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Exploring 3D Data Reuse and Repurposing through Procedural Modeling

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CHAPTER 8

Exploring 3D Data Reuse and Repurposing through Procedural Modeling

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Introduction

Most contemporary 3D data used in archaeological research and heritage management have been created through 'reality capture,' the recording of the physical features of extant archaeological objects, structures, and landscapes using technologies such as laser scanning and photogrammetry (Garstki 2020, ch.2; Magnani et al. 2020). A smaller quantity of data are generated by Computer Aided Design (CAD) and Building Information Modeling (BIM) projects, and even fewer data are generated through procedural modeling, the rapid prototyping of multi-component three-dimensional (3D) models from a set of rules (Figure 8.1.). It is unsurprising therefore that in archaeology and heritage, efforts around digital 3D data preservation and accessibility have concentrated on high-resolution 3D data produced through scanning and image-based techniques (Hardesty et al. 2020; Richards-Rissetto and von Schwerin 2017).

Establishing best practices, cultivating a community of experts, and developing infrastructure for this kind of 3D data in the archaeological and cultural heritage domains have been the focus of several coordinated efforts in Europe over the past decade (Fresa et al. 2015, Remondino and Campana 2014, Taylor and Gibson 2017, Vecchio et al. 2015). A series of European projects including 3D-COFORM, CARARE, and their successor projects, made particularly notable contributions (D'Andrea et al. 2013, Kuroczyski et al. 2014, Papatheodorou et al. 2011, Pitzalis et al. 2011, Remondino and Campana 2014). These projects were primarily oriented toward 3D data captured as part of conservation and heritage management work. Issues of preservation, accuracy, fidelity, access, and associated ethical issues of ownership, stewardship, contextualization, and interpretation were, appropriately, the center of extended disciplinary debates (for example, Magnani et al. 2018, Santana Quintero et al. 2019, Ulguim 2018; and more broadly on digital ethics Dennis 2020 and Richardson 2018). File size, geometric complexity, the diversity of 'standard' formats, evolving platforms for delivery, and presentation online posed challenges that continue to re-emerge today (for example, Digital

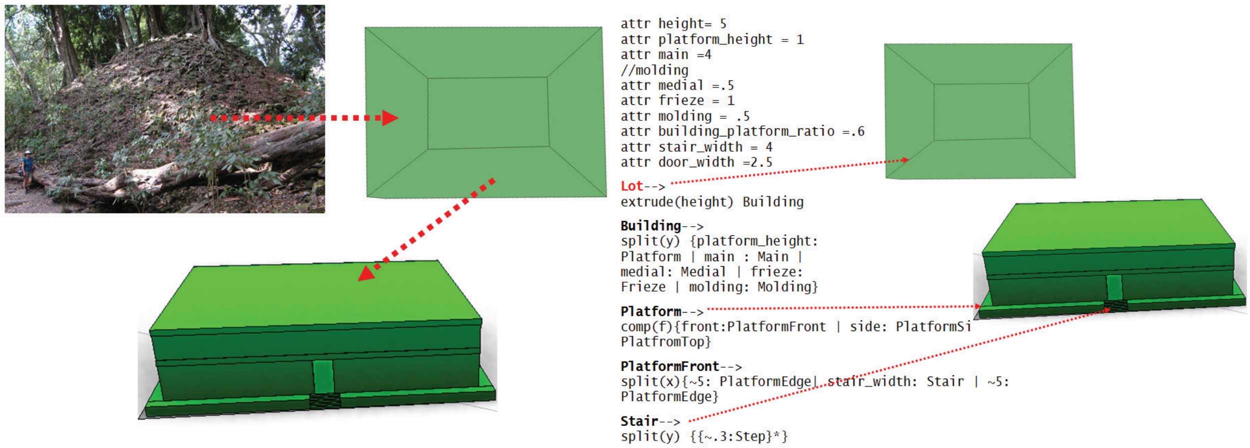

Figure 8.1. Scripted rules for procedurally generated ancient Maya architecture. *Source: MayaCityBuilder Project.*

Lab Notebook http://culturalheritageimaging.org/Technologies/Digital_Lab_Notebook/, Jensen 2018a, Koutsoudis et al. 2020, Münster et al. 2016, Rahaman et al. 2019, Rourk 2019).

To these efforts, heritage practitioners working in the context of architecture and urban development communities added workflows and tools designed to make CAD- and BIM-produced 3D models FAIR (Findable, Accessible, Interoperable, and Reusable). Such work provides a foundation for broader efforts to make data in 3D digital archaeology and heritage FAIR (Apollonio et al. 2012, Leventhal 2018, Pocobelli et al. 2018, Saygi et al. 2013, Wilkinson et al. 2016). These CAD and BIM projects also advanced the development of archaeological information infrastructures and workflows for 3D data by incorporating more extensive use of paradata, while also grappling with issues of uncertainty and intellectual transparency in the interpretive modeling process (Bentkowska-Kafel et al. 2012, Denard 2012).

