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PrismArch

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Deliverable No D3.2

Initial report on UX and usability guidelines in VR-aided design environments

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Abstract	PrismArch aims to develop a virtual environment for professionals from multiple design disciplines to collaborate on building projects in the AEC industries. In the previous Deliverable D3.1 ETH carefully reviewed the requirements as they are provided by our design partners in Deliverable D1.1. Based on a cognitive account we study design activities in terms of team-wide information flows (cf. D.3.1, sct. 5.1) and in terms of the cognitive characteristics of involved design media (cf. D3.1, sct. 5.2). Based on more recent developments in the project as they are documented in T6.1, D1.2, the *present Deliverable D3.2* now focuses on guiding the user experience (UX) development in a concrete and fine-grained manner. Interface components are discussed in detail in relation to the cognitive principles provided by the predecessor deliverable in view of the upcoming design decisions to be made. At the time of writing, the platform's application domain, designing within today's AEC industries, has not been studied comprehensively so that guidance in the development process cannot solely rely on existing research and empirical studies. ETH therefore expects that developing studies on cognitive aspects as well as the testing of the user interface will be an ongoing activity that takes place in a step-by-step manner and in close coordination with all project partners. In preparation for upcoming empirical work the deliverable discusses options for controlled studies alongside highlighting the advantages of more qualitative interview- and observation-based approaches, especially when working with small samples of highly specialised expert users.
Keywords	design practice, immersive virtual reality, design media, tracing paper, distributed cognition, sequence diagrams, cross-disciplinary collaboration

Copyright

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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
DOF	Degrees of Freedom
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
TUI	Tangible User Interface
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)*

‘...’	*Single quotes for direct citation from an external source.*
“...”	*Double quotes for higher-order direct citations within other citations, informal, figurative expressions, presumed perception of a (fictional) user, and whatever else the authors find them useful for.*

Executive Summary

PrismArch aims to develop a virtual environment for professionals from multiple design disciplines to collaborate on building projects in the AEC industries. In the previous Deliverable D3.1 ETH carefully reviewed the requirements as they are provided by our design partners in Deliverable D1.1. Based on a cognitive account we study design activities in terms of team-wide information flows (cf. D.3.1, sct. 5.1) and in terms of the cognitive characteristics of involved design media (cf. D3.1, sct. 5.2). Based on more recent developments in the project as they are documented in T6.1, D1.2, the *present Deliverable D3.2* now focuses on guiding the user experience (UX) development in a concrete and fine-grained manner. Interface components are discussed in detail in relation to the cognitive principles provided by the predecessor deliverable in view of the upcoming design decisions to be made. At the time of writing, the platform's application domain, designing within today's AEC industries, has not been studied comprehensively so that guidance in the development process cannot solely rely on existing research and empirical studies. ETH therefore expects that developing studies on cognitive aspects as well as the testing of the user interface will be an ongoing activity that takes place in a step-by-step manner and in close coordination with all project partners. In preparation for upcoming empirical work the deliverable discusses options for controlled studies alongside highlighting the advantages of more qualitative interview- and observation-based approaches, especially when working with small samples of highly specialised expert users.

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 (cf. D3.1, Introduction).

The present report is concerned with the discussion of UX and usability guidelines for VR-aided design environments that are pertinent for the development and evaluation of PrismArch.

1.1 Approach

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. Deliverable D3.1 puts an emphasis on understanding and linking the project overall vision with a cognitive science account: The fields of distributed and external cognition provide us with a theoretical foundation that allows us to study human task performance both at the individual and at team levels. Taking into account the cognitive properties of specific design media, be it tracing paper or a fully immersive three-dimensional virtual environment, we not only study which task-related information is processed in interaction with the different physical and digital tools and media. Moreover, we seek to develop a qualitative understanding of how the information can be presented most effectively, especially in relation to the requirements in a highly specialised application domain as is the case for the AEC industries (cf. D3.1 sct. 2.1).

According to the Description of Actions, 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)

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.'

The purpose of the present deliverable is to identify selected user activities that are of particular interest for key decisions in the platform's design and technical development from a user experience point of view. For these selected activities we discuss cognitive issues based on existing literature in order to guide and inform upcoming design decisions from a cognitive point of view. Concerning Research Activities RA3.1 and RA3.2 (Description of Actions), we discuss options for empirical studies and make suggestions for key elements of these studies, i.e. experimental setting, materials, participants, task instructions, experimental conditions to compare, and so on. These serve to illustrate the key cognitive issues for VR-aided collaborative design, and also serve as preliminary consideration for the upcoming empirical work by ETH (D3.3). Beyond informing the ongoing design and technical development empirically, the data to be collected may serve as training data for designer models as part of the work in work package WP2, provided the amount of collected data is sufficient.

1.2 Theoretical and Background and Existing Literature

At this point we refer to the first chapter of Deliverable 3.1, which has provided an overview of key literature on design practice in general and in the AEC industries in particular, team collaboration, navigation in virtual environments as well as the methodological foundations rooted in distributed cognition work by Hutchins (1995a) and others, work on external representations by David Kirsh (2010) and others.

The general framing taken in Deliverable D3.1 to consider collaborative design as a set of cognitive processes that are distributed across several team members (with a high level of domain-specific expertise) and mediated through external representations (graphical and other media, physical, digital, display-based, immersive VR) can be summarised in a set of concise statements and research questions:

- How spatial content is presented visually can greatly influence how a design task unfolds from a cognitive perspective.
- How can the immersive environment provide task-critical information adequately?
- How does a particular medium support the task?

2 COGNITIVE ISSUES AND RESEARCH QUESTIONS

This chapter will visit topics and issues that we see relevant from a cognitive science perspective and/or in relation to the guidance of the user experience development for the future PrismArch platform.

2.1 Navigation, Prior Knowledge and Cognitive Load

There are three types of interactions with PrismArch where 'navigation' will be relevant. First, how will users 'navigate' using the PrismArch interface, in other words how they access buttons, menus and action sequences to achieve their objectives. Here it needs to address the additional consideration that users' are immersed in VR and information/actions (e.g. menus) appear in a wide space in front of them (sphereing concepts introduced by ZHA).

Second, users will need to “navigate” to their “place-of-work”, the specific locations or part of the 3D model(s) and/or their variants that they are working on at a given moment. For instance, imagine an architect and an MEP engineer who are working independently but concurrently through the PrismArch interface on two different spaces of a large development; the architect is refining one of the lobbies of the retail podium, while the engineer is implementing MEP infrastructure for the office tower. What happens when they put the headset on? In large projects like this, with hundreds of functional units (retail/shops, office floors, residential etc) zooming in/out to the target room, may not be the most efficient way to get to the ‘place-of-work’. The user needs a way to highlight, select and effectively transfer to a specific spatial unit (e.g. room, etc), pick-up work from the previous work-session such as the previous day, or visit a location that has been flagged by a colleague asynchronously.

A third type of navigation concerns *curated/guided tours* as part of design reviews, in a sort of spatial to-do list. In this scenario, imagine the project leader is conducting a design review with the client. They are all connecting remotely using individual VR headsets and screens, and they must visit specific spaces to agree on outstanding issues. In a physical review, the printed plans are usually laid on the table and pointing gestures focus everyone’s attention to the same elements, and advance discussions. In an immersive environment this has to be achieved with different means. How does the main-user (meeting leader) ensure everyone is in the same space, looking at the same things, and can point and show their ideas? How do they ensure the group moves together to the next space that needs to be discussed? Online workshop tools, like *Miro*™ or *Conceptboard*, have a presenter mode where all attendees stop exploring and see the exact screen of a single user. A similar approach is necessary for design reviews in VR. Moreover, effective navigation from one space to the other will be essential for PrismArch’s usability in large projects. Navigation in large buildings can generally be difficult, and it would be beneficial for professional users to reduce/remove the associated cognitive load especially during workflows / meetings etc. For instance this could be achieved by a user who prepares / pre defines a route or a sequence of views through multiple rooms/spaces, akin to a fly-through. This can be achieved by drawing a polyline or by selecting spaces to visit from a list. This view-sequence can be shared with other team members, followed independently or visited during a design review, to ensure multiple users can navigate synchronously or asynchronously through a common itinerary relevant for their workflow.

From a distributed/external cognition point of view ‘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’ (D3.1, sct. 6.1). This conception can be applied to navigating architectural space, or the “space” of archived projects, or even the menu structure of an interactive user interface. How cognitively demanding this anchoring process is, i.e. how easy or difficult it is for users to do, depends not only on the complexity of the structure itself, but also on how far its visual representation clarifies or highlights key aspects to the user. Beyond prior knowledge, its conceptual structure will also have an influence on how users “expect things to be and how they will look like”, where they will search for which kind of additional cues when searching for specific items or locations. This can be thought of as an ‘expectation’ of where to find certain things (information, actions) on the interface. As Noyes summerises

> ‘When confronted with a new device or when using a familiar one, we have expectations about how it will or does work. These expectations are part of the interaction process and are important in the sense that they will influence our immediate and later use of the technology/device.’
>
> (Noyes, 2005).

