Extended Reality (XR) Applications in Architectural Practice: Towards a Development Framework

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Abstract. Extended Reality (XR) applications allow designers to experiment with design concepts and examine design solutions in mixed-reality environments. XR technologies, from virtual reality to augmented reality, have proven potentials to enhance the design process and improve design outcomes. However, XR applications in architecture, engineering, and construction are limited mainly due to primitive XR technology—both software and hardware. Further research on how to develop these applications thus deems necessary. This study focused on XR use cases in architectural practice, identified six key XR affordances through a case study and then discussed their relationships with three components of the creative design process in architecture (concept, knowledge, and environment). The results are presented as a framework that can serve a reference for developing the next generation of XR applications for architectural practice.

Keywords: Extended Reality · Augmented reality · Design process · Concept-knowledge design theory · Architectural practice · Architects · Affordances

1 Introduction

Digital Media such as Extended Reality (XR) offers experiential design opportunities in mixed reality environments [1]. XR combines real and virtual design environments and supports a new form of contextual and multi-dimensional human-machine interaction [2]. This can foster creativity, enhance requirement analysis, boost design productivity, and facilitate feasibility studies in architecture, engineering, and construction [3–6]. While XR has proven potentials to enhance the design process and improve design outcomes, XR applications in these domains are limited mainly due to primitive XR software and hardware [7, 8]. Hence, research on the XR development is the necessary first step to address the challenges associated with the industry-wide adoption and effective use [2, 8]. To this end, this research focuses on XR use cases in architectural practice with the hope of offering a novel approach to XR software development in general.

This study proposes a framework recognizing the key requirements for XR-supported design in architecture. Within this framework, we examine the features,

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benefits, and limitations of current XR tools on the market, align the analysis of those tools with the best practices of the field, and identify when and why they can meet design process requirements. As a result, we identify six key affordances related to developing the design concepts, examining design concepts, enriching design environment, simulating design scenarios, validating design solutions, and improving design logic. Further, we explain how design process requirements are fulfilled by these affordances with reference to the *concept-knowledge-environment framework*—an extended version of the *concept-knowledge design (process) theory* [9]. The final framework proposed by this study can inform the design of future XR applications, allow professionals to select the right tools that best suit their needs, and help researchers understand the adoption and implications of XR technology in architectural design.

2 Background

XR technologies offer unprecedented opportunities to revolutionize architectural practice by enhancing design productivity while reducing errors and saving the trifecta (time, money, and resources) [4, 8, 10]. In this study, we refer to XR as a broad category of many types of real-and-virtual environments generated by digital technologies including Augmented Reality (AR), Mixed Reality (MR), Augmented Virtuality (AV), and Virtual Reality (VR)—see Table 1 for the definitions [8, 11]. For example, XR includes both AR and MR affordances as users can virtually interact with the environment in real-time with or without occlusion between virtual content and the real-world. Similarly, XR benefits from AV and VR technologies that can recreate a virtual version of reality within a digitally regenerated world. However, beyond AV and VR, XR combines elements of the virtual world and allows them to interact within the real world. XR application goes beyond traditional virtual rendering methods used in VR applications that have both been proven inadequate in support of creative design and in particular, architectural design [12–15].

Table 1. The definition of XR components

Augmented reality	The real world still exists with all its objects and features; however, virtual objects or information are purposefully added to allow real-time interactions
Mixed reality	The real and virtual worlds combine to form one completely new hybrid and interactive reality rather than the mere addition of elements to reality
Augmented virtuality	Th display of real objects or information onto a virtual world. The user would be within the virtual reality while manipulating real objects
Virtual reality	The digitalized version of a real environment or virtual representation of a reality in which objects and information are only limited to that regenerated reality

XR has shown the potential to revolutionize the architectural design process [4, 8]. The appeal of XR tools in architecture lies in the idea that they can more efficiently support the design solutions and construction efforts (e.g. programming, material selection, lighting, and circulation). XR applications allow the project stakeholders to interact with the environment, experiment with design scenarios, and examine different options before actual construction [5, 6].

