presentation of the *PrismArch Platform Onboarding Sequence,* our design partner ZHA clearly distinguished between two user interface modes or configurations: (1) The personal work sphere (PWS) contains all sorts of tools that users can interact with. Here, the personal data sphere (cf. the following subsection) has an experiential quality and serves as a personal space in which users can choose and configure their individual tool set. (2) When entering architectural space the view ‘widens’ and the personal sphere is supposed to be 'less visible' - so as to allow users to fully immerse in architectural space. Architectural space, according to our terminology is where three-dimensional content can be inspected, presented, manipulated – where design takes place. We will provide a proof-of-concept study in the next subsection, how visibility control, sharing and presenting content, making public markups, taking private notes and the like may be accessible while maintaining a fully immersed experience. We will return to some of the points in the following section.

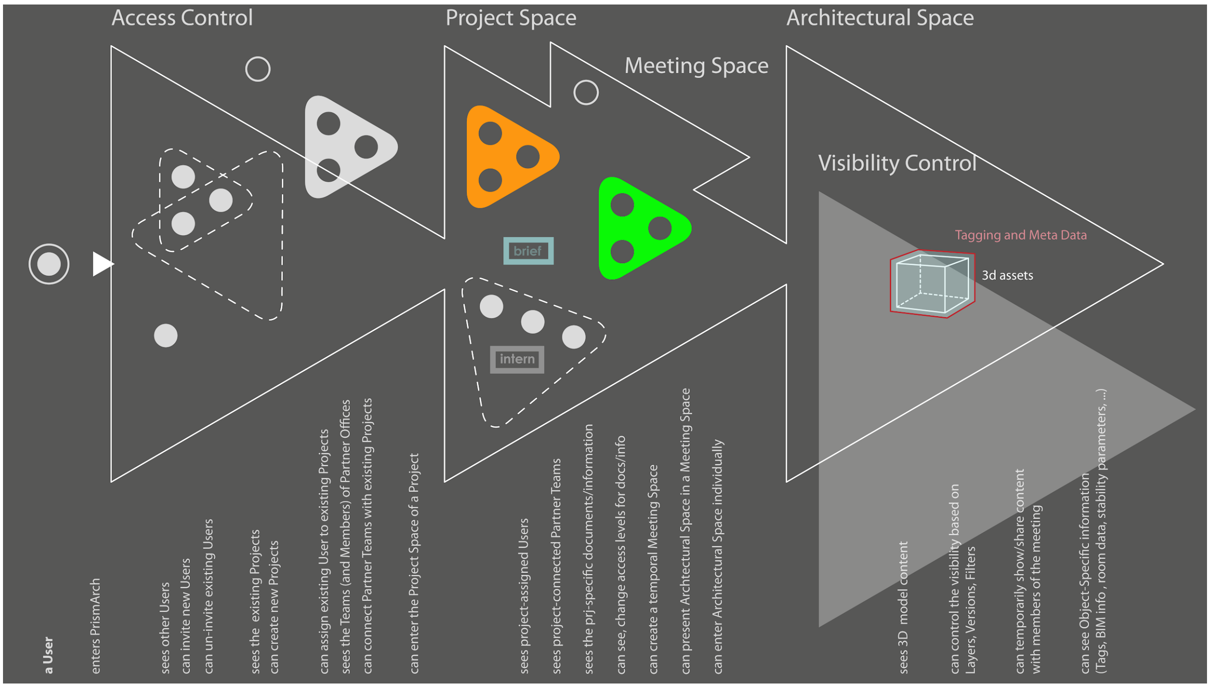


Figure 4: Overview of a navigational concept for configuring functions into a spatial organisation. A user that 'enters' (logs on to) the PrismArch platform can navigate in a sequence of three spaces. Each space provides a different level or granularity of control.

Tracing Paper Revisited: Immersive Collaborative Design

Is it possible to transfer (or migrate) the functional role that tracing paper has in the traditional design process into a three-dimensional immersive virtual environment? How can the related functionalities, as studied in the cognitive task analysis (ch. 5), be provided in an immersive design environment? The sequence of sketches or conceptual mock-ups presented here serves as a proof-of-concept. The explicit way of indicating different visibility settings for private, public and temporarily shared content are inspired from a traditional layering system in a three-dimensional CAD system. As such they are functionally valid in the sense that they indicate key information to the user. What is also apparent, though, is that the visibility-modes indicators are achieving this in a rather non-immersive and conventional way. In that sense they are rather pointing out what will need a more elegant solution for a truly immersive experience. Regalling the subsection on *Co-presence and Immersion* there are a number of social aspects that are being "dealt with" by having separate mostly two-dimensional media within physical space, especially the visibility and confidentiality of information, privacy, co-presence. The spatial configuration of people and physical infrastructure such as meeting tables, plans, notebooks, tracing paper, personal tablet computers, projectors etc. are well-established practices that allow us to organise social matters "in" three-dimensional space. The moment we conflate all these separate spatial representations within one immersive three-dimensional space, these social matters will have to be organised in a different way. By collapsing their spatial boundaries and extending them to be (overlapping) three-dimensional “layers”, each medium’s specific social role (e.g. private/public) can no longer be maintained through the spatial configuration, as was the case in the conventional setup. S*phereing* is one of the key UX concepts ‘to demarcate and organise the complexity existing in the database’ (ZHA, internal communication, May 2021). It points to the possibility to address the issues related to unified immersion by reflecting some of the informational complexities in the experiential sphere of PrismArch’s users. The conceptual mock-ups presented here follow a different approach in that they locate visibility control on a separate level, in a space that is separate from the three-dimensional architectural space (sct. 6.1), as is the case in CAD systems and their *Layering* functionalities (sct. 3.1). In the present example this is achieved by means of an overlay display “on top” of the immersed view that indicates the visibility and sharing settings for each layer.

We developed the mock-ups in close coordination with the activities during a design meeting as described by Compy & Whyte (2018; cf. also chapter 4 of this document). Sequence 2 in Section 5.1 provides a sequence analysis diagram of the team communication in the design meeting in question. Particular emphasis is also put on how to relate this study to the markup and toggle perspective functionalities described in the user requirements (chapter 2; D1.1, Req. #7, #11).

Figures 5a, 5b, 5c each show two stylised views through virtual reality HMDs. The upper left view represents the situation of the presenter or meeting host, and the lower right view simultaneously shows the situation for a member of the audience or a guest.

The presenter sees the documents she or he prepared for the meeting. A list of items that can be shown or hidden instantly is provided, comparable to layers in a traditional CAD software. After starting the meeting (Figure 5a), the site plan and the brief are currently displayed for the architect but the site assessment is hidden. The engineer can only see the brief that has been shared by the architectural office with the consultants before the meeting and, hence, is available in her or his own data sphere, alongside a private notebook “layer.”

During the meeting (Figures 5b), users can share contents with others spontaneously by making specific items or “layers” become visible in the meeting sphere. Shared items can still be switched invisible on an individual basis, allowing for different users to configure their views according to their disciplinary needs. In this framework, the functional role of tracing paper can be implemented by means of a shared layer all members can see and edit. Correspondingly, private layers would be used for taking notes on an individual basis.

Concerning interaction design, it is an open question how to allow making all these control choices related to sharing and visibility without interfering with a fluent design activity. Nevertheless, the minimalist overlay of items allows users to remain immersed in architectural space while making changes to the visibility and sharing configuration. A set of few succinct gestures could bring up or hide such a minimal overlay, comparable to the mouse gestures for exposing all windows on contemporary window managers of desktop operating systems (windows, mac os, gnome).

Another open issue will have to be addressed with respect to perspectives and markup based on fixed views. For presentation purposes, the views of meeting members need to be coordinated. A consequence would be that their movement is no longer free but needs to be controlled by the platform or the presenter so as to maintain a shared view. A possible solution could be to pre-curate such views and indicate them by means of a 3d asset. comparable to a tangible 3d representation of the camera view in the side, front, top views in CAD systems. Visitors could then inspect the view object and thus anticipate the location from which they will be viewing the scene in the presentation.

