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RESEARCH ARTICLE

An augmented and interactive exhibition of an archived model for Frederick Kiesler's Endless House, 1959

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Abstract This research explores the potential of an immersive and interactive online archive to enhance our understanding of historic architecture through the study of models. It reports on implementing an augmented reality mobile application that exhibits a model for the unbuilt Endless House, 1959, by Frederick Kiesler. A reflective critique, from the researcher's point of view, and initial feedback from a small sample of architecture students, provides an insight into users' experience of the exhibition, its value as a research tool, and as an educational resource. Building on existing technologies and established research methods, we present an alternative way of exhibiting a large-scaled model for public engagement and research collaboration between academics, archivists, and conservators. Results discuss the development of the mobile application with interactive features specifically designed for an architectural audience. It touches on issues associated with documenting, interpreting, and exhibiting architectural models, emphasizing accessibility, accuracy, engagement, combining 3D and 2D digital assets, and user experience. It was found that the interactive and immersive features of the exhibition enhanced the researchers' scope to spatially inspect the model, visually experience it, collaborate with others, and strengthen connections between the model and other examples of Kiesler's textual and visual archival materials.

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1. Introduction

Pre-digital models provide a unique insight into our understanding of historic architectural practice and theory. Through the lens of advanced technologies, this research uses a case study — the original scaled model for the unbuilt Endless House, 1959, by the avant-garde (and often called "visionary") architect, Frederick Kiesler (1890—1965) — to highlight the role of models during the architect's creative design process. There is global historic interest in the work of Kiesler, with significance to contemporary practice (Bollinger et al., 2015). His work is archived and has been exhibited globally, but most recently in London (Shiraishi, 19AD; John Morgan Studio; Steierhoffer et al., 2019) Vienna[1] (Bogner, 30 Nov 2018—31 Dec 2021) and New York (Gadanho and Springstubb, 27 Jun 2015—6 Mar 2016), and an exhibition: Walter Pichler and Friedrich Kiesler, planned for March 2022 at the Österreichische Galerie Belvedere, Vienna. And so, the creation of a new, online resource attempts to break down geographical constraints and connect artefacts archived in different locations[2] by improving global access. The project posits that immersive and interactive online archives enhance architectural research spheres (including historical and contemporary concerns) through the study of models.

Models that have been digitised for research tend to focus on better understanding structural principles and buildability. It is rare for a three-dimensional (3D) digital reconstruction of an architectural model to be made accessible online or for users to be able to self-navigate and inspect it. There are examples of 3D architecture models, with limited interactive features, that have been embedded into digital ebook publications, such as the discussion on the O/K Apartment with key architects (Lynn, 2016). To our knowledge, there are no other examples that are similar to the case study presented here, which allow users to spatially interact (to this degree) with a digital reconstruction of a historic architectural study model.

The research presented here is contextualised by discussing the significance of the Endless House model as part of Kiesler's oeuvre. It also recognises that digital reconstructions and analyses of unbuilt designs are established research methods (Webb and Brown, 2016). We aim to expand these methods by exploring the research potentials of a hybrid form of online exhibition - a combination of accurate 3D scan data, 3D modelling and production techniques, 2D archival material, and interpretative text embedded within a mobile application. This paper thus presents the implementation of an augmented reality (AR) mobile application of Kiesler's 1959 Endless House model. It questions how we might better use advanced technologies to enhance the study of this and other historical architectural models by offering analytical interactions (e.g. the experience of space and light, and tactility through inspection) with a digital reconstruction of the model embedded with supplemental information. In this way, this application posits a virtual exhibition "space" situated not in a real or a virtual gallery but within the AR fabric of a model itself.

2. Theory/context

2.1. Precedents

Physical architectural scaled models are typically stored in private archives and collections, or can be found in one of the recognised organisations of the International Confederation of Architectural Museums. The Architectural Models in Context[3] project is a welcome forum; it shares research on architectural models with the public and through schools programmes, including a current exhibition, 'An Alphabet of Architectural Models' in London, and an accompanying book (Horsfall Turner et al., 2021).

There has been a significant increase in online access to archives and exhibitions, primarily virtual tours of historic buildings and museum collections; this may have been partly accelerated by demand during the Covid-19 pandemic. Many virtual exhibitions/tours can be found online (Google Arts and Culture, 2021). This research is specifically interested in how historic *architectural* study models and associated works are archived and shared for research purposes. In the main, online architectural archives exist as galleries of images showcasing scans of original drawings, such as The Archigram Archival Project[4] and RIBA[5] collection. These are both fantastic resources, but the models are usually depicted as photographs.

More recently, the AA Archives have been exploring alternative ways of documenting and providing access to models by making online films of its collection of architectural models available, each rotating through 360° (Architectural Association Collections). An excellent example of a digital archive with interactive features is the Soane Museum and Model room, which exhibits the museum building and a series of models within it. The virtual tour allows visitors to fly through transparent walls whilst getting a glimpse of other parts of the house. Then they are visually transported towards the Model Room, where they can inspect models (scale and rotate) while simultaneously referencing image-based drawings and a description (Sir, 2021).

2.2. Why study the Endless House model?

This research focuses on the study model by the architect, designer, and theorist Frederick Kiesler, for the unbuilt Endless House, 1959 (Fig. 1.), — a design that embodied utopian ideas for housing/living that he developed over

[1] There are approximately two exhibitions each year at the Kiesler Foundation: Exhibitions - Kiesler.

[2] The largest model (scale 1:16), discussed in this research, is in storage at the Whitney Museum of American Art in New York City. Jason McCoy (Estate) houses another model and MOMA has the first Endless House model, 1950. The only study model on permanent display is at MUMOK in Vienna.

[3] Architectural Models in Context — Architectural Models Network (wpcomstaging.com).