Expectations can be influenced directly by familiarity with a particular system, but also through the background knowledge an expert might have on the domain in general (Kankainen, 2003). As

Kainkainen notes, users rely on an internal mental model of how to conduct actions, which is based on expectations formed by previous experiences with a specific product but also with other similar products. Sometimes innovative products introduce new types of interactions and affordances that users do not have prior expectations of, and thus need to be introduced carefully by the product design team. Subsequently, each experience with the product generates new expectations and informs future interactions/experiences (Kankainen, 2003). This is also discussed below in Section 3.1 about mappings from one modality to another.

To give two simplistic examples: webpages optimised for mobile phones increasingly replace the hyperlink menu from text to icon, substituting 'menu' with ☰ (the "hamburger" icon), as users have come to expect the functionality associated with this symbol; this was not possible before sufficient number of users are aware of this now common practice. Sharlin et al. (2004) provides the QWERTY keyboard as an example for a not immediately intuitive but 'well-learned' user interface (cf. sct 3.1). Another, more spatial example is that frequent restaurant visitors will most likely expect the restrooms to be in a more segregated part, possibly without being consciously aware of why they expect them in certain types of locations. Architects' expectations can be more sophisticated in so far as they might be aware of the typology of a building, in turn, using their additional expertise and background knowledge to restrict their expectation to the locations where water and excess water supplies are likely to be located the building type at hand. Needless to say that they can be expected to solve the task faster and possibly with a different cognitive effort compared to the architectural lay person.

For a system designed for as complex a domain as AEC design, prior knowledge of the particular project as well as professional experience in general are major factors shaping the way the system will be used, which strategies users will employ in interacting with the system (e.g. actions to design, add new elements, or edit geometry) and in navigating extensive bodies of extremely complex content. In addition, given the diverse roles and activities of PrismArch to enable cross-disciplinary work between architects, engineers and stakeholders in a unified environment, consideration should be given to the fact that not all users of PrismArch should be expected to have the same degree of familiarity with the PrismArch interface, or with CAD in general in the case of stakeholders (cf. also D3.1, sct. 2.2). Its success will depend on enabling both new, naive, and expert users to negotiate complex workflows and project spaces. Section 4.1 will return to this point in more detail.

2.2 Scales and Project Space Navigation

Different design representations and physical media each come with their specific characteristics, and, hence, capability in supporting human cognition in performing certain tasks much more efficiently. Deliverable 1.2 presents user interface requirements for an on-boarding humans from the "physical" to the "virtual"—let the human mind make the transition from being immersed in physical space, with all its tangible experiences, the sunlight, the dust, where monitors, keyboards, and handheld devices are isolated pieces of hardware that are occasionally able to "display content", into a world where the display is endless, surrounding the human senses entirely, so that a new space emerges, the virtual space to get immersed in.

> 'Every on-boarding member should be allowed to configure their personal avatar, which resides inside their Personal Work Sphere (PWS). Inside the PWS, the user can complete the avatar configuration and customisation for the VR'
>
> (D1.2, sct. 3.4)

Virtual reality has the capacity 'to translate between scales of space and between different levels of detail,' (D3.1, sct. 2.2) in turn pointing to the need for PrismArch to develop a considered approach to the question how spatial content can be represented in a manner suitable to multiple design-related tasks in order to support and complement human cognition in understanding and doing design work on the different scales (spatial, detail, temporal). Scales are especially relevant with regard to designers being able to appropriately anticipate the experiences future users' will have of a building project under development.

On one hand, the capacity to change scales continuously is an essential strength and rationale for integrating VR into the design process. For architects who are trained to do conversions between fixed-scale representations such as plans using their imagination, a precise spatial representation can help anchor one's own intuitions—how small or large a space is 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.

The topic of *spatial scales* is particularly relevant to the topic of how PrismArch users will perceive, understand and, hence, be able to *navigate* within and between design projects. As introduced in D3.1 We can distinguish between *figural* space (a screen), a *vista* space that can be apprehended without the user's movement (a room), and *large-scale* space like that of buildings, where the person learns the space by integrating multiple views over time, and finally *geographic* that can only be perceived through media like maps (Montello, 1993). One feature of spatial cognition is that our mental representations of space (cognitive maps) 'borrow' their orientation and alignment from our environment. Each individual space (i.e. the direction of the walls) imposes an intrinsic or local 'reference frame'. External landmarks and environmental features, e.g. the orientation of streets, also provide an extrinsic or global reference frame. Spatial memory and sense of direction emerges as the interplay between these reference frames (Meilinger et al. 2014). Typically the 'local' reference frame (e.g. room) is adopted, but when there is a mismatch between the building and the room, confusion (i.e. errors) can arise. Consider visiting a building that is positioned in an oblique angle, rather than parallel to the street; in such cases often people mistake their orientation as parallel to the street (e.g. when pointing at non-visible locations). Having views outside the room / building can assist with connecting the local and the global/ extrinsic reference frame. Typically this is achieved by physical windows, but VR also affords walls with reduced opacity and other methods which facilitate the orientation of users (Li et al, 2016). While the main designer of a building may not require external support for her orientation in the project space due to the familiarity with the project itself, this issue can be important for disciplines that spend less time 'inside the project' from consultants to clients (not architecturally trained). Typically, zooming in/out is the most effective way to re-establish orientation and/or move between spaces, when one is working on a top-down or 3D view (e.g. in CAD or 3D software). However, this may be unnecessary or even introduce additional fatigue if one or more users are collaborating 'inside' a building using immersive VR. Imagine a designer having to zoom-out during a conversation in PrismArch to reorient themselves, or a client that feels disoriented after a series of transitions from one space to another.

Additionally, moving across scales works differently in VR compared to physical space. In VR, representations are singular objects playing specific roles in presenting certain aspects, supporting specific tasks, and serving particular purposes. Typically in CAD workflows, drawings have an orientation within the screen and in order to move across scales or regain their orientation, such as from the room to the entire building, users zoom in/out. In VR however, zooming in/out will reach its limits when dealing with large urban/architectural projects, like stadia, mixed-use buildings etc. In principle, a user can scale or "fly" or "zoom in" from the view of the entire planet earth (or even other planets, if their professional work happens to engage in extraterrestrial architecture) into a particular design project and further onto a particular object, a door handle, say, mounted to a particular door belonging to that project. This vertical integration of scales or views allows the user to integrate multiple reference frames that are typically not related cognitively, simply for the lack of opportunity and need to make that integration in the first place. Consider standing in front of the vending machine at the third underground level (B3) in a parking garage after driving in via a complicated, curvy trajectory underground. Most likely you won't be able to point back to the junction where you left the motorway a few minutes ago. And there is simply no need to make that integration because what matters is the vista space inhabited by the control elements of the vending machine "in front of you".

Nevertheless, zooming in from planet scale to door handle scale would allow users to spatially integrate the orientation of that door handle with the rotation axis of its home planet, once it will have been mounted at the door in the completed project. There are certainly interesting design opportunities in this, especially if we consider architectural elements or other objects whose orientation with respect to other elements (inside or outside the project space) matters. However, the future users of the physical door handle will most likely not have access to the orientation of the planetary rotation axis simultaneously with touching a metal handle mounted on some interior door. A more human-centred, navigation scale will likely be more appropriate for creating designs that are rooted in everyday practices of the future users.

> 'By using full size human figures, we enable an accurate representation of scale. It is important to humanise the avatars, to uphold the ethos of human-to-human interaction (as opposed to perceiving our collaborators as monsters or robots)'
>
> (D1.2, sct. 3.4.1)

Along these lines, Deliverable 3.1 has suggested to structure the navigational space within PrismArch in accordance with users' conceptual view so as to provide interface features and possible user actions at a suitable scale and reference frame that makes sense from a cognitive and task performance point if view (D3.1, sct. 6.1).

Another scale to consider is that of time. Design projects typically develop over long periods of time, and over many iterations. In some cases the project itself requires dealing with "time" for example when one works on an existing building that has amalgamated over time – this is often the case for historical sites, hospitals, extension projects etc. Within the project space itself, there is an important need of organising and exploring temporal aspects (such as previous or parallel project iterations) or time-based components of the work itself, such as simulations. Today, these aspects of temporality are resolved in different pieces of software; design iterations are saved in different files, and simulations are explored in dedicated software. How should they be presented to the user in the unified project space of PrismArch? How does a user interact with the temporal units of different project components (discrete temporal order of past versions, continuous time of a solar gain simulation)?

Conceptually, we can relate the *vertical* transitions in project structure to the traditional use of different (fixed) scales in architectural design practice, implemented or materialised through the different plan representations, each of them used for specific purposes, supporting different operations and key activities that are required in the various phases within the course of a design project. *Horizontal* transitions in project structure point to issues regarding the (hierarchical) structuring of design projects. They are to be distinguished from movement in three-dimensional architectural space, whether presented in a virtual or real environment.

The prototypical horizontal movement in a project structure would be to move from door handle to door handle, i.e. horizontally within one class of objects. This, in turn, would allow users to move in typological and/or project structural space, at the same time being teleported through physical space to the respective locations of the visited object instances. The latter point highlights the challenge for users to remain oriented in the architectural space when navigating by means of the conceptual or typological project structure.