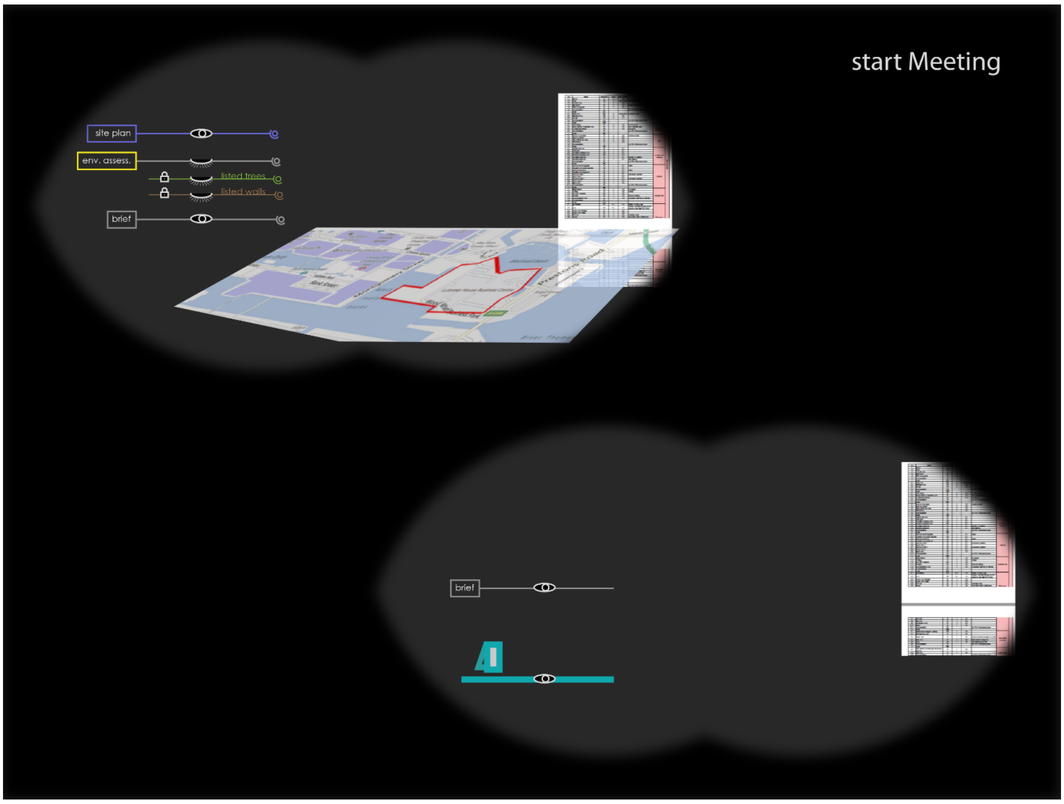


Figure 5a: The upper left view represents the situation of the *architect* or meeting host, and the lower right view simultaneously shows the situation for the engineer, being an invited guest in this meeting. Site plan and brief are currently displayed for the architect, the engineer can only see the brief that has been shared by the architectural office with the consultants before the meeting. Content currently on display is indicated by an opened eye symbol, content that is available but hidden is indicated by a closed eye.
Note: The Conceptual mock-ups are considered prototypes for exemplifying certain aspects of a possible implemtation.

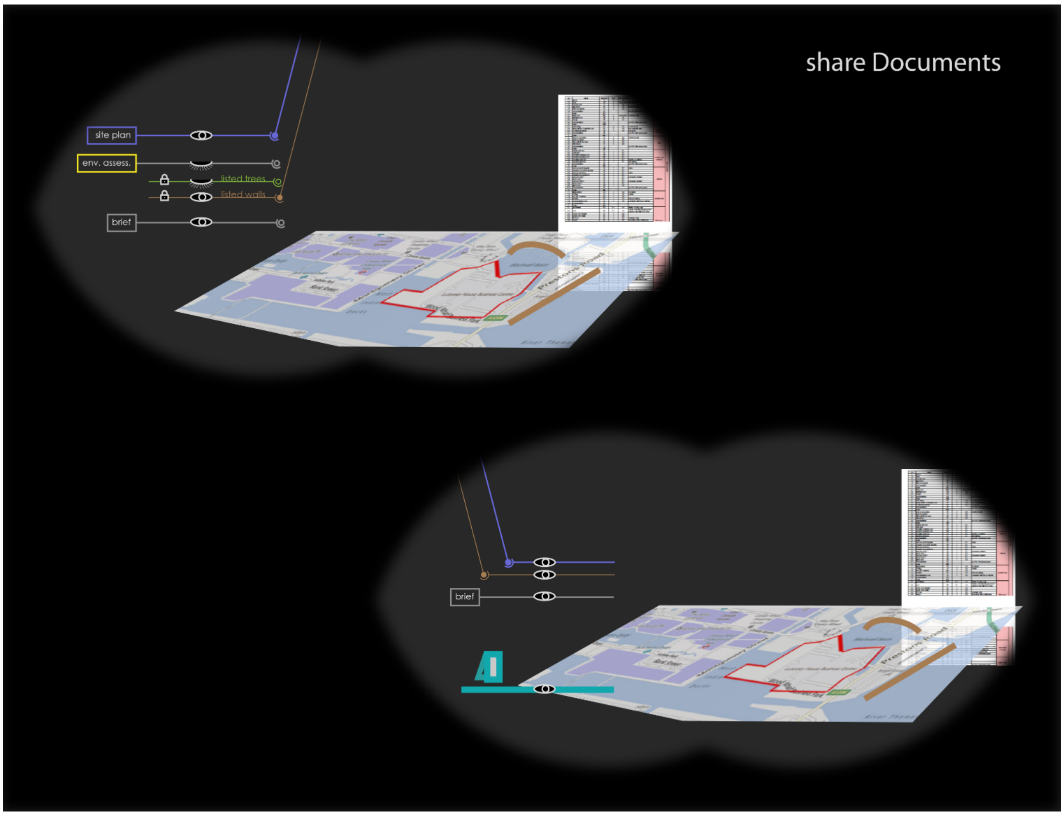


Figure 5b: The architect shares the site plan as well as the listed walls with the engineer, who can choose for her or himself to hide or, as presented here, show the shared layer. Shared items are indicated by a diagonal line leading upwards.

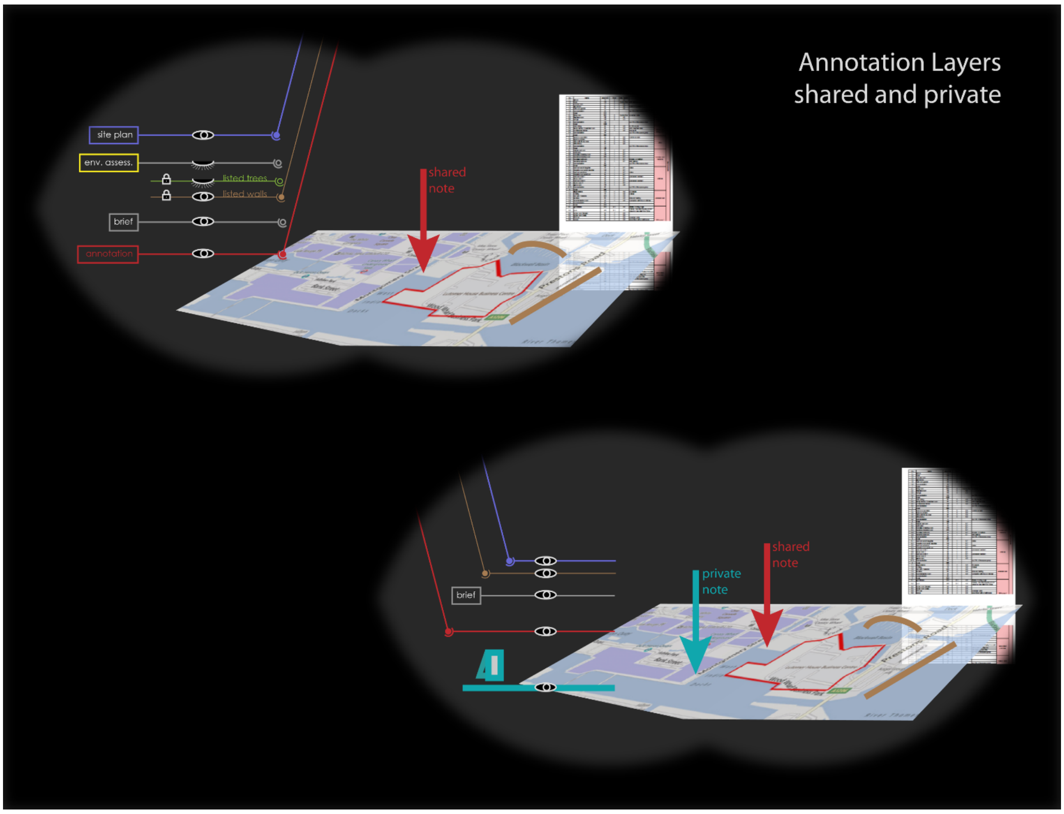


Figure 5c: A shared annotation level or layer (red) can be seen and edited by all meeting members, comparable to the tracing paper in Sequence 2, sct. 5.1. A private annotation layer serves as a notebook.