[4] http://archigram.westminster.ac.uk/.

[5] https://www.architecture.com/about/riba-library-and-collections.

Fig. 1 Frederick Kiesler making the Endless House model, 1959 (@Frederick and Lillian Kiesler Private Foundation PHO_806_Endless_1959).

three decades. This particular study model was made for the *Visionary Architecture* Exhibition at MOMA (1960). Kiesler originally intended to build it at full scale in the Sculpture Garden at MOMA, but it was never constructed for financial reasons. Projects "considered too revolutionary to build" were selected for the exhibition in order to celebrate the future architecture, in the hope that "vision and reality might then coincide" to teach the broader public about avant-garde visions for the built environment (Drexler, 1960).

In 1926, the Kieslers travelled to New York City from Paris — where Frederick Kiesler had exhibited his "City in Space" at the International Exhibition of Industrial and Decorative Arts in 1925 — in order to curate an international exhibition of theatrical arts. Kiesler was the youngest member of the De Stijl group and associated with well-known artists and architects, and he established a reputation as something of a maverick (Bogner et al., 2001; Phillips and Bogner, 1989; Phillips, 2017). His extant artworks and models are located in several locations, with models and works archived and exhibited in the Museum Moderner Kunst Stiftung Ludwig Wien (MUMOK), the Frederick and Lillian Kiesler Foundation in Vienna, the Jason McCoy Gallery (Estate), the Museum of Modern Art MOMA in New York City, and the Whitney Museum of American Art in New York City.

The Endless House and Kiesler's many other works have drawn continuous public and scholarly interest since at least the 1980s, as evident in the number of recent research publications, books and museum exhibitions around the world. The model for the Endless House has been celebrated as a provocation of ideas in numerous exhibitions, including the Visionary Architecture (Drexler, Sep 29—Dec 4, 1960), Folds Blobs + Boxes: Architecture in the Digital Era (Rosa, 3 Feb 2001—27 May 2001), and Wander, Labyrinthine Variations (Guenin and Désanges, 12 Sept 2011—5 Mar 2012), since it was built for such an occasion and has continued to be exhibited in this way, most recently at MoMA (Gadanho and Springstubb, 27 Jun 2015—6 Mar 2016). Another seminal exhibition, *Idea as Model* (1981) celebrated models as "studies of a hypothesis, a problem, or an idea of architecture." However, some models failed to satisfy the conditions of the exhibition because they represented an idea that was already fully elaborated in a drawing (Pommer, 1981). Kiesler's Endless House model was shown in this exhibition and referred to as one of the few models that contributed to the 'idea' as a model — also at the time of the dissolution of the International Style.

Kiesler's models have and will continue to be shown in a variety of exhibitions with varying interpretations. This is because many simultaneous ideas can be embedded within a model: "While a model is not solely a representational entity, [it] is rather primarily a sensible object of visual as well as tactile perception, it is itself experienced in fragments and in a continuum of the appearing of its manifold visible aspects" (El-Bizri, 2007). In this case, each iteration of the concept of 'Endless' embodies productive and critical shifts. Iterations are not limited to the scaled models, but the relationships between the model and other media: photography, sketches, poetry, and orthographic drawings. According to McGuire (2021), "The strange curvatures and apertures in the house were thus not designed as a static representation of what a 'built' Endless House would ultimately be — the model was not a literal representation of The Endless House. Rather, it was but one possibility of An Endless House." Kiesler's final model for the project was but one suggestion of how an architect might define space to suit many inhabitants and multiple ways of living. In this, the model was but one iteration of a potentially built work.

Just as Kiesler built and rebuilt multiple models of the Endless House over at least a fifteen-year period — the first model of the Endless House was created in 1950 — model making in architecture is primarily a form of iteration. Schuldenfrei states that "the roles of writing, the use of media, and relationships between object, image and reproduction are key to the discussion of iteration. Where 'iteration' is referred to as the proliferation of outputs in the creative process" (Schuldenfrei, 2020). Iteration is described as the pushing forward of new conceptualisation of a form, where a shift in representation and conceptual thinking leads to new and stronger ideas (Schuldenfrei, 2020). Therefore, seeing the Endless House model as an iteration in the context of other models and other media is necessary to understand and interpret conceptual shifts that were made during the architect's creative process.

2.3. Documenting and archiving models

Historical architectural models vary greatly in terms of size and the materials used to construct them and they can be a challenge to archive and conserve. Conservation methods for preserving fragile architectural models are synonymous with their significance and purpose. A survey of architectural models at MOMA defined the purpose models as either *Primary* — fabricated at the initial stage of design, sometimes abstract in concept — or *Secondary* - focusing on a particular building or site. In both cases, they fit into two categories: *Study Models* - to generate design ideas and *Presentation Models* —to persuade a client (Delidow, 2013). Gu (2020) equates the approach to interpreting architectural models with that of an archaeologist, recognising that textual and visual sources capture multiple conditions of the model, such as its materiality, haptic qualities, and how

it was made. "Thus, research on models involves reading what is present in the archive to describe the purposes and procedures of absent objects" (Gu, 2020).

Generally, archival material can be accessed online as image-based resources (as mentioned in Section 2.1). However, access to models is often limited to photographs of the model, a request to view a model by appointment, or a wait until it features in a future exhibition. Only two of Kiesler's models are known to have been digitised; that includes the largest model he made for the Endless House, which was scanned as part of a previous project (Niblock, 2015) and used in this research. The other model is for the Grotto for Meditation, proposed in 1963 for New Harmony; the scan was utilised in research which looked at how contemporary architecture is inspired and informed by biomorphic design and biomimetic processes (Vrana et al., 2008).