Recently introduced VR applications fall short in satisfying these needs [14, 16, 17]. Firstly, VR is not a viable choice when the design or the design environment is complex, constantly changing, or hard to verify. This is a commonly cited problem with the available VR applications that renders 3D models for the walkthrough. Secondly, VR environments are also isolated from both real-world and project stakeholders. While in certain cases such as training simulators, this can be considered a benefit of the program, it is not an asset when it comes to the architectural design process. Architecture is fundamentally a socio-cultural endeavor; meaning that user, designer, builder, and other stakeholders must be in constant communication and deliberation. Therefore, reducing all design elements into a purely virtual environment may isolate the stakeholders from reality and limit their interactions. Thirdly, the accuracy and fidelity of the regenerated reality in a VR environment is an issue when it comes to architectural design, engineering, and construction. This is due to the inherent separation of realities and the complexity of digitalization of all the details in VR environments. Lastly, enhancing productivity is challenging in using current VR tools. For example, time could be spent on correcting mistakes in a virtual environment, rather than taking the object in actual reality and merely adding virtual elements onto it for a more efficient assessment.

Advance augmentation can address the aforementioned issues to a great extent. For example, AR applications in construction have proven to have intuitive visualization capabilities serving functions such as review of different layers of information, quality control, illustrating the location of concealed works, and facilities operations and maintenance. Similar benefits have been realized in engineering and architectural applications as well. The question is, however, how these applications can systematically and formally support the design process. To answer this question, we use the concept-knowledge design theory as a guide to operationalize the architectural design process and then to discuss how this process can be supported by the next generation of XR applications.

3 Concept-Knowledge (C-K) Design Theory

C-K Design (Process) Theory looks at the reasoning applied throughout the design process and strives for continuous and incremental improvement [18]. First introduced by Armand Hatchuel and his colleagues, the theory has proven to be a practical way to model the requirements of a robust and well-reasoned design process [19]. This theory defines design-reasoning as a logic of design development, refinement and organization processes—when a new object (concept or knowledge) is generated. The C-K theory is traditionally structured around three pillars: knowledge, concepts, and operators. *Knowledge* within this theory (K) is defined as a set of propositions with a logical status according to the current knowledge of the designers. The K space within design describes all objects and known facts from the point of view of the designer and that can be organized and documented for current or future reference. *Concepts* (C) refer to a set of design propositions or possible solutions within concept space. *Operators* build upon the premises of knowledge, concepts, and their interactions. The four central operators, K to C (disjunction), C to K (conjunction), C to C (C expansion), and K to K (K expansion), collectively denote the design process that is illustrated in Fig. 1 [18, 20].