The present developments around the force-directed graph structure are directed towards a query interface that will allow users to

> 'filter user demanded inputs from the project data nest, [...] to visualise the filtered information with simple geometries (Metadata Nodes). The user interacts with the Metadata Nodes to preview and trace back the associated project information. The proposed tool enables the user to load queried Design Objects and its associated project metadata and information.'
>
> (Deliverable D1.2, sct. 3.6.1.d)

To make an attempt to integrate the conceptual, typological, *non-spatial* relational aspects of that project information with the *spatial* structure of the architectural project, in which the user will be immersed in, highlights a number of cognitive concepts worth revisiting in this respect.

First, such an integration should make an attempt to connect the non-spatial information and the representing UI elements in relation to the *user immersive space* (the space in which the user is immersed), in such a way as to allow this user to maintain their attentional focus and spatial orientation at the time. To give an example: Standing in front of one particular door handle, a user might choose to query for several conceptually similar but spatially remote objects, say, door handles. Reviewing the query result should be possible without requiring the user to put cognitive effort into unnecessary switches in spatial scale, spatial reference frame, or otherwise having to redirect their attention more than necessary. The user should be able to review the entire query while still "standing in front of the door to the ground floor living room," where she or he initially started the query.

Second, presenting the information in a non-disruptive way as outlined above will require the system to relate the presented information to information already presented to the user. Recalling Kirsh (2010), when working with external representations, humans need to 'establish a coordination between what goes on inside their heads and what goes on outside,'—in this particular case, users will have to integrate what has been queried and is then presented to them 'outside,' by the system, into their understanding 'inside their heads' of where they are and what is the space they are immersed in and what are the things they already see around them. From a systems' development point of view it is worth considering whether identifying a suitable scale and frame of reference could possibly be facilitated by the upcoming work on designer modeling as part of the AI-based inferences on user behaviour (Deliverable D2.3).

2.3 Views, Perspectives, Content Visibility

A core component of PrismArch platform is the differentiation of displayed overlay information depending on the discipline-specific information requirements. Early on this was phrased as one of the *Objectives* as

> 'the necessity for an interdisciplinary tool capable to address the unique requirements of each discipline both individually and simultaneously, where all authors will be able to work on the same architectural project and perceive it in their own, different way that best suits their needs.'
>
> (Description of Actions, sct. 1.1)

This feature has great potential especially in terms of reducing cognitive load, by omitting information that is not relevant for their particular discipline, in turn preventing users from being overwhelmed by information displayed on behalf of other disciplines. However, care must be taken to ensure sufficient overlap in the presented content so that users can align their views on the content as well as their (cognitive) understanding of what they see and how they interpret it in conversations across disciplines (cf. Carlile, 2002; D3.1, sct. 2.1).

When several team members need to coordinate their positions (and views) in an immersive environment additional complexities emerge. Depending on the spatial location of a user in space their 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.

One of the key lessons that can be learned from the tracing paper case study (D3.1, sct. 3.1) 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.

When one user is presenting to an audience of fellow users, discipline-specific information of the presenter will most likely be required to be visible for all participants in the same way so that the mixed-discipline audience can follow the argument of the presenter.

Tasks such as reviewing a master model based on the results from a structural analysis detecting and resolving *clashes* have the potential to involve designers from two or more disciplines requiring content to be presented in a joint way so that alignment is possible in a collaborative activity.

How these and similar tasks unfold cognitively depends on how the mode of presentation supports the users in anchoring (cf. D3.1, sct. 5.2) the involved discipline-specific information sources. The task may be performed by one person or by a group of people, and they might rely on different combinations of external media. Within the distributed cognition approach it makes not much of a difference for the overarching cognitive description of the task. What changes, however, is the quality and quantity of information to be processed by the individual human(s) and this depends on how much of the overall cognitive effort is taken over by the external media and how the information is presented in these media; be it analogue, traditional digital or fully immersive presentation modes. For instance, *visually* anchoring or integrating content from several sources within one view can transform the overall cognitive task so as to transform the individual human activity from a complex cognitive operation into a much less demanding visual task.

During a design project, multiple design alternatives and variants are generated by one or more teams, to explore the design solution space, find solutions to issues etc. Typically design alternatives are laid out next to each other and discussed exhaustively. How can this collective work be achieved in collaborative VR? Figures 3.5.1a and 3.5.1b (D1.2) provide an impression of how a meeting situation could be realised in a virtual environment. In a CAD environment, the project has absolute coordinates (that may, in cases, correspond to GIS and other informational layers), thus the ‘traditional’ way of “moving each alternative 100 meters to the left” may be less appropriate or even hinder integration with other workflows. For instance, how do users explore 3 different circulation layouts, overlaying simulations of pedestrian movement? Are the alternatives separate files, imported as references (XREFS) or are they part of the same file? The solution presented as part of the PrismArch unified data sphere foresees a possibility for users to snapshot different versions of the same asset and ‘curate’ them for a future meeting (cf. for instance D1.2, sct. 3.6.1.c on the use of the query functionality in connection with meeting preparation activities).

Returning to the clash detection example again, detecting spatial clashes between two complex 3d models might be nearly impossible to do reliably for a human with both models being presented side by side in separate view. An aligned 3d view will already improve the situation by removing the need to mentally anchor corresponding locations in separate visual displays and to detect clashes based on mentally representing the spatial configuration. Instead, the alignment is achieved visually, supported by the external medium, which may be a 2d tracing paper overlay or a 3d juxtaposition of two models. Exemplary evidence comes from episode I3ZOe (Appendix A) in the interviews: 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.; cf. also D3.1, sct. 5.2, *Visually Inspecting Spatial Data*). Further improvements can be achieved by color-coding models and layers in a suitable way and by automatically highlighting spatial overlaps (areas that are enclosed by both structures).

But there are other situations, where not only strict spatial overlaps indicate issues to be resolved. For instance, aesthetic and structural considerations may interfere with each other without necessarily producing a spatial clash in the strict sense. Finally, changes in the architectural domain might affect structural aspects in a way that is not easy to spot visually at all but requires a careful review with sufficient structural expertise (cf. I5AAa, 4., Appendix A). In this case, visually overlaying the architectural model with the structural might even lead to a visual representation that is too cluttered to read off the structural aspects relevant to the reviewing human expert. Additional visualisation tools to support users should be considered (e.g. highlighting changes or intersecting geometries, etc).

2.4 Social Space, Team Collaboration, Workflows and Confidentiality

Regarding collaborative activities, the section on *Co-presence and Immersion* (D3.1, sct. 3.3) points to the requirement 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.’

Section 6.1 in Deliverable D3.1 discusses how physical space allows design teams (and human societies in general) to organise social matters by relating aligning or ‘anchoring’ (Hutchins) conceptual and spatial reference frames to one another: `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’ (Dt3.1, sct. 6.1). Departing from a meeting situation, different visibility configurations are made possible through the use of traditional media. In order to allow for a flexible handling of visibility and confidentiality settings in a more digital approach, prototypical activities such as “users can share content with others spontaneously” combined with the possibility to switch items “invisible on an individual basis” again, or “taking private notes on an individual basis” need to be implemented based on on private, shared, hidden, and visible content allowing users to quickly switch between items hidden from other meeting members and shared or public modes, in which created content can be seen by some or all other colleagues in the team. The aspect of co-presence will be challenging to maintain alongside mechanisms giving users adequate means of controlling access to company-owned content, differentiate information display according to individual and discipline-specific needs, in turn allowing users to deliberately dive (or drift accidentally) into personalised or discipline-specific visual configurations and content spheres.

At the same time, current collaboration tools in VR offer a partial solution to this by displaying a schematic avatar of the ‘collaborators’ who are in the same VR space. How should this initial approach scale up to large and complex project spaces remains open, and is essential for the usability of any tool. The gaming industry has identified many solutions on the question of how can people who are co-present be visible to each other as an overview: avatars of people who are on the same space, littles icons of people who are on the same file (but in different places, similar to google docs), text information which disciplines are present, e.g. 'ZHA: 3; ACT:1', locations of other players in the same level on a map-like representation, and so on. Section 2.1 of Deliverable D3.1 provides a more thorough account of spatiality and social interaction in immersive virtual environments.