Strategies for archiving the digital assets of architectural models are often driven by a conservation agenda, with no universal method for exhibiting these digital models for public study. The Smithsonian Project has been at the forefront of sharing 3D models from museum collections online. Their mission is to increase knowledge through the use of three-dimensional capture technology, analysis tools, and distribution platform (Smithsonian 3D Digitization, 2021). An equivalent platform for the general public to use is Sketchfab, which publishes 3D models that anyone can share and download as VR and AR content (Sketchfab, 2021). Both platforms exhibit models from various disciplines/themes (including historic buildings) but there are very few architectural study models included.

2.4. Models for research and public study

The virtual reconstruction of buildings and models is recognised as a scientific method (Demetrescu, 2018). To date, much of the scholarly and practical work in this field has focused on the recording of extant buildings (Shaw et al., 2017), or the digital reconstruction of formerly existing buildings now lost or demolished (Münster, 2013; di Mascio et al., 2016). A major attempt to digitally reconstruct the building and contents of the former Public Records Office in Dublin, lost to fire in 1922, is currently underway (Crooks and Wallace, 2020).

Recent notable works, which emphasise engaging users remotely via a digital artefacts, through which they can access further archival information, include the release of an online, annotated model of Edinburgh Castle which allows the audience to explore and engage with the site and artefacts inside (Historic Environment Scotland, 2020). Similar projects have seen the reconstruction of parts of Lincoln Cathedral to produce a prototype for an interactive virtual reality exhibition (Fig. 2) with a focus on inspecting the architectural elements, combining scan data and storytelling (Yuqiang et al., 2017).

Examples of digital scanning and investigations of unbuilt designs are somewhat rarer, perhaps understandably due to the lack of 3D physical material to scan if a project is never constructed. Yet many significant, but unbuilt architectural developments, from Wren's first designs for St Paul's in London, to Lutyen's Liverpool Cathedral, and Kiesler's own work, have left a physical legacy in the form of carefully crafted models (Glancey, 2008: 233—4).

These models can be scanned, investigated, and disseminated as a form of architectural study and communication. One arguable example, and certainly the best known, is the current construction of Gaudi's Sagrada Familia, where fragments of original models destroyed during the Spanish Civil War have been scanned and reverse-engineered for design development (Gaudí et al., 2007). Similarly, Heniz Isler's models were scanned and analysed to describe, for the first time, the relation between geometry and the structural behaviour of shell structures (Borgart and Eigenraam, 2012).

The theoretical justification for such scanning is not simply to increase the possible global audience for the models, but the 3D modelling of a lost or unbuilt piece of architectural heritage can represent a method of investigation in its own right. As Webb (2012: 2) notes, ' … *the construction of the digital models enables a forensic analysis of the designs … the reconstruction or simulation of events produces an investigation into what may have occurred. The process of constructing a digital model of an unbuilt, damaged or destroyed architectural artefact is used to augment our understanding of them.*'

The case study described in this research builds on existing methods and attempts to virtually remove any geographical barriers by providing remote access to a digital reconstruction of the largest model (1:16 scale) of the Endless House design, to give a sense of scale (walkthrough), experience of space and light, and tactility through inspection.

3. Methods

Contextual literature and a review of existing approaches used to digitise, interpret, and exhibit architectural scaled models for study formed the basis of this research. In this paper, a case study on the implementation of an augmented reality mobile application that exhibits a model for the unbuilt Endless House, 1959, by Frederick Kiesler, is reported. The mobile app showcases architectural ideas through immersive and analytical interactions with the app. Existing scan data, as part of an earlier piece of research (Niblock, 2015) was used in the development of the app.

This research therefore builds on previous work and contemporary approaches to online exhibitions, whilst offering an alternative approach in combining AR models and analytical simulations with expert narratives.

3.1. App development

It began with a Design Charrette - a hands-on workshop with collaborators, involving a content developer, curator, conservator and academic researchers. The Charrette started from the point of view of the researcher, questioning: "what can we learn through studying the model from different research/expert perspectives?" and "how can we interpret and narrate Kiesler's ideas through the model?" The outcome of the charrette reflects the experts' need to present their knowledge through an interactive AR exhibition to enhance the transfer of knowledge to an educational resource (this is discussed further in Section

Fig. 2 Digital Model Exhibition scene, with isolated objects and free section function (Yuqiang et al., 2017).

4.1). The charrette acted as a catalyst for focused archival research - to gather other media in support of the experts' interpretations (as discussed in Section 4.2). A content developer, Hotknife Digital Media (HKDM), was employed to develop the app; they were involved in all creative decision making, thus helping to transfer the experts' knowledge and interpretation of the model into an AR interactive and immersive app.

3.2. User experience and validation

A small number of architecture students responded to a user experience survey (distributed online), where they were asked to respond via Likert scale and written feedback to a series of questions, written by the research team, to ascertain their level of engagement with the app. The questionnaire included open-ended questions, which encouraged participants to explain their experience in more detail. Areas of consideration included entertainment and appearance, engagement and embodiment, preferred media, and location and style of learning. Participant responses provide an insight into users' experience of the exhibition, its value as a research tool and as an educational resource. This choice of experimental and analytical method was informed by a close reading of Konstantakis and Caridakis (2020) who note that questionnaires are a particularly well established method for measuring User Experience (UX) in AR applications due to their ease of use, efficiency, accessibility and lack of required expertise from participants.

The architecture students were invited to participate in the research by downloading the mobile app, exploring it in their own time over a period of a week, and then providing feedback through an online questionnaire. Participants included architecture students in year 1 undergraduate and postgraduate level, from Queen's University of Belfast and the University of Hawaii. None of the participants had ever accessed the model prior to testing the mobile app. The participant group is representative of young adults, potential museum visitors, with an interest in architecture but have no specific knowledge of Kiesler. The sample group was targeted because they qualify as non-experts, with an average understanding of 3D virtual applications and interfaces, and therefore provide a student comparative critique of the User Experience (UX), and on the effectiveness of the application as an educational resource compared to lecture-based learning.