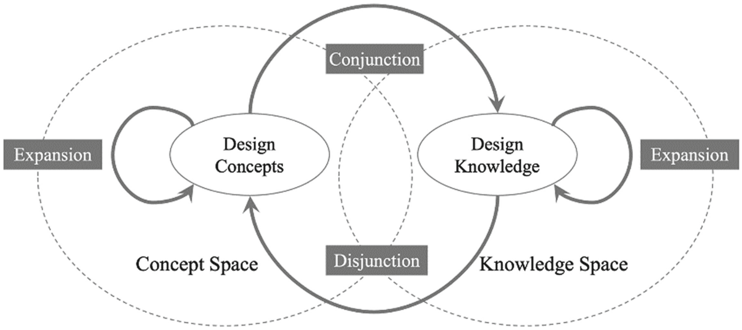

Fig. 1. C-K Design Theory based on the Hatchuel and Weil's *Design Square*

Overall, the C-K theory not only offers a comprehensive formalization of design processes, irrespective of the design domain, but also allows explaining the design discovery process when assisted with computer technology. We argue that modern architectural practice can be modeled after the C-K design theory. In architecture professional practice, the initial design is decided upon using propositions from existing design concepts and knowledge. At the start of the project, previous knowledge informs new design concepts (disjunction). For example, preliminary design takes place after the first meeting with a client to capture their needs and preferences. Schematic designs are developed next in line with what the client requests, available resources, zoning, topological and geographical restrictions among many other factors. These designs are then, explored, expanded, given added details, and elaborated upon by different project stakeholders (C expansion). This refers to design development that requires further meetings and communications with the client. This is where most of the work takes place as plans and schematics are further refined and readied for possible use in the third stage, which is the construction document. After several rounds of iterations, the final design becomes new knowledge informing construction (conjunction). Lastly, this process contributes to the expansion of K that guides future designs. Conjunction and knowledge expansion contribute to both project's knowledgebase and the firm's knowledgebase (e.g., construction specifications). Figure 1 serves as a visual representation of the four processes.

While the C-K theory can be applied and explained how modern architectural practice operates, it falls short in explaining the role of ‘environment’ and its impact on concept and knowledge expansion [9]. The environment is the key element that defines both design opportunities and constraints. While in the real world, we are not able to expand the environment (in the sense we develop design concepts and knowledge), virtualization and augmentation technology allow us to experiment with the design concepts and verify our knowledge in an extended reality environment. Therefore, to model the architectural design process, we adopt the extended version of the C-K Design Theory: Concept-Knowledge-Environment or CKE framework [9, 18, 20]. This framework suggests that creative design practice can be modeled as the interplay between three interdependent spaces with different structures and logics: the space of concepts (C), the space of knowledge (K), and the design environment (E)—an extended or mixed environment in our case. Accordingly, we can use the CKE framework to model architectural design practice as three external operations (interactions between C, E, and K) and three internal operations (concepts, knowledge, and environment expansions). These operations—conceptualized below and illustrated in Fig. 2—refer to the key 'design process requirements' in this study.

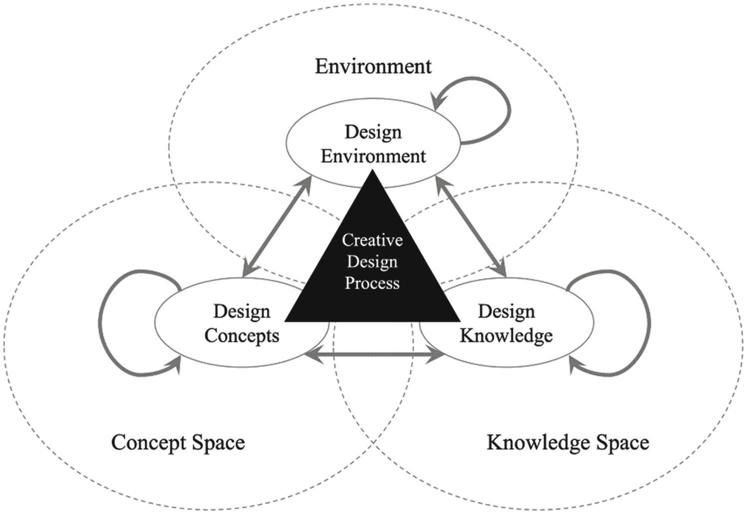

Fig. 2. Creative design process: Concept-Knowledge-Environment (CKE) framework

- **The interplay between C and E**: Architects should be able to modify the design environment according to their design concepts and define new concepts based on the target environment.
- **The interplay between E and K**: Architects should be able to model the environment to formulate new knowledge or interpret knowledge to understand the environment.
- **The interplay between K and C**: Architects should be able to develop innovative design concepts (e.g., design alternatives) based on existing knowledge or validate new concepts (e.g., design prototypes) as new knowledge.
- **Concept expansion**: Architects should be able to develop design concepts creatively, independently, or in collaboration with project stakeholders including their clients.

- **Knowledge expansion**: Architects should be able to expand their knowledge critically and contribute to both project and the firm's knowledgebases.
- **Environment expansion**: The design environment could be expanded with the new layer of internal or external information or objects related to the site variables (e.g. climate) or conditions (e.g. geography).