6.2 Data Spheres – Sphereing

Initially, the *data sphere* was introduced during the requirements development as is documented in D1.1, p. 11:

> ...we must examine what disciplinary demarcations will be necessary within the unified data sphere, and envision innovative data structures and data handling methodologies. All project information must be contained in one singular and flexible information structure that is capable of sustaining the entire project ecosystem...

Searching the *Description of Actions* document for 'sphere' produces zero results. While the data-handling aspect is evident from how the term is used in the above citation. A much more profound understanding of the data sphere becomes clear in combination with the vision of a unified immersive design space.

Through presentations by ZHA and discussions in project meetings (e.g. at the weekly meeting 2021-04-23), the data sphere matured into a tangible spatial construct that coincides with documents and other pieces of information that all have the same level of access privileges. *Sphereing* now describes the entire document-handling workflow inside PrismArch's design space (T6.1, sct. 1.3). 'PrismArch sphereing levels' relate PrismArch users to project information in compliance with access privileges: Departing from the 'personal work sphere' (PWS), a particular user can see, access, and change the information inside this sphere. The PWS can be enclosed by higher-level spheres that correspond to team-internal data ('Internal Discipline Specific'), project-wide 'Cross Disciplinary' data that has been shared with the entire design team resides in the 'PrismArch Project Sphere' (PAPS), data that has been approved to be shared with the client resides in, and so on. A user can see all the data that belongs to her or his PWS as well as the spheres which enclose it. In terms of access privileges, the concept strikes us as being mainly equivalent with group-based access rights management of contemporary operating systems, e.g. Linux; formally reviewing this further would be beyond the scope of this report.

Notwithstanding the above, the innovative potential of the idea of data spheres lies in their concrete reification as spatial entities. Scopes of data visibility and accessibility privileges can be seen and understood as actual spheres that implement the underlying abstract idea in three-dimensional space. They become tangible as components of the user interface. Users, in turn, can develop an intuitive understanding of which data belongs to which data sphere and how the data is or can be made visible to other users. By relocating a particular document or piece of data to a higher-level data-sphere corresponds to sharing the data with all users that are enclosed by the receiving data sphere.

Most importantly, the presentation by ZHA envisions the Personal Work Sphere (PWS) as semi-translucent which exploits the tangible quality - visibility across partly translucent spheres - to provide users with an understanding of how they and others can see data that is contained in higher-level data spheres: Higher level spheres reveal their content to a user as long as her or his personal sphere is contained in them. Sticking to the concept of the half-translucent sphere, a user can see the content of higher-level (larger enclosing) spheres against the backdrop of their own private content displayed inside their own private sphere.

Meeting spheres represent the temporal configuration of a group of invited individuals who can all see the presented content within the meeting, irrespective of whether they form a disciplinary or project-wide team and, hence, permanently occupy a common data sphere.

At the time of writing it was not fully defined how users would perceive the PWSs by others and whether content could also be presented at the outside of a data sphere.

In this respect, the PWS is to be distinguished from the abstract concept of sphereing as a

> topological data division which is not geometrically visible and only exists to envelop a collection of data. The sphering functionality works within three dimensional world coordinates with the PAW time aspect, and helps distinguish Immersed Humans from Project Content - both exist in the PrismArch Singular Database (PASD).
>
> (T6.1, sct. 1.2)

In principle, the outside of a data sphere could be understood as a broadcast from a single user to all users who can see this user. Would there be a useful application for presenting content at the outside of, say, the PWS of a user? Sticking with the translucency metaphor, what would it mean if an information is placed at the outside? In terms of information dissemination, placing a profile picture or a status message in a social media context can be considered equivalent. “Dressing-up” my personal sphere in a personal “skin” would be comparable to choosing the appearance of my personal avatar in a multi-player video game.

Sphering and Git

Project-internal consultations concluded that the version control system Git™ together with cloud-based collaborative platforms GitHub™ and GitLab™ provide a large set of functionalities that meet the above requirements (sct. 3.2). Revolving around the notion of a history of transactions, each version of a project can be seen as a node in a network of transaction histories.

Starting from an empty repository (or any other version in a repository), a new *child* version is derived based on a *parent* by applying a transaction or ‘diff’. Together with meta-information such as author, timestamp, text comment and a checksum or *hash* a uniquely identifiable *commit* is created. Each commit is connected with its parent by cryptographic means, thus ensuring the integrity of each unique version that is constituted by its entire history of transactions, starting from the initially empty repository. It is important to understand the term *parent* not in a hierarchical sense as the child being subordinate to the parent, but rather in terms of a predecessor in the networked history of transactions.

> The data model that Git uses ensures the cryptographic integrity of every bit of your project. Every file and commit is checksummed and retrieved by its checksum when checked back out. It's impossible to get anything out of Git other than the exact bits you put in.
>
> (Git Website)

Git was developed for collaborative software development which differs from architectural design in fundamental ways, we nevertheless consider it an example that is worth studying. Although fascinating, for the scope of this report we refrain from discussing the sophisticated technical features. Rather our focus is on the interaction of the users on a level of abstraction that is suitable for understanding how the system enables a collaborative workflow that allows users to work in parallel and, at the same time, maintain a consistent version history of all transactions made by all involved parties.

Figure 6 studies the case of an structural engineer using the latest architectural model as a basis for developing a company-internal structural model (which will not be shared with the architect). The results will later be propagated to the architectural model based on an export from the structural model. The sequence is defined by *T6.1, Task A.Struct.3* as one of the user scenarios (cf. sct 4.2). The sequence model in Figure 6 addresses the issue of keeping engineering calculations confidential while sharing the results with the wider project team (cf. sct. 3.2).

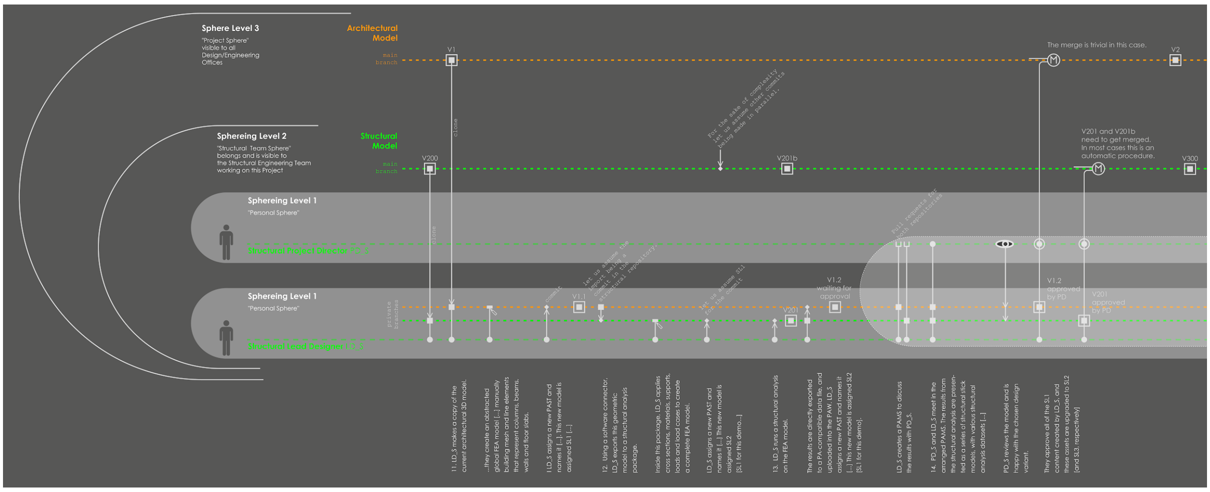


Figure 6: A graphical mapping of transaction histories (commits) onto user interaction sequences.