4. Development

4.1. Interpretation - Design Charrette

In advance of the Design Charrette, the 3D model was shared with collaborators who reflected on the model, wrote a short story, and discussed how to narrate *through* the model. Invited experts with knowledge of the work of Kiesler, model conservation, and structural analysis were asked to write short narratives for the exhibition *reflecting on the model*. Each author drafted a piece of text pursuant to their research area and interest in Kiesler:

- '*Pursuit of Ideas*' by Niblock (Lecturer in Architecture, Queens University of Belfast);
- '*Model Photography*' by Zillner (Conservator and Curator, at the Austrian Frederick and Lillian Kiesler Private Foundation, Vienna);
- '*Conservation*' by Delidow (Assistant Conservator, the Whitney Museum of American Art);
- '*Correalism*' by McGuire (Assistant Professor of Architectural History, Theory, and Criticism, School of Architecture, University of Hawaii at Mānoa);
- '*Shell Structure*' by Harding (Lecturer in Architecture, University of Reading, UK).

Then, during the online charrette with the content developer, Andrew Whitney from HKDM, we explored possibilities for how different media (3D models, archival materials, texts, and animations) could be combined (see Fig. 3). We examined how technology can help make connections between different artefacts and tell stories about the model; how it accurately exhibits the ideas it represents; and how to encourage users to create their own interpretations. These connections are discussed in more detail in Section 4.4 Immersive Experience and in Section 5.2 Combining Fragments.

4.2. Archival research

As stated in Section 2.3, interpreting architectural models is similar to that of an archaeologist and involves reading what is present in the archive to help describe the purposes of the model. Unfortunately, access to the Frederick and Lilian Kiesler Private Foundation in Vienna, which holds most of Kiesler's archival materials, was restricted due to

the COVID-19 pandemic. As an alternative, Gerd Zillner, archivist of the Foundation, conducted focused searches and provided digital copies of materials as the research developed; each author was thus able to select archived paintings, drawings, and photographs to support their narrative for the model.

4.3. Production of the app

With a small budget, creative AR/VR production company HKDM were asked to provide an augmented reality iOS mobile application of the Endless House, which was intended as a prototype. HKMD authored the Endless House app in Unity (a game engine) that enabled output to iOS and Android platforms from one project build and thus allowed for greater interaction than, for example, a web-built application. AR foundation was used within Unity as the main AR engine, which integrated both ARkit and ARCore, iOS and Androids AR engines. The completed Endless House app (Fig. 4) can be downloaded for iOS devices here.

The original brief required HKDM to utilise existing technology to develop an accurate 3D model and embed it within a mobile app that allowed users to virtually interact with the model (in scale, rotation, section, and walk-through), to view it from interior and exterior angles, and to make connections between different media, including texts and additional visual sources.

A scanned high-resolution model of the Endless House was provided to them; it was imported into Autodesk 3ds Max, which is a software used for making 3D animations, models, games, and images. Here, it was 'unwrapped' - the surface of a 3D object was translated into a 2D plane. Because the scan data didn't include the colour channel, the model was textured in Substance 3D Painter software in order to match the surface material of the original model (cement, steel wire mesh, and plastic) as accurately as possible. The model was then lit and rendered in Autodesk 3ds Max software, paying attention to the light entering through the various openings, since interior lighting is critical element of the model. To emphasise this, HKDM used volumetric rendering and paused during the fly-through to simulate changing daylight patterns. Redshift, a graphics processing unit renderer, was used to accelerate rendering.

The original scan data was highly detailed and as such was not suitable for display in AR on a mobile phone due to both download size and performance that could be achieved in displaying the model in real-time. HKDM used a process called 're-topologising' where a low-poly version of the Endless House is created across the surface of the high-resolution model. The high-resolution detail and difference is then projected onto the low-resolution model and stored in a normal map. This technique is used regularly in computer gaming to increase the perceived complexity of an asset.

Unity is a C# cross platform game engine, it allows for publishing to PC, Mac, Xbox, PS5 and most mobile devices, in all over 20 platforms. It is a fast and flexible environment to create once and deploy across multiple platforms. For this reason, Unity was chosen as it was the most efficient method and possibly only method, of producing an AR app' that could integrate all systems required to accomplish the brief and publish across the required platforms. It allows for rapid editing and iteration in