With knowledge of how the CKE framework is applied and how modern architectural practice operates, we can examine the features of XR applications and determine their affordances. This would help ensure that the requirements of the architectural design process identified earlier can be met by the next generation of XR applications. Further, this approach would pave the way for co-design in architectural practice [21].

4 Case Study

We reviewed six XR applications available on the market at the time of this study in order to identify their key features and functionalities. To select the applications, we used a theoretical sampling approach to select programs that are recommended in architectural journals and that support both design development and documentation/presentation [22]. Further, applications were narrowed down to three cases based on their popularity or utility. Table 2 provides the list of these tools. After the case selection, we examined the tools' documentation for the list of features and coded data for each application [23]. Then, the relevant features were categorized based on their use cases across the applications. This allowed us to identify the intended functions (designed affordances) [24]. We coded different groups of affordances enabled by each group of features and then applied hierarchies to select and verify the key categories of affordances [25]. Lastly, the relationships between the listed affordances and design process requirements were enumerated and examined according to the Needs-Affordances-Features perspective [26].

Table 2. The list of applications reviewed as part of case study

AR Tool name	Tool description
ARki (iOS application)	ARki allows instant augmented reality experiences with features such as real-time lighting and layering of various 3D models
Morpholio (iOS application)	Morpholio trace supports augmented reality sketch-walkthrough with features such as 3D model augmentation, dynamic and live walkthrough, and real-time tracing and design alteration
Unity reflect (Desktop application)	Create real-time 3D experiences, including in AR and VR, from Autodesk Revit, BIM 360, Navisworks, SketchUp, and Rhino

Features were grouped based on the design process requirements informed by the CKE framework (Table 3). As expected, features supported more than one requirement, such as virtual tours, interaction with XR objects, import and export files, and create simulations. The key features were centered around empowering the design team, including architects, to create XR models, join workspaces, and utilize XR visualizations for both design development and presentation. However, the analysis revealed that there was a significant difference in the utility of these applications in terms of interactivity and collaboration. However, all tools offered features supporting XR tours at the actual construction site. These features provided greater synergy between clients and architects during the design development phase.

We examined the features in the relationship with three components of the CKE framework—concept, knowledge, and environment—to identify the required affordances enabled by different groups of features. Design concept development, independently or interdependently to knowledge space or environment, could be supported by a group of features allowing on-site visualization and rendering different design options. These features enabled designers and other project stakeholders to design in a dynamic environment supported by augmented reality or virtuality. The case review also showed that the programs with more virtualizing features such as tracing, real-time lighting, and interactive layering fulfilled more experiential design needs than traditional AR or VR tools that focus on presentation. These features mainly corresponded with the expansion of the environment and how it supports both concept and knowledge development. The evaluation of design in both virtual and augmented environments was an example facilitated by features such as dynamic scaling to lighting. We assumed that clients/users could be part of the environment and therefore, they should contribute to the concept development. Supporting this assumption, the XR technologies studied here could connect the design team to the client and engage the client with features such as presentation, co-design, and critique. One of the noted benefits was the design team's capability to define different design scenarios and allow the client to experiment with them.

Table 3. The summary of XR feature categories and their relationships with design process requirements

Feature Categories	C ⇔ C	K ⇔ K	E ⇔ E	C ⇔ K	C ⇔ E	K ⇔ E
Build virtual models	X			X	X	
Create dynamic XR environments	X			X	X	
Interact with XR environment	X		X		X	X
Augment objects/information			X		X	X
Virtual and dynamic tours	X		X	X	X	X
Simulation (e.g., lighting)	X	X	X	X		X
Experimentation (e.g., materials)	X	X	X	X	X	X
Knowledge management		X		X		X
Workspace management				X		X
Collaboration features	X			X	X	X
Documentation features	X	X	X	X	X	X
Integration (with design tools)	X			X	X	
Integration (with XR tools)			X		X	X
Integration (with knowledge-base)		X		X		X

The findings suggested that knowledge-related features play an important role in design evolution and selection. The first group of features was related to integration (e.g. import and export 3D models), project documentation (e.g. journaling), and knowledge-management (e.g. building information modeling) that could help with both design and construction. Other examples included features such as sharing, commenting, and redlining. In the relationship between concept and environment, the design team however retained editing and similar admin level rights. These possibilities not only allowed expanding the existing knowledge but also contributed to firms' knowledgebase when the design is finalized.