In a meeting held in preparation of T6.1, when Scenario *A.Struct.3* was discussed in detail, the question was raised as to how far engineering modeling activities taking place on SL 1 should automatically be raised to SL 2 to be available in the company-wide archives. Even if the employee should leave the company the information should not disappear somewhere lost in PrismArch's data space, presumably attached to this employee's abandoned personal sphere but rather remain visible from within the company. Despite the fact that the project designer develops the actual work within SL1, it is ultimately dedicated to *merge* into and thus become part of the respective main branch, located on that sphereing level. So the ultimate SL or visibility of a commit is already decided when the repository was *cloned/forked* from. Merging branches into public repositories can have unanticipated consequences from a user's POV with respect to the visibility of commits that were previously only visible in the private repository. In the Git logic, what is pushed into the public instance of a repository is not just the final outcome but rather its entire history of commits. Each version cannot exist without the entire history of predecessor/parent commits. Put another way, even if working privately on SL 1 a user needs to be aware, which repository the work will be returned to after completion. Figure 7 presents a simplified Git workflow as an overlay to the full sequence analysis diagram.

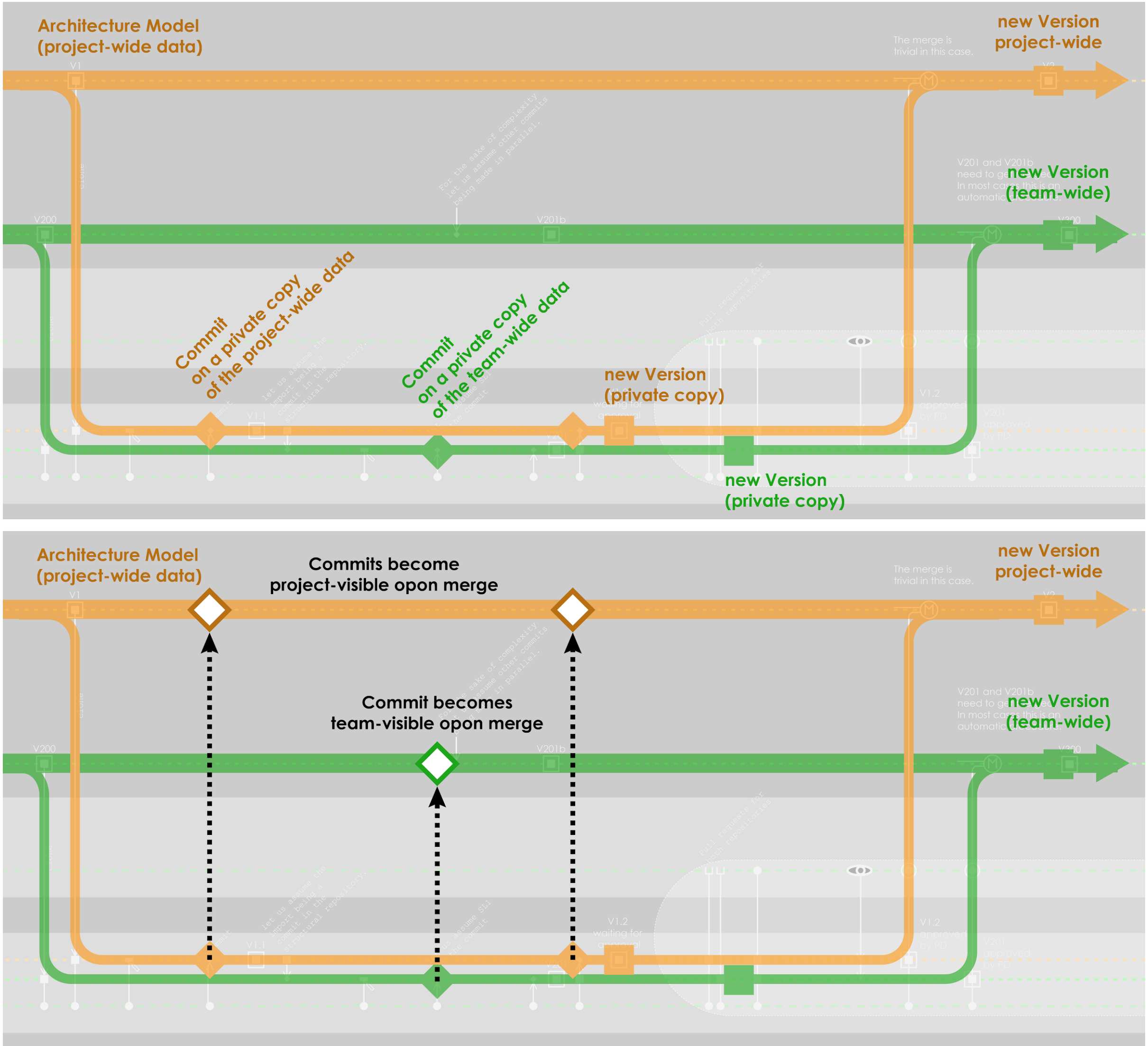


Figure 7: Schematic Git Workflow, overlayed on the above sequence diagram. (a) Commits are being made in private copies of the project-wide repository (orange) and the team-wide repository (green). (b) After the merge, the formerly "private" commits become visible in their respective main branches. Team-specific information remains on sphereing level SL2 and no confidential information, such as engineering calculations, is disclosed to SL 3 (visible to the other project partners).

6.3 Guidelines

The present section re-visits our research and conceptual efforts as they were extensively presented in the sections and chapters above towards so as to

> provide guidelines that, in conjunction with the user requirements, will lead research developments of RO4 (Blending CAE simulations and BIM in VR). Ultimately, this objective aims to enhance the usability of the VR environments by ensuring optimal user experience.
>
> (Description of Actions, p. 4)

The International Organization for Standardization published general guidelines for evaluating the *Ergonomics of human-system interaction* (ISO/TR 16982:2002). Regarding the navigation in virtual environments Benyon (2014) reviews a large number of research related to user experience to be

> understood as a whole and cannot be broken down into their constituent parts, because experience lies in the relations between the parts. Interactivity involves the combination of people, technologies, activities and the social and cultural contexts in which the interaction happens.
>
> (Benyon 2014, p. 10)
>
> A medium has to be physical, otherwise it would not be able to do these things; there would be nothing to make thoughts, ideas and feelings percep-tible to others. Being physical the medium also includes our bodies and the movements, gestures, touches, perceptions and audible expressions that we have.
>
> (p. 16)
>
> However, the other side of the experience is that the user feels disembodied and if he or she looks down, they will not see their feet unless a programmer has thought to include some representation of feet in the display
>
> (p. 41)
>
> Designers should aim for a “responsive environment,” ensuring the availability of alternative routes, the legibility of landmarks, paths and districts and the ability to undertake a range of activities. Gordon Cullen was an architect who focused on the gradual unfolding nature of vistas as one walked through an environment. His ideas of “serial vision” led him to develop the sense of “hereness” and “thereness,” making people aware of where they were going and making the environment legible so that they find their way and enjoy the experience (Cullen, 1964).
>
> (p. 72)

We addressed the topic on a more project-specific basis. The user requirements (chapter 3), the user activities or design process episodes (chapter 4), as well as the analysed work practices in the cognitive task analysis (chapter 5) are the objectified basis for all subsequent developments. Modeling key requirements and work practices in cognitive terms is a fundamental step towards a more generic set of principles and guidelines for shaping the user experience of the future platform.

Our findings about design media and their application in the professional workflow will yet have to be adapted and to be applied to the future system’s prototypes. Making this transfer will ultimately reveal what is necessary to provide a coherent user experience in the AEC context at hand.

User Group

First and foremost we need to acknowledge that our *user group* (UG) consists of experts in collaborating on design projects as well as in performing tasks that require a high level of *expertise and training*, both regarding the conceptual understanding as well as in handling the technical tools adequately. Unlike with online platforms for lay users or for the general public, we expect that users will need a considerable amount of training with a system of the complexity of PrismArch. Learning to use a contemporary CAD system may well be a comparable challenge for an inexperienced user.