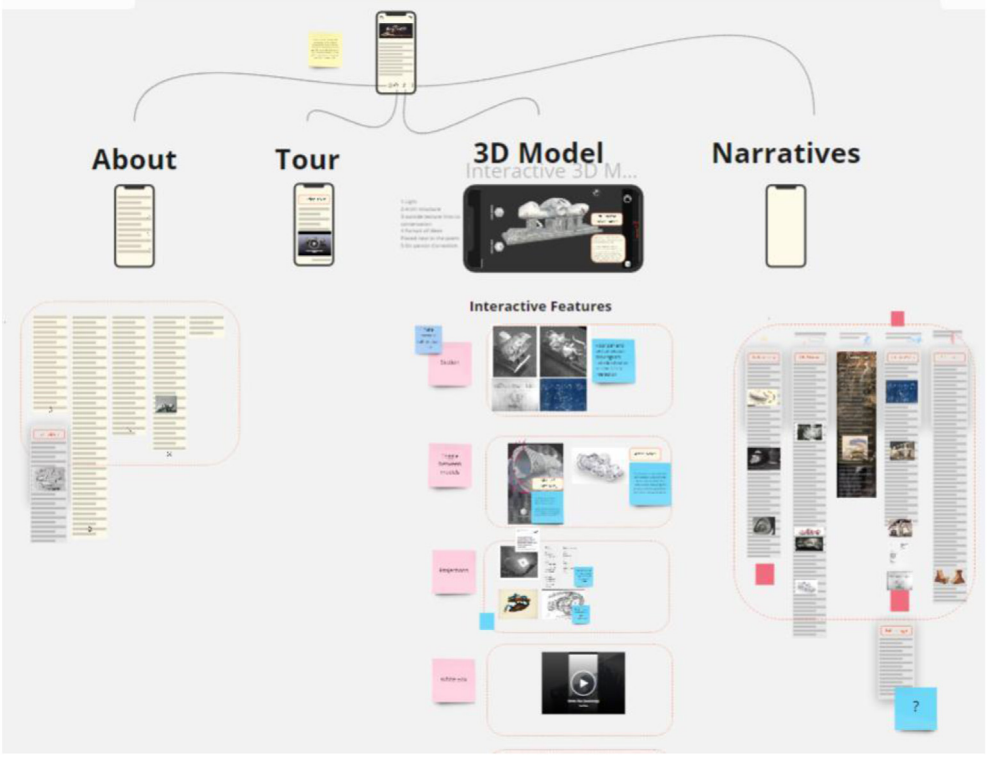

Fig. 3 Design Charrette: 3D model viewer and miro board.

Fig. 4 Endless house mobile application.

development cycles with real time preview of design alterations.

Miro was initially used to originate and coordinate the applications concept and content. Adobe XD to produce wireframes of the app' and to define the app's UI layout. Adobe AI was used, through several iterations, to design and create the app's visual appearance in detail, including all icons and colour schemes. These assets can all be integrated into Unity to create the app's UI.

Google and Apple have their own proprietary AR API's, ARCore for Android and ARkit for iOS. Unity provides an overarching interface, AR Foundation, which combines mutual capabilities from both platforms, again allowing for authoring in one platform and publishing to both Android and iOS while using the very specific AR features of both systems. A key feature available in AR Foundation and adopted for the project was the ability to use planar tracking to place the AR in the user's environment, as opposed to cumbersome image or QR Codes previously required to trigger AR sessions. Planar tracking means that we can anchor digital augmented content to the reality around the user, for example a table, floor, or ground. After launching the AR-experience, the user will move their device around a bit to help it recognise planes around it where we will locate the digital assets.

Unity is a very flexible development environment; it allows us to create specific shaders (shaders describe how an asset is drawn on screen) for a specific use, such as the slicing of the main Endless House asset where we defined the transparent areas of the model, to allow the cutaway sectioning of the model.

4.4. Immersive experience

During the Design Charrette, a desire to engage with different audiences through the 3D model was discussed. Consideration was made as to the types of immersive experiences that might reflect Kiesler's original intentions and go beyond traditional types of representation within printed media. Firstly, the visitor is given the option to take a pre-defined video walkthrough (tour) of the Endless House model. The second experience encourages users to freely explore the model as augmented, within an environment of their choice. Thirdly, a more focused study, using a coloured background, allowing inspection of the model without distraction from the environment.

As per Kiesler's original intentions around the embodiment of space, an important feature is to immerse the user within the model, to look beyond the sculptural exterior. The video tour guided visitors through the spaces and highlighted the intended function of each space, with an embedded daylight simulation (Fig. 5) adding to the immersive experience. The guided tour offered a more prescribed experience of the model and acted as a useful introduction to it.

Comparatively, the augmented walkthrough allows the user to scale the model (to the degree where they go inside it) and to examine what it might feel like in different environments, from urban streets and city parks to open landscapes and gardens (Fig. 6). However, it is not always desirable for the user to view the model as an augmented reality, especially if they are in a small cluttered space or a shared environment. For this reason, a coloured background option was developed to help users focus on the model when they are inspecting it, as seen in Fig. 7.

Existing technology - planar tracking - allows easier access to the model (instead of using 'traditional' AR tracking), thus removing the requirement of an image to initiate and anchor the AR content. It uses the phone's depth sensor to detect the horizontal and vertical surfaces in the user's surroundings in which the AR (Endless House model) is anchored, allowing the user to place it in any surrounding, such as a floor or a table. As mentioned in Section 2, Kiesler's original physical model is relatively large (approx. 1:16), allowing some interesting viewing possibilities, such as in outdoor locations. When launched, the model appears at the same scale as the built form, with the user able to position the model at a desirable height, scale, rotation and to walk through it, encompassing Kielser's original intentions for the model, which is not always possible with original artefacts too fragile for such a use.

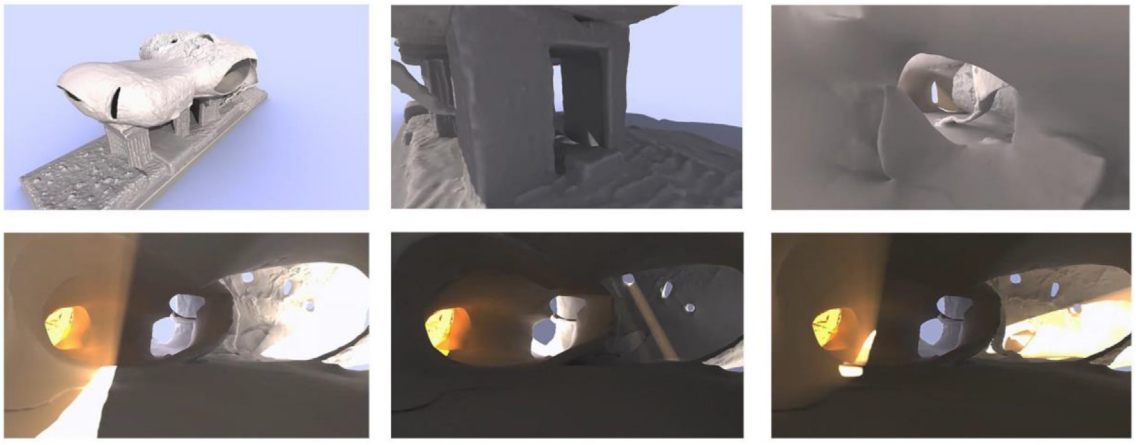

Fig. 5 Video Tour with integrated Daylight Simulation.