In contrast, procedural modeling's geometrically simple, lego-like 3D models have received little attention from the community concerned with digital 3D infrastructures, standards, and practices (Coelho et al. 2020). Various sectors employ the approach to create multiple virtual reconstructions (simulations) and to explore alternative constructions and arrangements with varying properties. These multiple, nesting-doll reconstructions redeploy components such as buildings in different arrangements according to diverse rules (Figure 8.1.). In archaeology, they have been used to investigate ancient Roman, Greek, Egyptian, and Maya cities in connection with core research questions about the emergence, character, and experience of urban life (Dylla et al. 2009, Fanini and Ferdani 2011, Kitsakis et al. 2017, Piccoli 2014, 2016, 2018, Richards-Rissetto and Plessing 2015, Saldana 2014, Saldana and Johanson 2013, Sullivan 2017, 2020).

This modeling work affords new types of analysis such as visibility, mobility, and acoustic studies, and fundamentally aims to lead to new knowledge and reinterpretations of ancient cities (Coelho et al. 2020). For example, Elaine Sullivan (2020) employed Geographic Information Systems (GIS) with procedural modeling to re-contextualize monumental structures within the broader landscape at ancient Saqqara in Egypt across 2,500 years to explore the role of visibility in constructing a sacred funerary landscape. Through the process of procedural modeling, she integrates archaeological, art historical, and spatial data to simulate potential past landscapes of Saqqara to interpret (or reinterpret) notions of Egyptian culture. Through 3D WebGIS, she allows others to not only see the procedurally generated landscapes, but also interact with them. (Figure 8.2. illustrates a generalized procedural modeling process.)

The affordances of the infrastructures designed for 'reality-capture'-generated 3D models and CAD/BIM models are, perhaps unsurprisingly, not well suited to the needs of the procedural modeling community, as they were not designed with this community's requirements and practices in mind. Procedural modeling prioritizes 'concept capture,' the recording of scholarly interpretation via hypothetical

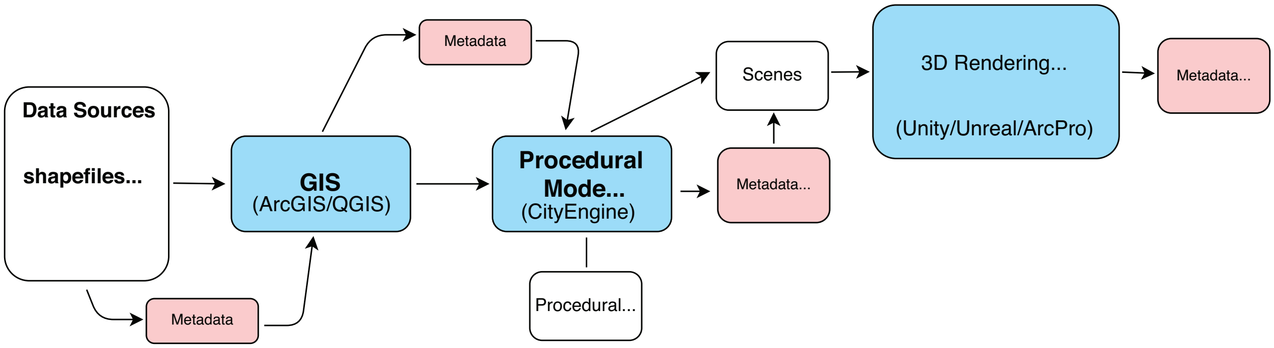

Figure 8.2. Generalized procedural modeling process, illustrating key points at which metadata and paradata are created or transferred.

models and multiple simulations. Consequently, it has different data preservation and accessibility requirements in two basic yet important ways. First, reuse and repurposing of data for archaeological reinterpretation are integral to its practice. Procedural modeling involves remixing and re-contextualizing multiple data sources, allowing us to explore and understand connections between different ideas and intellectual legacies represented by varied reuse of elements in different models. This emphasis on reuse contrasts with the emphasis on preservation and access often associated with reality-captured 3D. Second, 3D procedural models are geometrically simple but contextually and semantically complex. It is essential that information on the models' biography is legible and updated through the reuse process. Their geometry is valuable primarily as an explicit, mutable conceptual representation of an object or structure. Pragmatically, the systems with which these models need to be interoperable are different; tight integration with the systems used to reproduce procedural models is of primary concern. These requirements differ significantly from those for reality-captured 3D and CAD/BIM generated 3D models, which center on archiving, visual presentation, and interaction of the 3D geometry (Beetz et al. 2016).

The aim of the "Keeping 3D Data Alive: Supporting Reuse and Repurposing of 3D Data in the Humanities" (KDA) project was to design an information infrastructure and workflows to meet these requirements, while making procedural models FAIR. In making the data more readily available, citable, remixable, and intellectually reusable, we hoped to enrich procedural modeling as a research practice that produces archaeological knowledge through repeated reuse, recombination, and reinterpretation of 3D models. In undertaking this work, looking beyond the FAIR framework and open research agenda, we reflected on the priorities of the procedural modeling community and considered what makes a 3D model valuable in the context of procedural modeling-based research. Three practices emerged that we suggest should be enabled and encouraged through infrastructure design in order to support the broader aims of this community. These are generous reinterpretation, reflexive strategies of collaboration, and engagement with the biographies and intellectual legacies of (digital) things, which we discuss in detail below.