3 GUIDELINES

With respect to recommendations and guidelines for user experience development it must be noted that PrismArch is intended for a highly specialised user group. It remains true that no general guideline can be given in such a situation without running into the danger of over-simplifying matters in a way that is inadequate for the particular purpose at hand, as we have argued at length in Deliverable D3.1. A minimal example having emerged recently from an internal communications with our AEC partners revealed a use case in MEP design that underlines our point: A user needs to retrieve a particular technical component from a list of several thousand items in a menu/folder structure. It should be clear from such examples that any standardised guideline or empirical study on menu-design cannot account for the domain expertise required to effectively use such an interface and to make an appropriate choice from that list. Similarly, professional CAD software makes extensive use of information input through (physical) keyboard and command line interfaces to choose from hundreds of different commands, each of them using additional arguments to restrict and parametrise the commands' exact behaviour further, again in a keyboard command line manner. In order to achieve desired results, users must choose precisely the appropriate command so as to maintain the digital model's integrity, supported further by additional functionalities like vertex, object or grid 'snapping', restricted movement along certain axes etc. Failing to do so often results in undesired model corruptions such as misaligned polygon edges and so on. While expert users are able to control software components with hundreds of commands through keyboard and scripting interfaces, usability guidelines for a general audience will most likely suggest to provide guidance to users through wizard-type of interfaces for "more complex operations," such as setting up new documents. Hence most CAD interfaces combine both extensive sets of icons and keyboard entry to support users with different levels of expertise. Physical keyboards also support well-trained users in entering commands without the need to take their eyes from the screen. This allows the eye fixation to remain stable in the visual medium, in turn, increasing the capacity to visually anchor locations in the visual display of a plan, for instance. Transferring this level of expert-user mode (i.e., command-line) to VR raises multiple questions, whether the PrismArch interface can be used only without or with a keyboard too, and resolving the trade-off of how to maintain nimble VR menus to accelerate work versus giving access to a rich set of production tools. Speech recognition is currently being integrated for notes-taking functionality and, in principle, could also be used for accessing commands. However, considering co-immersion of multiple users in the same virtual space will introduce additional complexities to using speech as a component in a command-based human-machine interface since speech is at the same time the primary modality for spontaneous verbal exchange between human peers. When multiple users work in different immersive spaces but are physically co-located "in the same office" they would all have to give verbal commands to their CAD software potentially at the high rates that are typical for expert CAD usage work flows.

Overall, it must be noted that the aspects covered by existing studies are often too specific or geared towards a high-level comparison of different systems at a high level of abstraction. As a consequence, deriving guidelines from them is not straightforward. Furthermore, study participants are often students who were recruited in an educational context so that conclusions drawn from the studies might not apply for expert users in an industry context. Specifically, in a professional context, users of any software are expected to be familiar both with the tools and with the projects/case-studies they are working on. The deep familiarisation with the space and its properties is the result of repeated work, and cannot be easily emulated in a laboratory study where participants typically have 1-2 hours to learn and perform a set of tasks. In other expert usability studies, such as the evaluation of new interfaces for air-traffic controllers, the tasks are standardised and repeatable and the tests are conducted with experts and not laypersons. In the context of PrismArch, expertise with the tasks and workflows is necessary but the layout, properties and constraints are unique to each project, which makes the simulation of tasks through artificial case-studies more challenging. In an ideal scenario, the evaluation of the new tool would be performed on ongoing-projects where the test-users are in-fact continuing their work using the new tool. While this approach would likely yield the most useful insights, pragmatic considerations such as project confidentiality, may limit our ability to conduct such testing.

3.1 Migrating Design into the Virtual

When it comes to interaction with complex technical systems with the need to manipulate content in a precise manner, migrating these established, robust, and ‘well-learned’ (Sharlin et al., 2004) mechanisms of interaction into a fully immersive setup, a careful investigation of the involved activities in their entirety is required. Epistemic actions (cf. Kirsh, 2010; Gu et al. 2011) may arise in interaction with physical objects (van den Hoven & Mazalek, 2011), in tangible interfaces (Lou Maher & Lee, 2017), or gestures on physical design media such as plans (an overview can be found in Park, 2021, sct. 2.4.1; cf. also Brösamle & Hölscher 2018).

Castelo-Branco et al. (2021) analyse and test different configurations for performing life-coding for algorithmic architectural design within an immersive virtual environment. Despite this well-defined and relatively restricted scenario, their analysis already reveals various sources for complexities arising from the requirement to manipulate algorithms from within VR while at the same time being immersed in the structure being generated by the (very same) algorithms. Dossick et al. (2015) study potential for unexpected discoveries in collaborative virtual design. Jin et al. 2020 compare immersive virtual design environments with more traditional design media with respect to their impact on collaborative design activity and outcome. Gu et al. (2011) study the types of interactions in ‘synchronous design collaboration.’ By comparing (a) ‘3D virtual worlds for supporting remote design collaboration where design activities can occur at the same time with the participants remotely located’ with (b) ‘tangible user interfaces (TUIs) for enhancing co-located design collaboration by augmenting the perception of the shared design drawings or models through tangible interactions with the digital design representations’ the authors evaluate ‘changes of designers' cognition, communication and interaction’. Departing from the notion that ‘the focus while designing is on the shared design representations (i.e. sketches, drawings and models)’ the authors study ‘types of digital media for design representation, the types of interactions for creating, modifying and exchanging the shared drawings or models, and the types of communication means provided to the design team.’ Their category-based quantitative analysis reveals characteristic differences regarding activity patterns of the studied pairs of designers between the different design environments (a, b, c). They also give recommendations for future studies as well as designs of environments for synchronous design collaboration. Yet, their report on the quantitative results takes place on a relatively abstract level so that it remains difficult to develop an in-depth understanding of what are the underlying cognitive mechanisms producing the respective activity patterns on an operational level. Comparing (a) 3d virtual worlds and (b) tangible user interfaces the authors find the latter ‘through a direct tangible interaction’ to allow designers to ‘use their hands and often their entire bodies for the physical manipulation.’ Although considered a specific property of tangible user interfaces (TUIs) by Gu et al. (2011) controllers with force feedback systems and improved sensor technology for capturing fine-grained motion, including markerless tracking of body posture and hand gestures, make it reasonable to assume that some of the TUI-specific principles will generalise to VR systems in general in the near future.

Related work (Sharlin et al., 2004) concludes that ‘successful’ tangible user interfaces (TUIs) depend on ‘physical/digital mappings’ that are ‘successful spatial mappings’ at the same time. Three *criteria* suggest that, first,

> ‘the relationship between the spatial characteristics of the TUI’s objects and their use must be spatially congruent and/or well known. Second, physical/digital mappings must unify input and output space. Here, we advocate that the purely digital distinction between both input and output spaces and input and output devices must be eliminated. Finally, physical/digital mappings must enable trial-and-error activity.’
>
> (Sharlin et al., 2004, p. 338)

Sharlin and colleagues quantify *spatial congruence* in terms of the *degree of integration*, in turn referring to Beaudin-Lafon who defined degree of integration as

> ‘ratio between the number of degrees of freedom (DOF) provided by the logical part of the instrument and the number of DOFs captured by the input device.’
>
> (Beaudin-Lafon 2000, p. 450)

Sharlin et al. continue with the example of the computer mouse which

> ‘affords two DOF or dimensions of motion, while the cursor does as well—a good ratio of 1. Beaudouin-Lafon [...] also discusses a ‘‘degree of compatibility’’ that measures the similarity between each of the actions performed on an object, and its application response. With a mouse, moving the mouse to the left moves the cursor to the left. The mouse is not as well-suited to controlling image plane rotation, though it can be modified to afford this action.’
>
> (Sharlin et al., 2004, p. 339)

Regarding *spatially congruent mappings*, their first point, they add that

> ‘spatially incongruent mappings can also be quite efficient, if they are well-learned. A classic example is the QWERTY keyboard, which maps the largely non-spatial alphabet to a spatial keyboard layout.’
>
> (Sharlin et al., 2004, p. 339)

We discussed earlier in connection with command line interfaces in CAD software that the PrismArch’s user-group can be expected to be highly trained with respect to interacting with complex pieces of software that support large, specialised command sets.

Their second point, that ‘physical/digital mappings must unify input and output space’, reminds us of a quote by Bowman where *interaction fidelity* is defined as as

> ‘the objective degree with which the actions (characterized by movements, forces, body parts in use, etc.) used for a task in the UI correspond to the actions used for that task in the real world.’
>
> (Bowman, 2012, cited in Deliverable D1.2, sct. 3.3.1)

When it comes to the technical means of achieving immersive experiences we are further reminded of *immediacy* as a concept for a medium's ability to be looked through, ‘directly onto the content’, i.e. the degree to which the medium

> ‘disappears from our perception allowing us to perceive what is beyond it. [...] The effect of a large screen and darkened room in a cinema also has the effect of focusing the audience’s attention on the content of the film rather than on the technical expression that makes the filmic space possible.’
>
> (Benyon, 2014, sct. 2.1)

These two concepts provided by Bowman and Benyon highlight slightly different aspects in that they focus on the smoothness of the movement on the one hand and the experiential quality of the immersion on the other.