On the flip-side, users who have learned to use more sophisticated ways of interacting with the system will be able to control the system more efficiently and ultimately be able to optimise their workflow. The situation is comparable to expert CAD users who fluently use hotkeys for choosing tools and actions and combine mouse actions with modifier keys to alternate tool-specific modes. For instance when scaling an object the modifier keys *shift*, *control*, or *alt* toggle between proportional or free scaling, modifying an existing object vs. creating a new (scaled) copy etc.

Interaction within virtual environments

What makes for a good drafting tool? (Evaluation Studies on UX, workflow, ergonomy). The question came up in an ETH-internal meeting, following up on the weekly PrismArch consortium meeting in mid of May 2021. There are studies on how different design media including CAD systems are used by designers within their workflow (e.g. Shih et al., 2017). Yet, we are not aware of any work systematically comparing drafting tools from an ergonomic POV.

Briefly discussing the matter revealed an important distinction to make with respect to the ergonomy of design (and other) software tools. While a software might have *available* all the necessary and desirable functions for drafting, they may still be not accessible within the overall flow of activities necessary in the task. The nowadays standard right-mouse-click-based object-attached menus as well as other object-specific controls such as gumball in rhino can greatly reduce mouse movements between edited content and conventional menus and toolbar items. For users who prefer to maintain their visual attention focussed near the content they are editing, such user interface features can ease the contextualised access to these functions without unduly increasing cognitive load or distraction.

Section 3.3 made it clear that there are a large number of spontaneous interactions with design media which hardly translate in a straightforward manner into immersive VR.

Sequence Diagrams

The sequence diagrams are descriptions of concrete occurrences of activities in design teams. By making explicit the interactions between team members, involved design media and documents, as well as exchanged information flows they provide a process-oriented level of abstraction of design collaboration. While design needs to be grasped in acknowledgement of its essentially graphical and visual qualities, the sequential analysis contributes a complementary account. It should hence be noted that the sequential description can tell us (a) who is involved in a certain activity, (b) which documents and media were used to support an activity and/or mediate the conversation, and (c) which information or documents were transferred between the involved actors.

With a view to the systems design and software development work ahead of us we considered sequence diagrams as defined by UML (OMG™/UML 2017) a reasonable point of reference. Additional elements extend the UML based vocabulary so as to graphically express types of actors and transactions, information access privileges, co-presence in meeting situations and the like. Nevertheless, we remain faithful to the spirit of UML in that each diagrammatic element clearly corresponds to an activity and its informational and transactional aspects. The diagrammatic representations follow a notational system and can be read from left to right as horizontal 'liveliness' of multiple actors performing activities simultaneously. Coordination between parallel workflows is required if and only if there is a vertical connection between two or more actors/livelines.

6.4 Next Steps

The sequence diagrams provided in Chapter 5 result from our attempt to model the user perspective on the design tasks as they are established in the respective professional practices today. Naturally, the role to be taken by the PrismArch platform in the future cannot be reflected in this analysis explicitly. Rather, it gives an insight into the way information exchange and design collaboration unfold in conjunction with traditional physical and digital design media. At the same time the sequential abstractions are strictly media-agnostic and it will, hence, be straight-forward to transfer them to other media, i.e. immersive virtual environments.

In order to drive the upcoming development of the PrismArch platform, the upcoming activities in WP3 will extend the diagrams by explicitly adding components from the systems design on the technical side. For instance, Figure 31 in Deliverable D4.1 (sct. 3.3.1) presents a diagram presenting several components of the system's design, clearly distinguishing components involved in 'synchronous' vs. components related to 'asynchronous' modes of interacting with the system. Integrating the components depicted in the D4.1 diagram with the sequential modeling of user interaction as presented in Section 5.1 of this document will be an important step in carving out and validating the overall implementation.

Towards the upcoming UX development, the extended diagrams will (a) reveal how traditional media will be complemented by or incorporated in the new platform, (b) identify the contact points between humans, traditional media and the new system, (c) ultimately guiding and validating the interface design from a cognitive point of view. In particular, key information flows are evident from the cognitive task analysis given in Chapter 5. The new system will have to accommodate these in a way that does not disrupt the established design workflow. Alternatively, if it is decided by the development team that established workflows shall or can not be maintained, an alternative workflow needs to be modeled for the disrupted parts.

As with each abstract model there is a certain degree of detail that is provided, with other levels of detail abstracted away. In a way each diagram belongs to a particular level of abstraction, in turn making evident the distinction of what is explicitly shown and what needs to be imagined. Thus emphasising the omitted parts makes it an excellent tool to identify what needs further clarification elsewhere, in terms of supplementary description, a more fine-grained zoom-in analysis or further research. For instance, Sequence 2 in Section 5.1 makes explicit, where tracing paper is used, who can interact with it and which other media are involved. What this sequence cannot provide is an a step-by-step micro-analysis of how architects interact with the medium, when they look where, how multiple sheets are recombined, whether they use gestures or the tips of their pens to point out locations to their colleagues or to help maintain a reference point for themselves, and so on. Section 5.2 gives a foretaste of what is still to be discovered on the microlevel. Deliverables D3.2 and D3.3 will make a comparison between (1) how designers use and interact with physical design media and traditional CAD systems and (2) how architectural and engineering designers interact with the PrismArch platform under development. We will combine fine-grained observational methods, as they have been successfully applied by Hutchins (1995a,b) and others in "media-heavy" field studies, with more specific behavioural measures. The former will 'record the essential interface features' and how they are used by architectural and engineering designers in order to 'control the various aspects of the VR environment.' The latter will monitor cognitive load as a key evaluation criterion in 'maintaining a natural and stress-free experience' (Description of Actions, RA3.2).

7 CONCLUSION

Compared to the requirements as reported by our design partners, the interviews added a level of detail that will prove valuable in the upcoming development and research efforts. Consulting with architects and engineers from our design partners in exploratory interview sessions allowed us to align our cognitive science perspective on PrismArch's application domain with their understanding of established professional practices. Presumably, what we could learn from the consultations with our design partners is not something they were completely unaware of. Yet, Departing from a lay person's perspective on, say, a set out drawing such as the one referred to in Episode I3ZOc in Appendix A we made the transition to an intermediate level understanding of the professional processes it is involved in. Narratives such as the one provided by Episode I3ZOc reveal some of the tacit (Polanyi, 1966) and practice-situated knowledge (Carlile, 2002).

Tracing paper as one of the most common physical design media served as a case study throughout the report in order to understand the work practices established in the design disciplines. Section 5.2 contributes insights on its media-specific characteristics from a distributed cognition perspective. From the cognitive task analysis we can derive a number of tracing paper *operations* that users of tracing paper are provided with. The Subsection *Tracing Paper Revisited* (6.1) discusses how its functional role might translate into *Immersive Collaborative Design* and how its characteristics as a new design medium affect the process. This clearly relates to the markup and toggle perspective functionalities described in the user requirements (chapter 2; D1.1, Req. #7, #11).

Future studies within and beyond this project should address research questions such as the following:

A. How is tracing paper transformed as a design medium (in terms of what it gives to the designer) when being implemented or re-defined as new tools to be used in a three-dimensional immersive environment?
B. How does this affect the overall design workflow?
C. What becomes possible with the new approaches, beyond replicating the "old" behaviour in a new medium?
D. Specifically focusing on the use of multiple traditional design media we can ask, in how far integrating them hinders designers in achieving a holistic view, for example by extra mental effort required to integrate them (Kirsh, 2010; cf. sct. 5.2).
E. Conversely there is the claim that designers fundamentally rely on using multiple media that cover different aspects (Farías, 2009; cf. sct. 5.2). This raises issues regarding how an equivalent behaviour is necessary for immersive environments and how these could be integrated.

From an empirical and evaluation POV this raises the question of how far markup functionalities in 3d can be considered equivalent with the capabilities of their traditional counterparts. Once the interactive capabilities of the PrismArch prototype are matured to a reasonable degree, a comparison between both media becomes feasible by means of observing expert users in solving tasks that represent typical application scenarios for tracing paper in traditional design. Before this is the case, mock-ups, storyboards and screenshots can be used to (a) apply the underlying cognitive operations to the new system in a *cognitive walk-through* (Wharton et al., 1994). This will help adjust the interface elements and behaviour so as to align with the required functionalities in the design workflow. (b) Asking design professionals, who have experience with traditional physical and digital design media such as tracing paper, and for their opinion on mock-ups and storyboards will give valuable qualitative insights for directing and refining the user experience design.