In a museum context, the augmented feature can also distinguish between people and surroundings, allowing people to freely walk within the space without interrupting the model. The AR uses the depth camera HKDM was able to utilise person occlusion. By default, virtual content covers anything in the camera feed. For example, when a person passes in front of a virtual object, the object is drawn on top of the person, which can break the illusion of the AR experience. To overcome this issue, ARkit can detect where in the camera frame a person is located and does not draw any virtual objects over that person. As the depth camera is utilised, it can also detect if the person is behind the AR object and therefore the AR object should be drawn over the person.

5. Results

This research explored the relatively new possibilities offered by combining an AR model of the Endless House with textual and visual sources for architectural research and education. The development of interactive features, specifically designed for an architectural audience, was among the experimental results. It explored the online archive as a tool to enhance interpretation (research) and for public study (educational resource).

5.1. Accuracy

As mentioned in Section 2.3, the 3D reconstruction of the model is part of previous research. It is a polygonal mesh file, generated from scan data (with millimetre precision) of the original model for the Endless House. It is *not* an exact replica of the model because: a) the laser scanner could not access some small surfaces inside the model and did not register the translucent perspex material on two openings, b) it is a reduced mesh, and c) the render used for material is a uniform representation of concrete. Overall, it was as close to the original model as was possible within the budget and constraints at the time of production (Niblock, 2015). The uniform grey colour applied to the external surface to represent concrete, however, felt like an extra layer of abstraction and reduced the sense of material embodiment. From a research perspective, the lack of colour in the scan data removed evidential traces of degradation, a sense of tactility, and materiality. This is

Fig. 6 Augmented model.

Fig. 7 Coloured background.

something that will be improved in the revised version of the archive, since a photographic survey of the original model became available and has been mapped to the surface (see Section 7).

5.2. Combining fragments

Combining different media within a three-dimensional archive was difficult to conceive. A priority was to allow users to explore inside the model, to experience and interact with it and other of Kiesler's related works. To heighten curiosity, several of Kiesler's works were hidden within the model (Fig. 8). This included a sketch, a surrealist style painting, and a poem projected onto the curved interior surfaces in three different locations. These additions added to the element of surprise, allowing the user to make further conceptual connections between the model and other image and text-based sources.

A challenge was the ability to slice the AR model interactively, both horizontally and vertically. HKMD developed a graphics processing unit shader, which dissected the model as the user runs their finger along a slider. A spatially interrogative tool, the live section feature slices through the model allowing the user to *inspect* the continuous shell structure dynamically in three dimensions. A characteristic of architectural representation is to flip between 3D and 2D drawings for different purposes, thus the 3D section feature enables a quick cross-reference between the 3D model and 2D contours. A reference to Kiesler's original drawings is made, momentarily, as the visitor explores the section (slice) feature. This ability to create a live section through the model and to cross reference an original sectional drawing emulates Kiesler's approach to documenting the form, since he had used the model to project shadows and trace contours, which later became plans and elevations (Fig. 9). Again, this form of spatial exploration would not have been possible using the original physical model alone.

Another consideration when combining fragments was how to display interpretations as integral parts of the exhibition. In a conventional exhibition within a museum context, it is not uncommon to find small display boards with interpretations next to an object. This often provides a snippet of information that helps the visitor to engage with the object and sparks an interest to learn more about it. In this project, we considered doing something similar by creating floating 2D display boards next to the augmented model. However, these boards felt disconnected from the model and didn't help narrate the project *through* the model. Therefore, in an attempt to embed the narratives with the model, a series of symbols provides clues about the content. The visitor can decide to click on the symbol and be transported to a text-based story. Further synergies are made between sources through the combination of analytical animations, including, for example, a 360 stress model and daylight simulation within the text-based narratives (Fig. 10).

The style of writing deemed appropriate for the virtual exhibition, we thought, should have three levels of information. The first level is an introductory story, with accessible language, that appeals to a general audience browsing for entertainment. The second level of information is for those who are more interested, and the third level of information is aimed at academics and researchers who wish to find out more detail and access further archival sources. Within each narrative, the researchers combined other sources, including, for example in the Psychology of Light narrative. Kiesler's original text, "Psychology of Light" (1950), which he wrote nine years before he made the 1959 Endless House model. This was combined with an archived sketch of his idea for a Colour Clock and a new daylight simulation of the model. This illustrates how Kiesler's architectural ideas from almost a decade earlier connected to the model and the importance of other archival sources to contextualise interpretations of models.

The relationship between the interactions and the content in the system can be summarised as shown in Fig. 11.

5.3. User experience validation and results

A few architectural students (seven) volunteered to pilot the Endless House mobile application and provided detailed feedback by way of a qualitative questionnaire. Students were asked to download the app and explore it in their own time, before being prompted to reflect on their experience and complete an online questionnaire (as outlined in Section 3.2). The questionnaire primarily sought to measure user enjoyment, engagement with different features, and the app's value as a tool to study models. A series of statements were presented and participants were asked to state to what degree they agreed or disagreed with these statement on a scale of 1—10.