Concerning their third point, *trial-and-error actions*, Sharlin et al. themselves refer to David Kirsh and define them as as those kinds of actions that

> 'often fail to bring us any closer to our goal, but can sometimes reveal completely unexpected information and shortcuts that would have been very difficult to find by following a straightforward, pragmatic approach.'
>
> (Sharlin et al., 2004, p. 340)

Again, using the computer mouse as an example to illustrate their approach they conclude that for

> 'higher-dimensional tasks from changing the view in a first-person shooter to editing 3D structures with CAD software [...] the mouse has poor degrees of integration and compatibility, and cannot claim to rely on any previously well learned non-spatial mapping. The mouse provides neither good I/O unification nor trial-and-error support.'
>
> (Sharlin et al., 2004, p. 341)

The authors step in for user interfaces that enable trial-and-error spatial activity, which they consider

> 'barely supported by the traditional human–computer interfaces, with the single physical mouse often mapped to many different virtual entities.'
>
> (Sharlin et al., 2004, p. 345)

Extending and applying the above to the issues related to interaction with immersive virtual environments we recommend interactive functionalities to be "object-centric" and "spatial-activity-sensitive". Interfaces should support a variety of gestures and these are not simply interpreted as atomic commands. Rather, their shapes, locations, configurations, and movements in space would allow users to modulate the input being made to the system. For instance, transforming an object in three dimensional space would preferably be implemented on the basis of one multi-finger gesture with movements of several/all fingers meaningfully defining the exact parameterisation of the object's transformation. The result should be the user experience of "grasping the thing and relocating it with my hands," in turn requiring the system to carefully map the fingers and their movements to specific parts of the object(s) to be transformed. Additional "modifyers" could be used during the action to restrict transformations regarding rotation, scaling, movement in all or some dimensions. The opposite approach would be to first choose a specific command or transformation to perform, say, proportional scaling in XY-direction with Z-direction being fixed, and then perform an action that gives the amount of XY-scaling. While the latter approach increases control greatly by reducing the degrees of freedom (DOF), the mapping between the controler's DOF and the manipulated object no longer match, i.e. the mapping is *spatially incongruent,* at least to some degree. On the flip side, situations would be considered undesirable where users had to use a single or relatively few elementary controlling actions to choose from comparably extensive menus or palettes. An extreme case of this situation would use four elementary actions (e.g. up, down, left, right) to navigate within and choose from the menu.

Following up on section 3.3.2 (Deliverable D1.2) on *Considerations for a Dynamic Interface Design,* which proposes an

> 'alternative UI paradigm that shifts away from fixed toolbox-like or palette-like examples like Gravity Sketch, and is more similar in nature to modular, node-based tools like Scratch or Grasshopper3D, where the composition of simple elements leads to novel, ad-hoc complex behaviours,'

we must warn to over-emphasise the compositionality aspect in any way that may lead to over-complex compositions of under-complex 'UI atoms.' In such a situation, the latter would be characterised by relatively sparse instrumental interaction whereas their various (!) compositions run the risk of undermining an overarching coherence. Instead, carefully designing a rich and functional behavioural repertoire for few non-trivial key UI elements that embody a holistic approach could be the more appropriate approach along these lines. We should also emphasise that *trial-and-error* is an essential component for learning an interface, and constitutes and contributes to the past and present experience of it (see above). Therefore, interfaces that introduce novel ways of experience and interaction, like PrismArch, should aim to enable trial-and-error by a robust system-design (e.g., failing gracefully such as return in previous state rather than crash when the user does something incongruent).

3.2 Visibility

In a setup that fosters all content to be accessible from within a fully immersive collaborative environment the system must enable users to *fluently control* their own and their colleagues' *view on content* based on aspects such as relevance for the task, confidentiality considerations, discipline-specific requirements and so on. In particular we do not recommend fixing any of these visibility settings in a hard-wired kind of way. Presets will help users to adapt complex view configurations without much effort. While the former should be self-evident, all settings must be adaptable by the users in each particular situation *on the fly,* from within VR and without leaving the immersiveness of PrismArch, so that users can adapt the system's configuration to situation-specific emerging communicative and cognitive needs.

3.3 Human Interaction, Virtuality, Simulation and the "State of Activity"

> 'When working, humans exploit visual, tactile and other sensory cues to deduce the state of their activity and its progress from the condition and motion of their tools. For much the same reasons, the need to maintain clarity of application state is well established in HCI [11].'
>
> (Sherman et al., 2004, p. 340; Reference no. 11 points to Shneiderman, 1983)

The relevance of this point was discussed at length in relation to providing users with a 'sense of spatial immersion and co-presence that adequately reflects the team configuration, task requirements, and underlying data model' (sct. 2.4, no. 1). One has to distinguish between different realities or layers:

(a) "real reality" (the physical world, "where am I"),

(b) "virtual reality" (the content that is displayed in front of me, whether this happens on a 2d display or in immersive VR, "what I am working on [within PrismArch]"), and the

(c) "computational reality" (the state of the information system itself, "is this simulation still running or has the process crashed in the background?", "Do these scattered polygones result from a corrupted file/data base or has somebody tried some de-constructivist approaches on yesterday's design?").

On the user side not every nuance must be known, but users need enough of an understanding so as to judge possible causes for what they experience and decide on their next (best) actions, notwithstanding without distracting or interrupting them unnecessarily in their workflow.

When it comes to integrating simulation and AI-based suggestions into the immersive work environment of designers, asynchronous background activities of the system(s) raise issues of how to achieve and maintain an adequate insight and understanding on the user side on the state of *their activity* on the one hand and that of the systems' activities going on "in the background", simultaneously or "in parallel" on the other.

The following case study exemplifies a scheme where the task state is directly available to the users through a tangible component of the user interface, whereas a more computational simulation-based component is provided by the system (literally) on top of that by a projection from on top.

> 'Piper et al.'s [17] Illuminating Clay (Fig. 5) is a landscape analysis tool based on interaction with a physical clay model. During interaction, Illuminating Clay visually augments the clay model with various real-time landscape functions, presenting information such as slopes, shadows, solar radiation, land erosion and water flow. [...] The surface of the clay model itself is the interface—it can be spatially manipulated to achieve the application goals, even without the placing of physical objects on it.
>
> [...]
>
> Illuminating Clay unifies input and output [...] offers a consistent representation of a major feature of the task state and, hence, a stronger physical fusion of input and output.'
>
> (Sharlin et al., 2004, p. 343; Reference no. 17 points to Piper, Ratti, & Ishi, 2002)

Through the different media (clay+illumination through projector) the user interaction and the background simulation are clearly separated into two realms, in turn imposing a hierarchy: The user can alternate the clay, the system can alternate the illumination, the system reacts to the changes in the form of the clay, which are solely authored by the user. The user may or may not react to the illumination provided by the system.

As discussed in earlier deliverables, in generative design approaches, the design team (architects, engineers and stakeholders) define a set of parameters/criteria and generate a few or thousands of alternatives (depending on the computational approach) which are the reviewed using performance criteria, diagram (e.g. often coordinate plots) and visualisation (e.g. Fink and Koenig, 2019; Wilson et al., 2019). It will be essential to transposing this process of iteration, evaluation of diagrams (information) and forms (designs) in VR, and given the rich information involved will greatly impact the cognitive load and usability of the interface. Reiterating the related topics of visual presentation we redirect to the corresponding section on *Visual Presentation and Design Media* and on Spatial *Alignment and Visual Inspection* in particular (Deliverable D3.1, sct 3.1).

3.4 Mapping Team Activities and System's Components

One of the action points laid out in Deliverable D3.1 envisages to 'extend the diagrams by explicitly adding components from the systems design on the technical side. [...] [in turn] distinguishing between "synchronous" vs. [...] "asynchronous" modes of interacting with the system'. As a first step in this respect, ETH prepared a draft of a diagrammatic representation which incorporates user activities as well as technical components distinguished in the systems design, in turn providing a holistic view on all key components that would later be involved in the team-wide design process using the immersive environment and its "back-end" database components such as the *Speckle*™ infrastructure (Speckle Systems Webpage) or *Unreal Engine*™ (Unreal Engine Webpage). All project partners revised and commented on the draft diagram, which was available to them by means of a *Miro*™ board allowing for simultaneous, synchronous, co-aware interactive editing by all partners. Miro, which was used primarily as a 2d graphical medium in these sessions, was complemented by a *zoom* session running in parallel (Zoom Video Communications Website). The interactive session triggered fruitful discussions on crucial points regarding (1) the interfacing between human users and technical components, (2) the role of different technical components in various forms of using the platform, i.e. synchronous and asynchronous interaction patterns. Several necessary refinements could be identified in during the sessions, especially related to the (3) handling of user credentials, the (4) review and approval of new design content, (5) the necessity to record not only 3d content that was explicitly created by users as such, but also to perpetuate traces of key user actions even though they might not have created design content explicitly, e.g. communicative gestures during meetings etc.

While ETHs draft diagrams triggered discussions and insights primarily by presenting an imperfect or incomplete account on the overall system's design, further efforts were then made by other project partners towards maturing key aspects so as to provide a more comprehensive specification. Towards this end, Deliverable D1.2 presents a careful discussion of different options for configuring one or several speckle repositories alongside their respective implications for the distribution of confidential data across the information infrastructure of multiple involved parties. In several earlier presentations and diagrammatic representations, ETH has touched on the topic—but could not fully resolve the issues at the time (Figures 1, 2, 3). An important step forward is represented by a much clearer diagram provided by AKT in response to one of the interactive sessions (Figure 4).