Picking up a loose end from above, there were several instances of sequence analyses which we felt were too abstract so as to reveal the underlying cognitive operations in detail. For instance, Sequence 2 in Section 5.1 explicates where tracing paper is used, who can interact with it and which other media are involved. What this sequence cannot provide is an a step-by-step micro-analysis of how architects interact with the medium, when they look where, how multiple sheets are recombined, whether they use gestures or the tips of their pens to point out locations to their colleagues or to help maintain a reference point for themselves, and so on. Regarding the latter point, gesture is known to facilitate cognitive operations in the interaction with design media (e.g. ETH's work on the role of gesture in design: Park, 2020; Brösamle & Hölscher, 2018).

Studying design media interaction in enough detail so as to describe the cognitive dimension of where an information is provided by a design medium, how it is retrieved and combined with other media, how individuals maintain focus (by means of gestures, mouse cursors, visual markup etc.) clearly points beyond what can be provided by self-reports and in retrospective interviews with design experts. We propose to carry out fine-grained observational studies in situ: To observe and carefully record interactive behaviour of architectural and engineering designers while they are actually engaging with the design media in performing domain-typical design tasks. Our literature review has brought up an extensive body of related work by a group of researchers around Jennifer Whyte, of which we exemplarily provided one source in this report (Comy & Whyte, 2018). As a next step we plan to comprehensively review their ethnographic work in order to then follow up with what else is needed to understand the cognitive dimension of design interaction. Eye-tracking and video-analysis of gestures are most likely on the short list of methods to consider. Related research activities at ETH include topics such as immersive media and augmented reality systems (Grübel et al., 2021 *in press*), eye-tracking in built environments (Emo, 2014), testing how navigation interfaces in VR impact spatial perception and spatial knowledge (Li et al., 2021), human behavior simulation in complex built and unbuilt environments (Gath-Morad et al, 2020) as well as in studying discipline-specific spatial abilities in architectural design (Berkowitz et al. 2021).

7.1 Collaboration across Professions

Having made that transition from the naive lay-person perspective to an informed understanding of the involved practices is a stepping stone for ETH to coordinate the upcoming empirical research and evaluation work as part of WP3. Beyond directing research activities in PrismArch, the present report aims to provide a more adequate idea of architectural and engineering design processes than is usually given in multidisciplinary projects. This deliverable aims to be a report in the truest sense of the word, explicitly reporting on our findings in an area of professional practice in which we ourselves are not experts. The diagrammatic representations provided as part of our analytic work strive to align our findings with the professional "vocabulary" in the design disciplines on the one hand, as well as in the technical fields on the other. Revisiting *boundary objects* again, they want to 'inhabit several intersecting social worlds' and 'satisfy the informational requirements of each of them' (Star & Griesemer, 1989). There is a correspondence between PrismArch as a project and PrismArch as a future design platform. In order to make this a successful project we need to align the professional views involved in PrismArch, so as to create a platform that will let professionals fruitfully align their views in future design collaboration.

In order to frame our approach theoretically we combine external and distributed cognition views (e.g. Edvin Hutchins, David Kirsh) with more specific research in the field of design studies (e.g. Jennifer Whyte) and design cognition (e.g. Gabriela Goldschmidt). Most of the work on architectural design draws on methods from various fields, including cultural sciences, cognitive science, psychology, sociology, but also organisation studies. The broad theoretical framing will allow us to onboard the expertise of other colleagues and integrate it into the preparatory work conducted up to this point. At this stage, the scope of the bibliographic collection is a broad one and it is targeted towards a practice-oriented application. Obviously, within the timeframe of this half-year period it was not feasible to provide a comprehensive picture of all relevant aspects for the development of PrismArch from a cognitive POV. Neither was it possible to incorporate an extensive overview on cognitive science theories and approaches playing a role in our view on the project as a whole. Making a contribution to topics in cognitive science fundamental research would require a more thorough review of the literature in a much narrower scope. ETH deliberately decided against restricting our efforts on selective aspects in the forming phase of the project. Instead, our research maintains a broad perspective that invites others to relate their work with the overarching project vision.

ACKNOWLEDGEMENTS

We would like to thank our interview partners Oliver Bray, Alex Grigoruk, Chris Lepine, and Marco Pavoni for their kind cooperation in offering their expertise on architectural and engineering design matters.

APPENDIX A: TRANSCRIPTS

Each episode relies on a report during one of the interview sessions. They are a condensed version of a full transcript. A full transcript would show pauses, hesitations, intonation, laughter, overlaps, etc., which is a level of fidelity that would have been neither useful nor feasible to provide in the time frame available. The collection is not comprehensive, meaning that the interview material is not covered entirely.

A.1 Notation

I1ZMa, I1ZMb, ...	Identifiers for each Episode: Interview 1, internal token ZM, episode a, b, ...
‘transcript text, terminology’	All direct citations are enclosed by ‘ ’ and they reflect the verbal material as closely as possible. We cannot provide a full transcript here. What we do provide, though, is a detailed account of the wording as it was uttered by the interview participant.
Researcher: ‘What can I see in….’	questions and clarifications from the researcher (interviewer)
‘text [...] text’	some part of the verbal material was omitted
‘word/world/wood’	In case an utterance is hard to understand, the researchers may give two or more possible interpretations (“of what they heard”), separated by /
‘[addition by the researchers]’	Commentary, clarification, and context to provide a better understand of the material is provided in [ ]
‘[best guess?]’	Something could not be heard properly. A best guess is provided as [?]
‘[?]’	something could not be heard properly and it was not even possible to provide a best guess alternatives
(inference or interpretation)	by the researchers

[mm:ss], mm:ss, [hh:mm:ss]	Timestamps follow-up shorthands such as [:ss] or [:mm:ss] implicitly refer to the minutes mm or the hours hh from the previous timestamp.
[VILLA], [OPD], [OTM], [BYW]	Case study shorthand for: Private Residential Villa One Park Drive One Thousand Museum Bankside Yards West (alias Wood Wharf)

A.2 Episodes

I1ZMa, 9:14 - Remote co-design

[VILLA]

1. Management presents the brief to the design team.
2. Designers work on initial design ideas, individually.
3. ‘brainstorming’ meeting
    a. Individual designers present their solutions to the entire team
    Open Question: Are the individual solutions generally shared with the team?
    b. Media: zoom, share screen
    c. One solution is selected to serve as a basis for the subsequent design process *(master model)*
    d. at this stage (or earlier) all files are available to the entire team on a ‘common server’
4. The design is ‘compartmentalised’ so that each designer can work on parts individually.
5. Each designer continues working on the chosen solution, focusing on the respective ‘room or area’ *(based on the compartmentalisation)*.
    a. ‘screenshot for immediate commenting by everybody’
    b. this helps ‘updating [team colleagues] constantly’ on individual progress
6. Individual *(two-way/three-way/...)* meetings are arranged for exchange between designers on specific topics
    a. ‘daily meetings between us’
7. Team meetings
    a. ‘with the whole team every two days’
    b. ‘presenting the screen and going through the 3D models’
    c. Design changes: ‘life sketches on the screen’

I2ANa, 37:46 - Engineering: Site Plan, Section, Rationale

-- transcript excluded from the public version of this document --

I3ZOa, 14:51 - Wind Tunnel Study

[OTM]

Purpose:

- 'simulate the effects of a hurricane'
- 'ventilation issues -air flows between buildings ... how we space them - structural loading issues'

This episode focuses on the last point, namely 'structural loading' aspects.