The results of mapping the identified features on the architectural design process revealed that concept-related features can differentiate design products within the environment, attract attention, and enhance the design approval by the clients. Design concepts are further enhanced when the XR application enables the development and examination of a design concept in collaboration with the client. In the same way, the examination of the design concepts is also facilitated by XR technologies more realistically and practically. For example, these technologies allow clients to monitor design concepts as they evolve while encouraging them to provide more timely and thoughtful feedback. In the same way, participatory design processes require interactional experiences that afford real-time experimentations with 3D models in an augmented environment. XR applications enable project stakeholders to explore potential design options, share knowledge, examine their findings, collaborate, and seek feedback from other members in an environment enriched with augmented information. This minimizes the misunderstandings between the parties and ultimately enhances the quality of the design outcome.

XR applications facilitate the simulation of potential design solutions that can create a more reliable and detailed understanding of possible designs. Making well-reasoned design decisions can also motivate the use of XR applications that afford design validation. Furthermore, architects have a vested interest in tracking and analyzing the use of their time and resources. Hence, dynamic integration between design and other knowledgebases (enabled by XR applications) can optimize the use of resources in validating a design solution. Also, the design process can be enhanced when architects and design teams can have more control over the utility of time and, therefore, make more reasonable decisions during the design process. For example, by using simulation and validation functionalizes, architects and clients can co-regulate the design decisions for the benefit of time. Additionally, architects need to be able to share knowledge with external collaborators including the clients which are paramount to an effective design process.

The environment is the source of inspiration for architects especially if it is enriched with information that is not readily available in a dynamic manner such as data related to lighting, temperature, and traffic. XR applications, with the power of simulation, can enhance the design team's creativity in understanding the environment and how different design elements including materials interact with the design environment. This can foster the evaluation of complex design concepts and forward the design development. Besides, this may lead to a higher level of engagement with the client and project team and thereby nurturing the culture of co-design. XR applications allow clients to experience the proposed design concepts in a more natural setting. This invites more constructive feedback and therefore, optimizes the number of iterations in the design and later minimizes changes in the construction document or plan. Lastly, augmented reality and virtuality both give the client a 'sense of control'. For example, a client can freely experiment with a 3D model before approving a design. This sense of control also enhances the client's trust in architects.

5 Discussion

The relationships between the features of XR applications and the requirements of the architectural design process helped us to identify six functional affordances. These affordances could potentially guide the development of future XR applications for architecture and engineering design in general. The implementation of these functional affordances would ensure that XR lives up to its promise of solving a plethora of design challenges. Our identified affordances include:

- develop design concepts
- examine design concepts
- enrich design environment
- simulate design scenarios
- validate design solutions
- improve design logic

Develop design concept enables designers including architects to develop their creative conceptual ideas and generate innovative design concepts in a shared augmented environment that enables project stakeholders to view, interact and manipulate the ideas. *Examine design concepts* refers to supplying an augmented environment that accepts mixed inputs—from human and non-human sources—and generates experiential design elements during the design concept development. *Enrich design environment* supports the design process by modeling and representing the possibilities, constraints, and expectations in an extended environment. S*imulative design scenarios* refer to XR technologies affordances that can assist architects by examining various design scenarios as part of the approval process. *Validate design solutions* are XR affordances that help test design concepts based on a mix of inputs such as environmental survey data, site constraints, and building codes and compliances. *Lastly, improve design logic* enhances design solutions by offering real-time access to project information, project knowledgebase, and existing design solutions in an augmented environment.