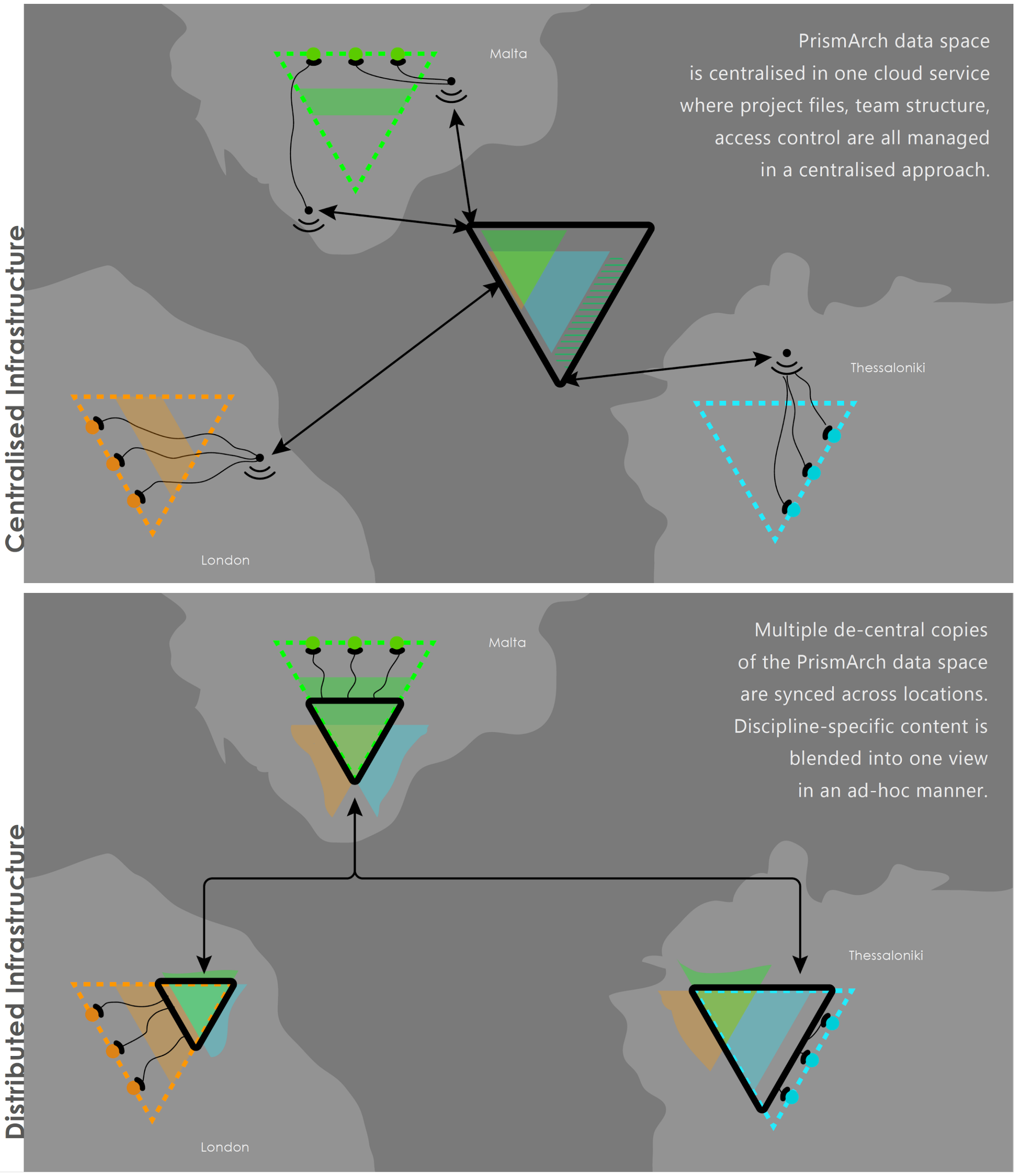

Figure 1 a/b: Slides from an internal presentation by ETH (March 2021). How centralised vs. distributed information architectures impact on privacy and confidentiality matters for future applications scenarios.

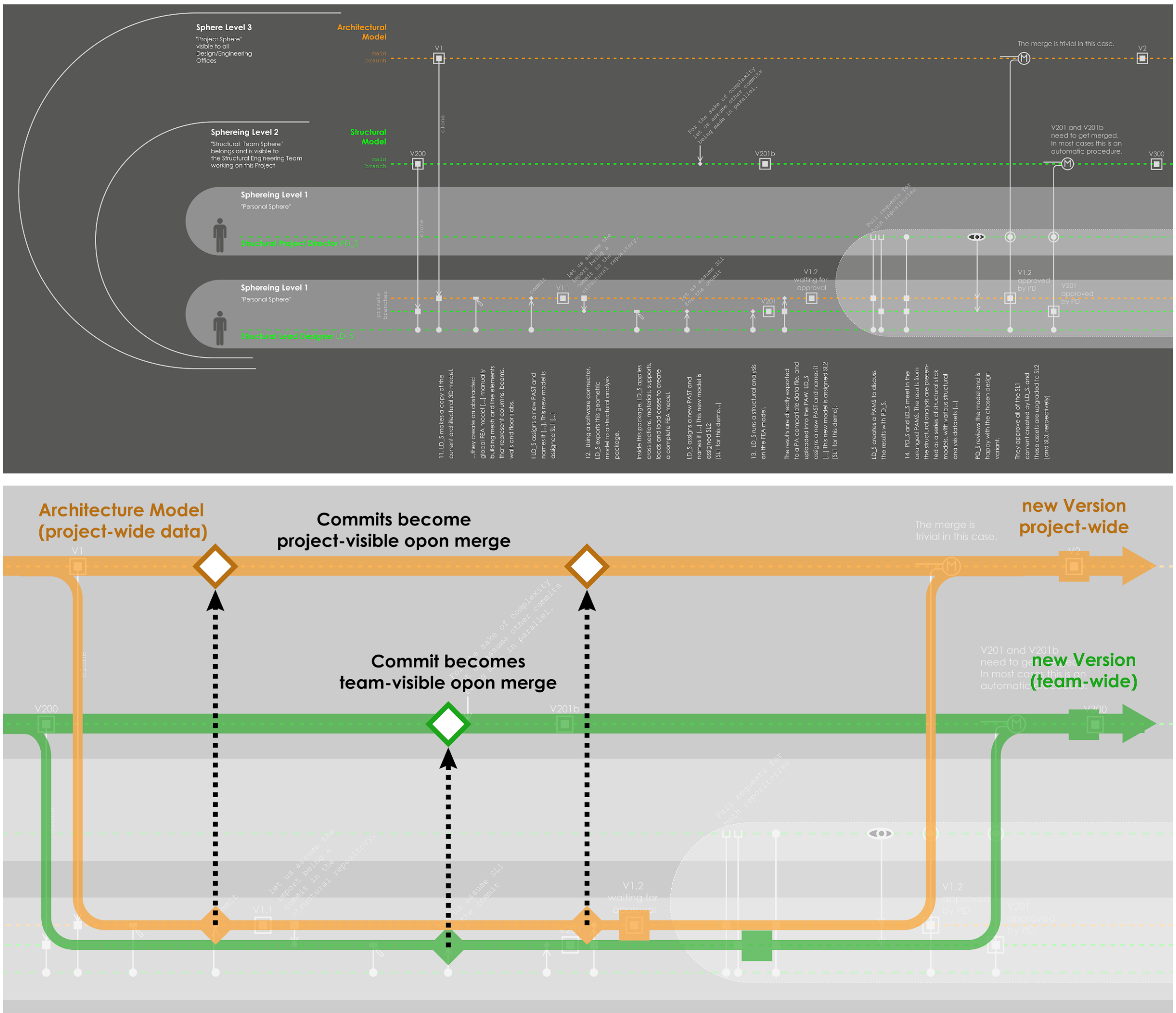

Figure 2 a/b: Sphereing levels (introduced by ZHA) related to a schematic Git Workflow with two repositories, each of them branching off private branches in local working, to be merged into their respective main branches at a later point, overlayed on the above sequence diagram (Deliverable D3.1, Fig. 7).