1. Main Architect provides a 3D model to an external consultant:
    a. 'Rhino'
    b. 'converted into an STL model'
2. 'they [the consultant] build their foam model'
    a. foam or wood
    b. with sensors built in
    c. 'put it into the wind tunnel'
    d. including the 'entire [block-wide] context'
3. The consultant provides 'loading information'
   (a heat-map or equivalent data).
    a. 'the loading information applied - to the facade'
    b. 'red areas at the top [17:24] ... correspond with areas receiving the most intense wind loading'

I3ZOb, 19:07 - The wind-load is propagated to the Structural Engineers

1. The Structural Engineers integrate 'the lateral loads as part of their calculation.'
2. If there is a high load 'you can compensate for it structurally ... something needs to thicken - or strengthen'.
3. (The Structural Engineer will then have to update the main Architect on the changes in the structural system)
4. (Who, in turn, will have to update the other external partners involved)
    a. 'moving into the actual facade design, that's then down to the facade engineer'

I3ZOc, 29:00 - Incorporating a new Construction Methodology

[OTM]

1. The geometry set-out and detailed drawings where developed for a more standard cast in place concrete system, 'solid concrete' but needed to be adapted to a 'GFRC permanent formwork system'.
2. 'Set-out drawing for solid concrete' exists but needs to be adapted to 'cast-in-place'.

   a. 'Now We need to understand … how you actually build with this system, how you build with it and what the implications are for the interfaces between this system and other elements … such as the concrete post-tensioned floor slabs and the glazing [29:46]'
   b. 'modify drawings as and when'
   c. 'A lot of the work was directed to the facade contractors'
   d. 'We would adjust … geometry [in] 3d modeling techniques, where we needed to make this system work.'
3. 'We would supply to the facade engineer with … both 2d and 3d drawings'
   a. 'they take the rhino model'
   b. 'chop it into … where they would have their joint lines - how big that panels can be [32:36] … ten, eleven feet '
4. 'then they release packaging information'
   a. which is described as a 'pack of 2d drawings which they then generated from their model or from the model they [have] taken from us'
5. 'and we check'
   a. 'any instances which we feel that would be [?]'
   b. 'it was a two-stage process … combined process'
   c. 'looking at the aesthetics'
   d. 'but also - assisting with the detailing some of these features of - '
   e. 'it is their detailing … how those panels fit together'
   f. 'we could, say, propose alternatives … cleaner details … less joints, that kind of thing'
6. 'there is also the contractors involved in this process as well'
   a. 'because they've got to build it'
   b. 'there is no highrise construction using this methodology'
   c. 'you have a team of people trying to figure it out at the same time [32:25]'

I3ZOd, 32:25 - Timeframes, Details on Facade Development

[OTM]

1. 'it is probably about four weeks'
   a. 'they would take this drawing'
   b. 'start at the podium area'
   c. the building 'was built with two different systems'
   d. 'ground to level 12 - that was concrete system'
   e. 'simplifies to straight - here'
   f. 'by the way the GRC panels have to be split up by level'
   g. 'they would start with this chunk [ground to level 12] and it would take them four weeks to produce that pack of drawings [37:09]'
2. 'we then have two weeks to respond to those drawings with comments'
   a. 'maybe they [have] done - trying to do something we do not approve of'
   b. 'discussions about what skope there is'; ' … an agreement a contract between the client and the provider'
   c. 'they have agreed which parts would be clad, which wouldn't'
   d. 'the back of these columns - because it's a car park - were not clad'
3. 'we … architects we didn't know that at that stage'
   a. 'that was new information when we received these drawings back [38:19]'

   b. ‘negotiate or discuss that with the owner’
   c. best practice: there would be ‘specification’ and a ‘schedule’
   d. [38:47] the late decision to do this...was bit of a back and forth negotiation between the client and the fabricator’
4. ‘we were stuck in the middle’
   a. ‘trying to ensure that it’s looking as nice as it can...everything is clean...we’re happy with everything [39:10]’
   b. ‘but also there’s a cost considerations … we wouldn't … [unclear] instruct the fabricator … produce more panels ’
   c. ‘so that four weeks for them to produce drawings...two weeks for us to respond [39:30]’
5. ‘in that four weeks period - we would have weekly meetings
   with the owner, the contractor [constructor?] and the engineer for the fabricator’
   a. ‘go through these drawings and discuss any issues’
   b. ‘they would start producing design drawings … [showing] the jointing’
   c. ‘once we are happy with that [40:16]
6. ‘they … go in to production drawings’
   a. ‘more detailed’, ‘completely dimension [dimensioned ?]’, ‘again 2d but every panel has a dimension and a [in the ?] detail’
   b. ‘those drawings would then go to the fabricator … to actually CNC’
   c. ‘we would [not ?] comment on those [40:35] at that stage they’ve already been signed off. ’

I3ZOe, 41:39 - Clarification on the Signing-off Process

[OTM]

1. ‘Once we … receiving 2d information’
   a. ‘we then requested the 3d model back from them as well’
   b. ‘so we could overlay that model with our model and see if ...it’s almost like clash detection’
2. Aligning the 2d information they provided with the 3d model… - it would be possible, ‘also something I did’
   a. take 2d plans and ‘layer them up level by level in a 3d environment … did this in microstation’
   b. ‘then … open the 3d model which we also had in microstation’
   c. ‘then, I could see if there’s any areas where they weren’t aligning or - [?] ...quite manual in many respects’

I3ZOf, 44:40, Views

[OTM]

1. Setting up views
   ‘on a day to day basis with the team internally [...] one of the things we tend to do quite a lot is’
   a. ‘we set up views in the model’
   b. ‘where you can test changes that were implicate implementing [implemented?]’

   c. 'for example [at the] top of the tower we have these [...] glazing [steels, steals?] again huge because of the wind load, which we have been discussing earlier'
   d. 'we designed something like this, very slender, thin and designed [draws a small sketch] - client couldn't afford that'
   e. 'they would then have to be thicker, so we did it like that [continues to sketch]'
   f. 'one of the processes is [...] setting up key views within the model'
   g. 'then designing different elements which we would place for these [steels, steals?] a simple [...?] clad or whatever it is [46:09]'
   h. 'and then testing the visual impact of those'
2. 'we have a fixed reference to compare'
   a. 'say you have fide designs for a column'
   b. 'couple of people working on that'
   c. 'you need to compare them like for like'
   d. 'so you need that fixed view so you have an idea of - well - how much light do I see'
   e. 'that is the beauty of having the model'

I3ZOg, 47:05, Overlay Sketching

1. 'this is exactly why we use zoom a lot [...] because we draw all the time'
   a. 'a lot of people just use the snip it [snipping?] tool in windows.'
   b. 'previously that is the kind of best way of doing it'
   c. 'create a window'
   d. 'and then scribble away that/there when/what you're talking, quickly '
2. 'this is interesting [...] these are all new tools'
   a. 'working with tablets now'
   b. 'drawing over the top of screens as we have descriptions'
3. *Researcher: 'Tracing paper on top of a screen'*
   a. *Researcher: '[senior designer] using their markup pen to draw on top of the screen that is shining through'*
   b. 'yes, I've done that too'
   c. *Researcher: 'the junior would later [...] try to adapt the model accordingly'*
   d. 'yes, that was March last year [laughter]'

I4ZCa, 33:15 Communication and Design Media

[OTM]

1. 'It helped that we had a good local architect [...] because the local architect was using the same software, the information flow was pretty much seamless [...] both teams drawing it up. It always felt like we were on the same page, never felt like there was a disconnect, it always felt that we are moving [in] the same direction [34:03]'
1. 'Something that also did help us a lot in understanding [...] the way the connections come together is - once that we did have the very detailed 3d model that was shared between all of us'

2. 'we also did a few 3d prints of specific regions or areas of the tower and when we [you?] looked at those - we showed it to the client, the client was like ah yeah I see how that's coming together'
3. 'A design like this, it has its complexity, it is even with the best sort of 3d visuals it's hard to really get your head around how some of these connections work [35:05].'
    a. 'So when we did these 3d prints - it was something that helped everybody - especially at the base of the tower, where the structure is very complex where it touches down, as well as at the very top of the tower [...]'
    b. 'we did a 3d print of just like one of these legs touching down, that was very informative'
    c. 'I think it just helped us see it physically, how all of these connections come together'
    d. 'Also, we printed one of these balcony areas to see how that cantilever worked and how that balcony came out - something else that was good.'
    e. 'It is really hard to pinpoint and say e xactly, [what we've] learned. It wasn't like we discovered something we didn't know. It was just like seeing it in a different way. [...] reconfirming to ourselves that we were solving it correctly? [36:53]'
4. 'It also gets people excited to see this sort of physical object.'
    a. 'You are working on these images, you're working on drawings, but to see a physical 3d object is always nice.'
5. 'along those lines, one of the big moments was actually seeing the mock-up in Dubai'

I5AAa, 33:26, Structural modeling

[BYW]