All students positively agreed that the app was an 'entertaining experience' with an average score of 8.6 where 1 is equal to 'Not Entertaining at All' and 10 is equal to 'Extremely Entertaining'. When asked what specific parts of the experience they enjoyed, there was preference for the "virtual walk-through" which gave an idea of what it would feel like from inside, the "analysis of light studies" and the "dynamic sections" through the model. Another student said the sections were "enlightening and helped me to understand the structure better" and the "appearance of (Kiesler's) original orthographic drawings was something I found informative and engaging".

On average, with a score of 8.9, participants positively agreed that they were engaged - curious to explore — when using the app. All felt a high (average 8) sense of embodiment (i.e., like they were inhabiting a real space) when virtually moving through the model. All participants viewed the application in their private rooms. One stated: "my location allowed me space and time to explore the model." When asked how the augmented exhibition compared to lecture-based learning, students generally felt it was more engaging and they enjoyed exploring the space first, in their own time, before learning the background information. One observation found that there is "no distinction between information that is more/less important" when compared to a lecture. Students appeared to value the analytical and immersive features, and the freedom to explore the model (in their own space and time) before delving into a detailed history of the model architectures. Compared to lecture-based resources, the exhibition was viewed as a more self-explorative tool with no hierarchy in

Fig. 8 Projected drawing for the Endless House projected inside the model.

Fig. 9 Live section of 3D model with embedded 2D original floor plan by Kiesler, 1959

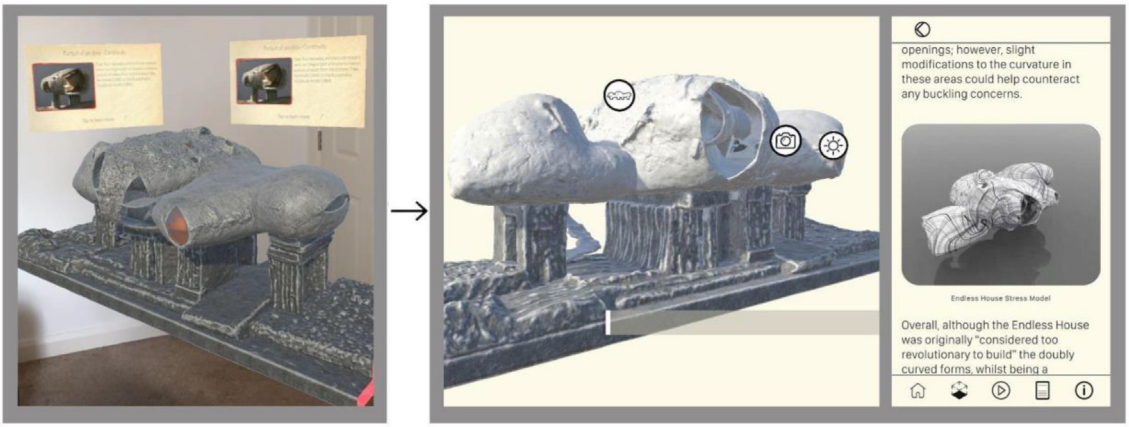

Fig. 10 Display board development.

the information provided. Counter to a book, the exploration takes place in a non-linear fashion as the user can explore different areas of information in an order of their choosing.

When reflecting on how the app and interactions helped to raise an awareness of the content (discussed in Section 2.2), one student explained that they preferred to focus on "just exploring it [the app] to have an overall