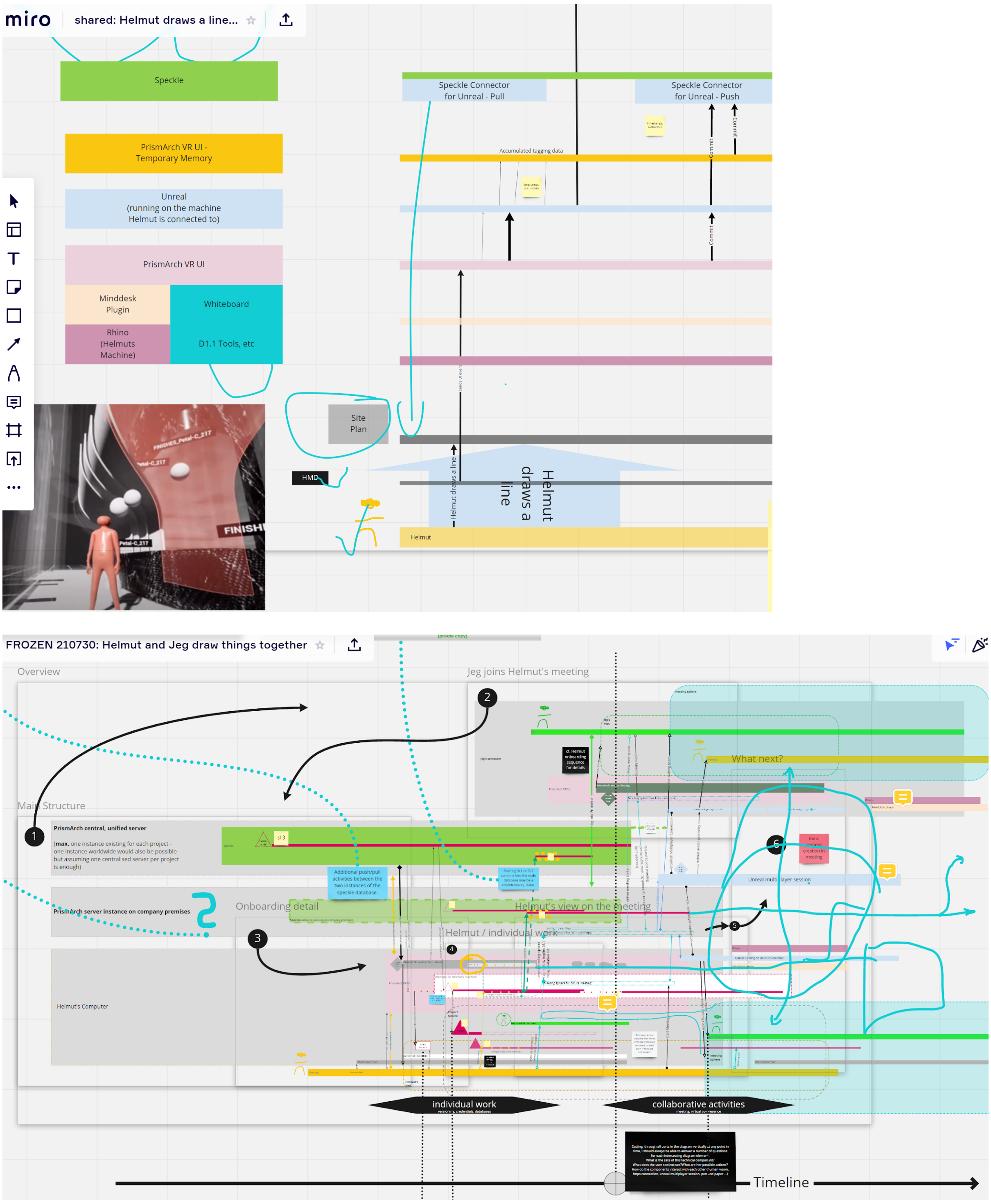

Figure 3 a/b: Two *miro*™ boards on User Activities and Systems Design, prepared by ETH, revised interactively in collaboration with all project partners (July 2021).

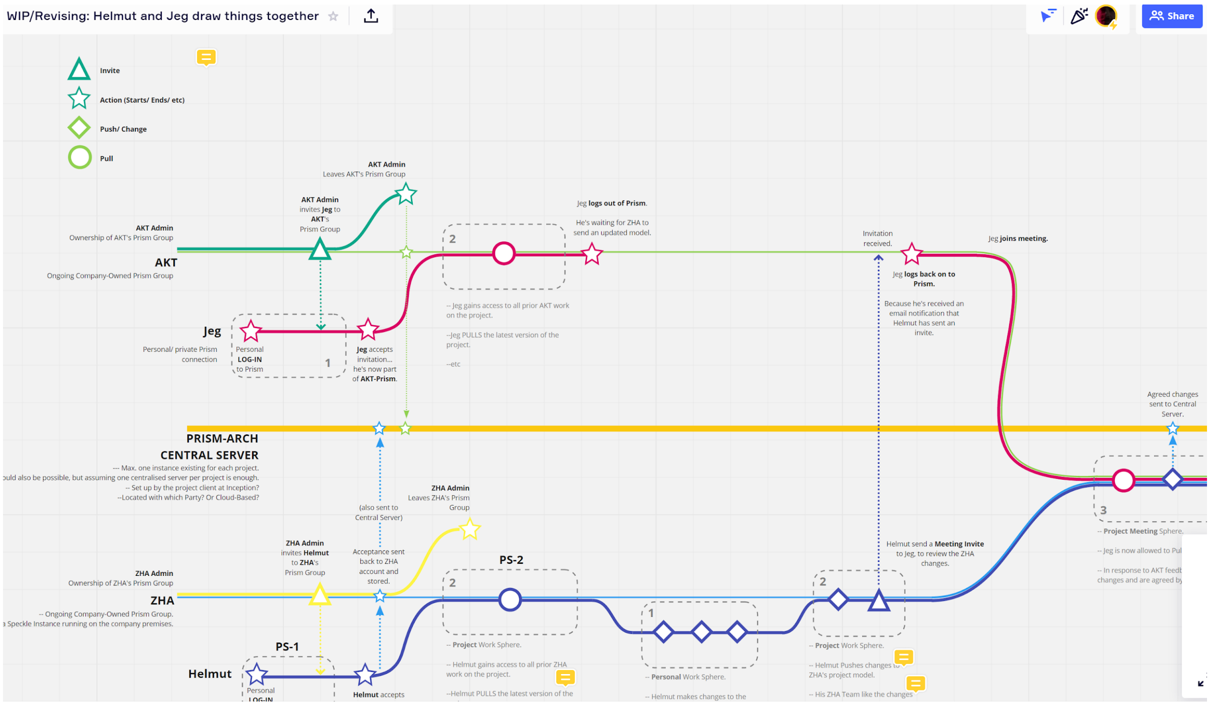

Figure 4: In response to one of the interactive sessions, AKT produced a diagrammatic workflow diagram that clarifies the user activities in relation to key elements in the information architecture, i.e. Speckle™ streams, commits, branches, merging, etc.

3.5 Open Issues on Design Alternatives

Finally, research topics and questions are constantly evolving alongside the UX design and technical development in the ongoing work by the technical and design partners. For instance, how the force-directed graph functionality will be integrated into the interface for querying and navigating project data is currently suspect to rapid development on the technical side. ETH expects additional topics to emerge in the near future and we will direct our upcoming work on the empirical as well as on the usability guidelines side accordingly.

4 FUTURE EMPIRICAL WORK

This chapter of the present report discusses options for future empirical work by ETH, in turn outlining key components for *behavioural experiments*, typically involving quantitative measures. Three empirical approaches are considered: An *experimentally controlled* approach which typically requires a relatively large number of participants, the recruitment of which could be difficult in a field as specialized as the AEC industry. *Interviews* with prepared design *case studies* and ethnographic *observation* work in *field studies* may provide dense qualitative data from studying relatively few participants and therefore complement the quantitative approaches. *Design protocol* studies often cover a middle ground in that they combine ethnographic observation with a quantitative analysis of category-based data analysis (e.g. Gu et al., 2011; cf also Park, 2021, sct. 2.4.2). As outlined in Deliverable D3.1, the *Next Steps* will be to

> '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).'
>
> (D3.1, sct. 6.4)

4.1 Controlled Behavioural Experiments

> '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. [...] 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.'
>
> (D3.1, sct. 6.3)

The above quote points to a more general issue regarding the experimental study of design performance, namely, the conceptual and technical complexities inherent in the domain of architectural and engineering design tasks. What is ostensibly evident from 'the rich diversity of the visual material' documenting the requirements in the AEC industries (D3.1, sct. 3.1; D1.1) on the one hand points to a large body of professional skill and experience required for performing the highly specialised tasks typical in design fields.

As already outlined, the ideal participants for a study placed in the application domain of PrismArch can be characterised as members of multidisciplinary teams with diverse background knowledge and professional expertise. For developing user testing studies and design experiments this poses the requirement to develop materials carefully so as to produce content at a credible level of complexity, in turn requiring an adequate briefing of the participants. Within the study, they will be confronted with content from one or more mature design projects, presented to them by means of high fidelity graphic media. Regarding the development of materials, Section 2.1 already mentioned the role of prior knowledge. Developing the case study materials, ETH will have to draw on the expertise and experience of our design partners, who, in turn, will rely on the extensive project documentation compiled as part of Deliverable D1.1.

Design projects often strongly rely on precedent cases which tend to be part of extensive bodies of archived projects in the respective design offices. For instance, when testing data-intensive applications such as the retrieval of archived project documentation, participants not only need to encounter a rich dataset in order to feel immersed in a 'real' project archive. In addition this data needs to be suitably aligned with their personal memory of the archived project.

This equally applies to qualitative studies with more holistic tasks based on design *case studies* as well as for isolated *stimuli* for the minimalist presentation modes typical for highly controlled experiments. At the same time, qualitative methods may also be used to generate and refine the materials in the first place (sct. 4.2), and, hence, can be considered more flexible when it comes to addressing matters related to AEC-specific domain knowledge.

4.2 Qualitative and observational approaches

Recalling our conclusion from the preceding deliverable (D3.1),

> '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.'

Especially the second point (b) remains a valid option in case a full-fledged controlled study is not (yet) feasible because tasks and materials still need to be defined on an appropriate level of detail. Identifying tasks and materials for experimental studies was one of the main motivations for conducting the interviews with future users, which were conducted and presented by ETH as part of Deliverable D3.1. Following up on this approach, materials for controlled studies can be derived by having experts comment on preliminary sets of materials.

4.3 Tasks

To a certain extent, the (design) activities or tasks to put under empirical investigation can be discussed independently from making a final choice regarding the specific empirical approach to use in the study. It should however be noted that the empirical instrument is not perfectly independent from the set of tasks and the key aspects that can be studied. In other words: Some activities are of general interest and may be studied in an immersive field study as well as in a controlled laboratory experiment. Other activities are too complex to be transformed into well-defined tasks for being studied under controlled laboratory conditions. Nevertheless, the present section focuses on activities and tasks of practical and scientific interest first, independent of the method to put them under study, which we will decide on at a later point, also in regard to feasibility aspects such as participant recruitment, confidentiality of project documentation, etc.