1. 'before the stage 2, before concept design we rely on some [...] guidances or basically - similar projects'
    a. 'there are different guidances [33:54] for example [...] in the elements [calcs??] we can define [...] there are different guidances so for example based on the length, based on the [...] loadings [...] what [are??] the structural element sizes would be'
    b. 'based on experience, yes [...] this is how we would approach that stage [34:21]'
    c. 'if we go further, this is where we [...] prepare some models`
    d. 'analytical models [...] can be split in two main models, which is the global model and local mini models.'
2. 'current [...] development[s] in softwares allows us to spot even very small discrepancies everything'
    a. 'it's [...] a good way but sometimes it is not [...] very useful [...]
    b. 'if it is a very simplified model [...] simplified structure, you would not go to this detail, it is easier to produce a 2d drawings [38:24]'
3. 'in terms of modeling [...] the architects are gonna be the first [41:40]'

   a. 'once we get some understanding about the structure [...] first of all we would draw it [...] as mark-ups'
   b. 'we take the[ir] model, we would potentially kind of split it [them?] by layers, by floor plans...[see where we can put the structure?]`
   c. *Researcher: 'this is happening in a 2d - sliced way, do I understand that correctly?'*
   d. 'we would take one floor plate, we would draw the columns - and then we would think, how they are going to extend [upwards movement with both hands, simultaneously] all the cores [42:25]'
   e. 'after that, when we have a [coordination? - phone is ringing] how this works we would start to draw it in a model'
   f. 'we would use the architectural model - in case - [...] there are too many softwares'
      (Import, Export is not always working well)
      [43:05]
4. 'when we start to put those columns we can see how this affects all the other floors'
   a. 'for example on one floor you have an apartment layout let's say on four corners'
   b. 'in the upper floors there is going to be one big apartment, potentially even duplex apartment, double store [...] even three'
   c. 'you need to know how this is going to affect the architectural layout [...]'
   d. 'at the beginning it is always kind of - it's about the layout, we would start working with the architectural layout'
   e. 'put the columns where it [they are?] less distracting the layout'
   f. 'and then we will see how it affects all the rest'
5. 'and then the facade comes into play'
   a. 'for example one column is [...] being placed right [...] on a window'
   b. 'you do not want to see it [...] the client doesn't want to see it [...] this is where the calibration starts [44:42]'
   c. 'instead of this column we can put a transfer beam and divert this column into two beams [...] go back, in order to have that opening undisrupted/undistracted [?]'
6. 'of course there is a price for it'
   a. '[...] the cost of the project is going to increase'
   b. 'if the architect is able to move the window away, and make the column straight [...] this will release the pressure from the structure, this will release the cost from the structure point of view'
   c. 'but it will disrupt the view'

I5AAb, 49:24, Visualisations from Structural Modeling

[BYW]

1. 'this is coming from an analysis model'
   a. 'this is what - kind of outcomes from the analytical model'
   b. 'we model all these elements'
   c. 'we put a load on it [...] we load the building'
   d. 'we se where we have most stressed area'

e. 'where the element is kind of at the - higher with the utilisation ratio, meaning for the strength'
f. 'we [... are] designing the buildings for the strength'

2. [...]
3. *Researcher: 'How do you input - how do you get at the structure for the modeling process [...]?'*
    a. 'sometimes we use the 3d model [...] provided by architects [51:51]'
    b. 'then we develop this in revit model' or 'in different occasions we would start straight away from the architects model, we would put the simplified elements[...] at the early stages [...] we would put the main structural elements that we just draw on the sketch [52:22]'
    c. 'we would extract them in the model - like building them in the model'
    d. *Researcher: 'as a volume, just saying: this is a volume of steel-reinforced concrete, for example? '*
    e. 'yes'
    f. 'we model the volume and then we extract it into the analytical software [that] analyses those - the different things'
    g. 'in other occasions could be that it's easier and faster to do it from scratch, by hand, so you are not using the model, [the] existing model [...] just building straight away from scratch'
    h. 'how the model, how the software knows what it is and how it needs to decide [...1 sec. of chopped-up sound...] the different and many parameters that you would need to insert in order [...] to tell the software what it is and how it needs to design - so there are many constraints that you need to assign [...]'
    i. 'like this column is only three meter high and is retained by the slab - so you would need to model a slab [...] you'd need to tell that this slab is 300 mil [millimeters] thick [...] a list of parameters that you input'
    j. *Researcher: 'by clicking at each element and say this - this type of slab, this is this type of concrete, the main direction of reinforcement goes like this and so on and so on, is it like - '*
    k. 'yeah, it's more or less like that, as I say [...] [54:23] it depends, if we are dealing with very complex models'
    l. [...] for example on Bank Side Yards [BSY case study] [...] Shared basement and three superstructure buildings [...] sit on top of that long big basement
    m. 'our raft, which is the foundation had to be designed in conjunction with the - the geotechnical parameters on the soil
    n. 'the footprint of that foundation is - is huge [...] there are different constraints, different loads coming from the top on different locations'
    o. 'if you would need to do it manually it would take like ages to do that [...] we are dealing with this in a data - you know, preprocessing and postprocessing'
    p. 'preprocessing is basically collect the data let's say in [...] excel [...] is very kind of powerful i would say in this way [...] we can sort out all the data that we would need in an excel table'
    q. 'and then straight away import it'
    r. 'some time we also use like python, we use [?] textbook'
    s. *Researcher: What data is it exactly?*

t. ‘mainly - some sort of codes so it’s mini codes, it’s kind of coding [56:14]’
u. ‘you would need to build a wall with the parameters of concrete [know ?] the steel [know ?] the timber, we would need to type it in, we would need to type the parameters like the geometry, we’d need to type uh length’
v. Researcher: ‘specifies building elements’
w. ‘yes [...] and then [...] imported in the software [] and the software kind of creates all the geometry for you’
x. ‘this is for very complex models’

4. *Researcher: ‘What constitutes an element in this process? Is it by floor, or is it a beam, or is it even smaller? [...]before we said we just use the volume that we have and start with this one but at some point you want to break it down into - into different components maybe - there is one step in between I’m still not really clear and see -’*
    a. ‘right, I see what you mean [...] if you look a the building as a footprint with [?] the envelope of the facade - this is not what is going to be imported into the analytical model’
    b. ‘we are just picking some specific elements that are going to be imported’
    c. ‘the main structural elements are going to be columns, slabs, walls, beams - this is what we’re going to select and import into the new model ’
    d. [...]
    e. ‘a good [...] example - on the left hand side we see the model that was used to prepare the drawings - and the model itself to use to prepare all the - to model all the structural elements’
    f. ‘and on the right hand side is a separate model - is basically analytical model which is [...] exported in a separate software [1:00:01] [...]’
5. *Researcher: ‘On the right hand side, how do you make these faceted subdivisions that the simulation would need in order to - like differentiate between mid floors, lower floors, higher level floors for example, or like [...] How do you cut it into pieces, if you will? You said finite element model, it sounds like you can count them?’*
    a. ‘Finite Element Model [...] each of the elements is going to be broken down by pieces’
    b. ‘there are 1d, 2d, 3d, let’s say, elements that you can insert in different softwares ’
    c. ‘1d is going to be like a stick element, like a beam, column’
    d. ‘2d element is basically something that, you know, forms one plane’
    e. ‘and the 3d is kind of extruded para [?] plane with some thickness depth’
    f. ‘usually we would work with 2d and 1d’
    g. ‘the 3d element design is [...] sort of a complex design and we would use it for the local element check but not for the global’
    h. ‘the one on the right hand side, it uses only 2d elements [:01:39] and some of the stick-like columns, for example [...] which are also 2d elements’
    i. ‘there are also some points, let’s say support points which are 1d element, but it’s not that important, really’
    j. ‘how we do it [...] on different floors [...] for example if I say basement [...] 3 meter height [...] we would draw columns only on three meter height’

k. 'and then we can [...] multiply all these columns, like, copy all those columns, floor by floor, if they continue on/to the top, but they will still contain, the length of this element is gonna be three meter'
l. 'and on each, let's say, column, if, if you have two columns, there is going to be a slab, or some beam, or anything that [...] restrains -'
m. *Researcher: 'that basically allows us to put a floor at that point, right?'*
n. 'yes'

Researcher: 'Ok. [...] now it feels like, complete [...] complete enough to get a picture.'

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