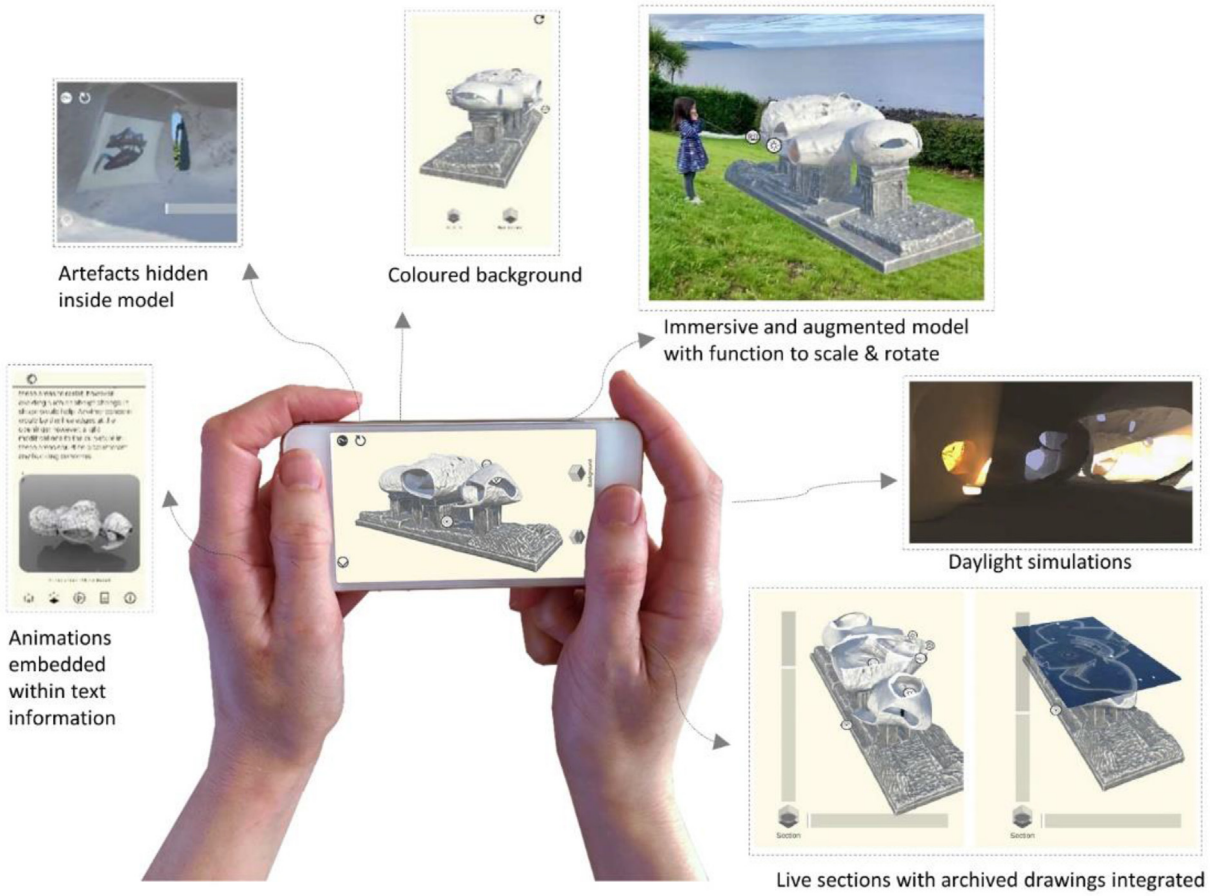

Fig. 11 Summary of the relationship between the interactive features and the content in the App.

understanding" since it was the first time they came across Kiesler's model. The same student then went on to state: "the app gave me a lot of new input and insights for future considerations. Something I take out of it is that there is no such thing as THE Endless House but rather AN endless house, which implies that Kiesler's theories of Correalism could be projected onto a large scale utopian master plan that is ever-growing and highly adaptable to its surrounding." Other students stated that they learned about "Correalism, futurism, and the possibilities of organic forms for building" and that they were inspired by Kiesler's "careful analysis of light studies."

When responding to the questionnaire all participants thought that museums should provide virtual access to historic models for public study, one commented: "Even if we're in the museum, a vast majority of them are trapped in the glass shield cabinet or (behind) lines. If these virtual museums are available, then we can explore the work more carefully." Another said:

> ... this is a unique way to communicate spatial aspects and give everyone the chance to explore such a structure in depth, on their own. It is important because it helps to understand the way of thinking of the person who originally made the model and to get a sense for what their visions of future as well as contemporary living looked like.

A few made recommendations to improve the experience of the exhibition app. One participant suggested that adding audio would help to improve the experience of the model, so the user could simultaneously listen and explore the model rather than stop and read text. An indication of scale at various stages of immersion was suggested, to help the user understand when the model is at the scale it was built (1:16) and when it is at the scale it was intended (1:1). Another student mentioned that more artefacts inside the model would further add to the element of surprise and increase their level of interest.

6. Conclusions

This research began by asking how we might use an immersive and interactive online archive to enhance the ability to exhibit and interpret historical architectural ideas conceptualized through model making. A critical reflection on a case study helped explore possibilities for research and education. The Design Charrette reflects the experts' need

to present their knowledge, and the use of AR enhances the transfer of knowledge to the public e.g. for educational purposes.

As described in Section 2, digitising and analysing pre-digital models is an established form of architectural research. Restricted access to museums during the global pandemic did, in some ways, play a part in developing how museums use technologies to document, archive, and exhibit objects. Here, we expand existing methods by introducing more accessible, augmented, and interactive features which aimed, in part, to better capture Kiesler's potential intentions in this version of his Endless House model.

As previously mentioned, there is a continued global interest in Kiesler's work, which is archived in disparate locations. The intention of this research was thus not only to increase public access to the model, but to provide a digital 'twin' to a museum's digital repository for conservation purposes. From the point of view of the researcher, the ability to *virtually* access the model and spatially inspect it (i.e., in scale, rotation, live sections in multiple directions, and walk-through) heightened the sense of embodied spatial and visual perception. The authors could co-produce interpretative research, focus on the model, and build on their experience and knowledge of architectural practice and theory. It helped strengthen connections between the model and other examples of Kiesler's textual and visual archival materials. Creating the app thus fostered research synergies between academics, archivists, and conservators to document, archive and learn from models.

This opportunity to combine the immersive and augmented experience of the model with other elements of Kiesler's work (poetry, painting, photography, and drawings) led to new ways of interpreting and exhibiting the model for different audiences - researchers, students, and public - that would not have been possible with the physical model alone. The user responses showed that the 3D archive/exhibition of the model enhanced curiosity, created an enjoyable and engaging introduction to Kiesler's work. As an educational resource, according to the qualitative responses, its greatest value is its accessibility and the informality of exploring the model before the exploration of further levels of learning provided by the app.

For a museum visitor, a visit to a museum or archive and exploring physical collections they have not yet seen can be a pleasurable and educationally useful experience. But physically touching or getting too close to these fragile assets are obviously restricted due to conservation considerations. This project and app doesn't claim to replace a visit to an archive, museum, or lecture. Rather, it adds an additional layer to these experiences and it also enables more global access to seeing models held in museum collections. We argue that virtually, and through a more immersive and interactive exhibition, the above-described app provides a new and useful way to spatially and visually communicate architectural ideas and the haptic and material qualities of a model, among other relevant and supplemental information provided for individual interpretation.

7. Further work

This research was limited by a small budget, yet it served as a pilot study to successfully explore an alternative way to virtually exhibit architectural models. Unfortunately, administering the feedback questionnaire during the COVID-19 pandemic resulted in a low response rate. The responses, however, were detailed and informative, providing a stepping stone to further research. The next step will be, therefore, to respond to the initial feedback and explore other interactive features, such as including audio stories, inhabited visualisations, a photorealistic external surface texture (similar to the image in Fig. 12), more hidden artefacts, and opportunities for participants to co-interpret the model within the exhibition space. We will build on from our experience to further explore the idea of scale perception and better ways of visualising large models, such as the Endless House 1:16.

Fig. 12 Photo applied to 3D model - shared in web-based platform Sketchfab.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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