Create Borehole Log Diagram

Senior Engineer_structure working on an assigned task … (D6.1, Task A.2):

> '...site photos, sketches, and a geotechnical report provided by the client. Her plan is to review the information contained in the report and compare it to the proposed massing of the building to make sure enough detailed information is present in the report and to highlight eventual additional information to require. The review will serve as a step to prepare a Site desk study.'

Creating a borehole log diagram is a good example to discuss the pros and cons of different approaches for studying a design activity that involves non-trivial input from (an) external document(s). The task can be described in its entirety in terms of the information provided as input, the informational transformation(s) it will need to undergo in order to produce the desired output. How this transformation can be achieved further depends on the formats in which the input is (re)presented, which cognitive strategy is chosen (i.e. the algorithmic approach, to put it in more technical terms), whether additional technical aids are used to support human cognition on certain operations, and which external representations are used to produce and stabilise intermediate stage results.

To study all of these components in detail the researcher has several options, as we have pointed out at the entrance of this chapter. In principle, despite its overall complexity the task is well-suited for being put under controlled conditions in a lab setting since the borehole log diagram is produced in relatively early phases of a design project and does not need extensive project-specific input. Briefing participants is therefore relatively straight forward. Nevertheless, a careful description of the overall project context as well as the detailed input typically found in a geotechnical report would have to be included in the case study information. An alternative approach would be to study the activity *in the wild* as part of an observational field study, recalling the observational approaches taken by culturally oriented researchers, e.g. Edwin Hutchins or Jennifer Whyte. Identifying the input information and its representational format can happen during the field observation, removing the need for preparing and pilot-testing the materials ahead of actually collecting data. Yet, the results from field observations will be tied to the individual episode, be qualitative in nature and may lack generalisation. Nonetheless, a quantitative study can always be developed to confirm or test specific aspects revealed by the observational work which, in turn, can also serve as a basis for compiling credible case study materials.

Risk Markup / Clash Detection

> ‘The MEP can use the markup tool in both early and developed stages of the project to highlight potential risks in coordination or mention potential health and safety risks. These may be issues due to tight spaces in services, not enough space for maintenance purposes (e.g. not enough space to unmount and fix a pump) or coordination and clash issues. This should be used in combination with the sectioning tool in order to be able to isolate a problematic area which need clash resolution or highlight the potential risk. The markup tool should be able to provide basic shapes (lines, circles etc) or even basic geometric shapes to give the ability to the user to better explain the solution (e.g. pipe reroute can be shown with basic cylinders)’
> (Internal communication, related to T6.1)

Discipline-Specific Information Overlays in Cross-Disciplinary Collaboration

Does differentiating the information display between members of different disciplines actually support or hinder conversational alignment? The question provides us with a prototypical example to highlight the challenges for empirical work inherent in application domains such as the one of PrismArch. Studying a highly specialised, content-heavy and media-centric domain under controlled conditions requires the study to replicate the complexity of the domain and to recruit participants who are experts in these domains.

First and foremost, customising the display for each discipline poses the challenge for an empirical study to identify situations in which a joint view alone is not sufficient, i.e., in which additional discipline-specific information is required to perform the task.

For studying this under more controlled conditions, participants could be asked to evaluate an architectural master plan in the light of the results of a structural engineering model or due to a change in infrastructure layout from an MEP side.

4.4 Experimental Procedure and Data Collection

Following the rationale of collaboration across design disciplines, an experimental procedure should involve two or more participants, possibly with different professional backgrounds. At least some tasks should involve some collaborative aspect; strictly speaking this does not necessarily require a *synchronous* interaction between the participants (in the sense of both participants being aware of each other's activities in a “real-time” manner). They could also review materials in a sequential, non-synchronous manner. Yet, the synchronous case is certainly the most prestigious application scenario for a collaborative platform such as PrismArch. Part of the participant pairs will be presented with information that differs between the two collaborating partners of a pair. This follows from the prismatic decomposition theme underlying the project, which is dedicated to providing customary information to the participants, based on their respective professional background. Participants will be given time to familiarise themselves with the provided case study information materials before they will start working on the actual design/review activities. Depending on the chosen method, audio, video, screen capture recordings may be combined with eye-tracking data as well as gesture recognition and other raw sensor data.

Researchers will follow strict scripts for participant instruction or, for interview-like schemes, a more open, semi-structured catalogue of interview questions may be chosen.

5 CONCLUSION

The contribution of the present deliverable is geared towards addressing specific topics currently relevant for the ongoing design and development efforts by our design and technical partners. Besides extending our literature review to more applied topics, studies, and methods in the field of user interaction, interactive and immersive technologies, as well as user experience design, wherever appropriate, we provided links to the theoretical background and the interview-based analysis of the design practices in the AEC industries provided in the previous deliverable (D3.1). At the same time, existing studies can give limited guidance for practical applications as they are often either ‘too specific’ to be applicable to the case at hand, or they are ‘geared towards a high-level comparison of different systems’ so that their abstract perspective makes them of limited use for informing the application context at hand (cf. sct 3). The well-informed intuition of an expert who is intimately familiar with the subject matter is often the best guidance one can expect. Our efforts will therefore remain twofold: On the one hand we will continue our exchange with the design partners on best practices established in the AEC industries. On the other hand, the technical developments are constantly becoming more concrete in the recent weeks so that the specific assessment of technical prototypes can be given.

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APPENDIX A: TRANSCRIPTS

Note: Appendix A is an updated version of Appendix A in Deliverable D3.1. For the sake of completeness we include all transcript material in the present report, independent of its presence in the predecessor document.

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

1. ' site plan is the first thing'
    a. 'or google maps'
    b. For instance: 'trees [...] do they need to be protected?'
    c. 'tracing where the building needs to be'
2. 'section'
    a. 'see the height of the water [...] depth of the water'
    b. Data for the section etc are based on research done earlier
    c. 'level of the water is changing […] over the year […] climate change […] in hundred years'
    d. 'structure of the soil'
    e. 'water on either side [of the wharf] so the system is balanced'

   f. ‘suck water on one side [...] the system is unbalanced - pressure of the water from one side [40:32]’
   g. use the section check any points ‘in the perimeter [... ...42:49] did you cover all the scenarios?’
3. ‘drawings [...] so I can explain my thinking - rationale behind’
   a. ‘I try to break every step’
   b. ‘so if people think there is a fail in my steps [...] they have the opportunity to say that’
4. For instance if we ‘build a basement in an existing basement’
   a. ‘if you want to have a deeper basement you have a very orange bit, if you have a shallower basement you have a very blue surface - at different depths’
   b. ‘[...] to the architects so they can import these lines [...] at different depths’
   c. ‘it is an old building [shows section of the basement]’
   d. ‘not visual [45:11] - it is all trigonometry which I wrote for my self; I share with my colleagues and then they send it out [to the architect?]’
   e. ‘the architect is looking after this headroom’
   f. ‘the more head-room you want the more soil you need to dig, so the more expensive the basement has to be’
   g. ‘I need to tell him: [...] if you want a cheap construction, or as cheap as possible, you need to reduce this one.’
   h. ‘this one is existing [...] an existing slab’
   i. to ‘excavate underneath, here, so it is more expensive instead of keeping the slab as it is right now’
5. Old wall of the basement
   a. ‘you excavate down but you don’t want this part to collapse’
   b. ‘this is an old wall of the basement’
   c. ‘the only way to excavate without this one collapsing [48:36] [points out a 40 degree angle from the foundation of the old wall, drawn in red in the drawing] is you start from this point’
   d. ‘this is the sort of conversation I have’

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:
   1.1. ‘Rhino’
   1.2. ‘converted into an STL model’
2. ‘they [the consultant] build their foam model’
   2.1. foam or wood
   2.2. with sensors built in
   2.3. ‘put it into the wind tunnel’
   2.4. including the ‘entire [block-wide] context’

3. The consultant provides 'loading information'
   (a heat-map or equivalent data).
   3.1. 'the loading information applied - to the facade'
   3.2. '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 were 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 lot of people just use the snip it [snipping?] tool in windows.’
‘previously that is the kind of best way of doing it’
‘create a window’
‘and then scribble away that/there when/what you’re talking, quickly ’

2. ‘this is interesting [...] these are all new tools’
   ‘working with tablets now’
   ‘drawing over the top of screens as we have descriptions’
3. *Researcher: ‘Tracing paper on top of a screen’*
   Researcher: ‘[senior designer] using their markup pen to draw on top of the screen that is shining through’
   ‘yes, I’ve done that too’
   Researcher: ‘the junior would later [...] try to adapt the model accordingly’
   ‘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]’
2. ‘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’
3. ‘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’
4. ‘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]’
5. ‘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.’
6. ‘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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Note: The Bibliography is an updated version of its predecessor in Deliverable D3.1. All literature and external sources are included in the present report (again), independent of whether they are primarily cited in this or its predecessor deliverable. The bibliography below hence gives a comprehensive overview on all sources used by ETH up to this point.

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