We claim our identified XR design affordances can satisfy the design requirements suggested by the CKE framework in the following manner [9, 18, 20]. Design ideas can be expanded by design concept development in XR environments. XR applications that afford examine design concepts help test the design options in an augmented environment. XR applications can enrich the design environment by augmenting the environment with an added information, knowledge, or concepts. Design scenario simulations allow experimenting with various design solutions in an augmented design environment. XR applications can facilitate the design solution validation by supporting a critical and systematic review of new design concepts based on existing knowledge or new knowledge activated by new concepts. XR applications can support knowledge expansion—related to both design process and design outcome—when it affords to improve design logic. We summarize these relationships in Fig. 3.

The alignment between the identified XR affordances and creative design requirements, if actualized, could support architects at different levels (a) design solution development (e.g. balance between creativity, possibilities, client's expectations, and other project's constraints by providing an immersive design experience), (b) collaborative examination of complex design solutions, (c) design verification and experimentation (e.g. minimize misinterpretation and accelerate approval process), and (d) design process and outcome performance for all project stakeholders (e.g. as a result of design efficiency, improved accuracy and access to up-to-date information). The proposed framework can be used not only as a guide to review the existing XR applications used in architecture but also as a blueprint to design and develop new XR applications.

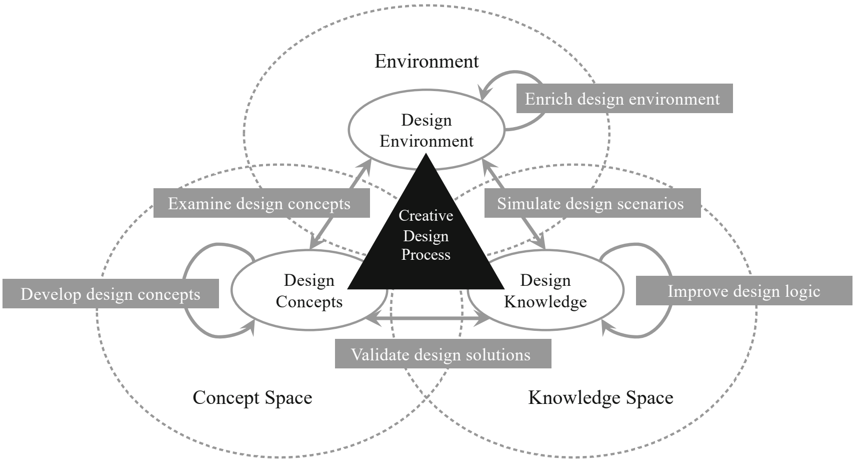

Fig. 3. The proposed framework for designing XR affordances based on the CKE framework

6 Conclusion

This study provides the opportunity for adaptive and effective XR application analysis on the part of developers, users, and researchers. Our proposed framework offers XR developers a guide for understanding architectural design and its requirements to hone the next generation of XR applications to address those requirements. In designing future XR applications, developers could use our framework to systematically analyze the key requirements of architectural practice. For example, developers could identify which affordances satisfy given requirements and which features should be implemented to enable those functional affordances. This has the potential to improve the chance of XR application success in terms of usability and adoption. Moreover, this framework can inform the evaluation of existing XR solutions for practical applications. For example, architects can use our framework to choose the application that suits their specific needs in six identified domains, development, examination, augmentation, simulation, validation, and improvement. The framework may also be used in the reverse method. For example, architectural firms can identify what design requirements are being addressed by certain features of the XR application in use and then use that knowledge to address any gaps present in their practice.

Examining the effects of each group of affordances on design outcomes is a rich avenue for future inquiry. For instance, future research could empirically examine how XR affordances may be designed, orchestrated, and presented to achieve the most meaningful and engaging experiences for architects, and clients alike. Researchers in technology fields can also adopt, test, and expand our framework to further investigate the role of XR applications in enhancing the design process in engineering and construction. Further, study into XR applications can propose more effective collaboration and communication mechanisms between different project stakeholders.

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