Aims and Choices in Designing the KDA Infrastructure

The KDA infrastructure intends to generate, store, and make accessible 3D procedural models of architecture in an open-source repository, linked to an open-source 3D viewer that allows scholars to reuse and repurpose 3D entities to create reconstructions ranging from individual buildings to entire cityscapes. In its initial development phase, we designed and constructed a prototype infrastructure and workflows to export and import 3D procedural models along with metadata, paradata, and descriptive attributes that trace use-biographies, allowing for scholarly reuse and citability. The initial development phase prioritized functionality, which supports citability because it was viewed as critical to enabling data reuse between projects and to encouraging scholars to take full advantage of the richness of the 3D data medium as part of academic publications.

Core Infrastructure Components and Workflows

The three core components of the KDA infrastructure design are script-based integrations with CityEngine, a Repository, and a 3D Viewer (Figure 8.3.). The project developed metadata schemas, selected supported files types, and designed back-end infrastructure and workflows around these key components.

To link the three main components of the infrastructure, we developed workflows to: 1) export 3D models along with metadata and paradata from City Engine using a Python script; 2) import the models with associated data into an open source repository that could assign a DOI (and track use-biographies); and 3) import models from the repository into a 3D online viewer for reuse with real-time geometry, metadata, and paradata changes tracked and stored in the repository (Figure 8.4.). The workflows aimed to minimize steps, standardize processes and outputs across user experiences and setups, and mitigate user error—all factors that affect data reuse. The scripts automatically perform the required tasks to ensure that the metadata, paradata, and attributes are standardized and packaged for export and import into the repository and 3D viewer.

Design Choices for the Repository

We designed the KDA infrastructure to complement and be interoperable with procedural modeling software such as ESRI's City Engine. It allows users to export 3D procedural models from proprietary software using standardized workflows and python scripts for import into an open-source repository. In the original project design, infrastructure was constructed around PostgreSQL—a widely used open-source relational database popular in the archaeological GIS community (see von Schwerin et al. 2013, von Schwerin et al. 2016 for details on MayaArch3D Project). However, because libraries are the main data stewards in the United States, we redesigned the infrastructure to use a Fedora repository, reflecting infrastructures commonly used in the libraries community. We were encouraged in this design choice by recent efforts in preservation and access of 3D data within libraries led by Community Standards for 3D

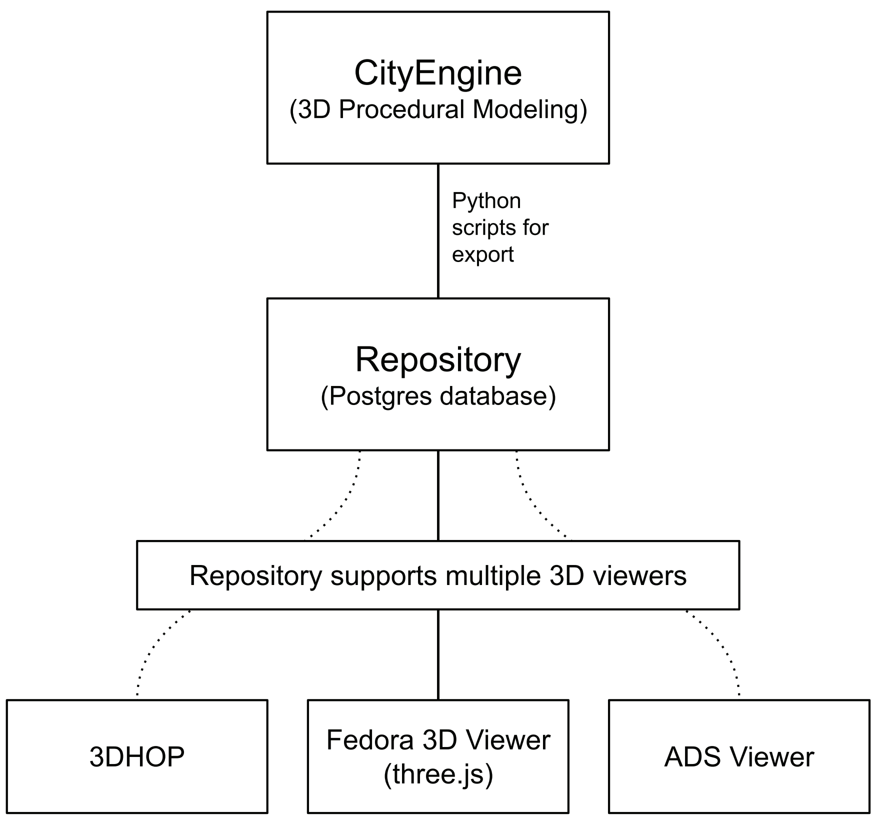

Figure 8.3. Keeping Data Alive (KDA) infrastructure design. A white paper with more technical detail on the core infrastructure is available at https://cdrhsites.unl.edu/keeping-data-alive/whitepaper.html (Richards-Rissetto et al. 2018).

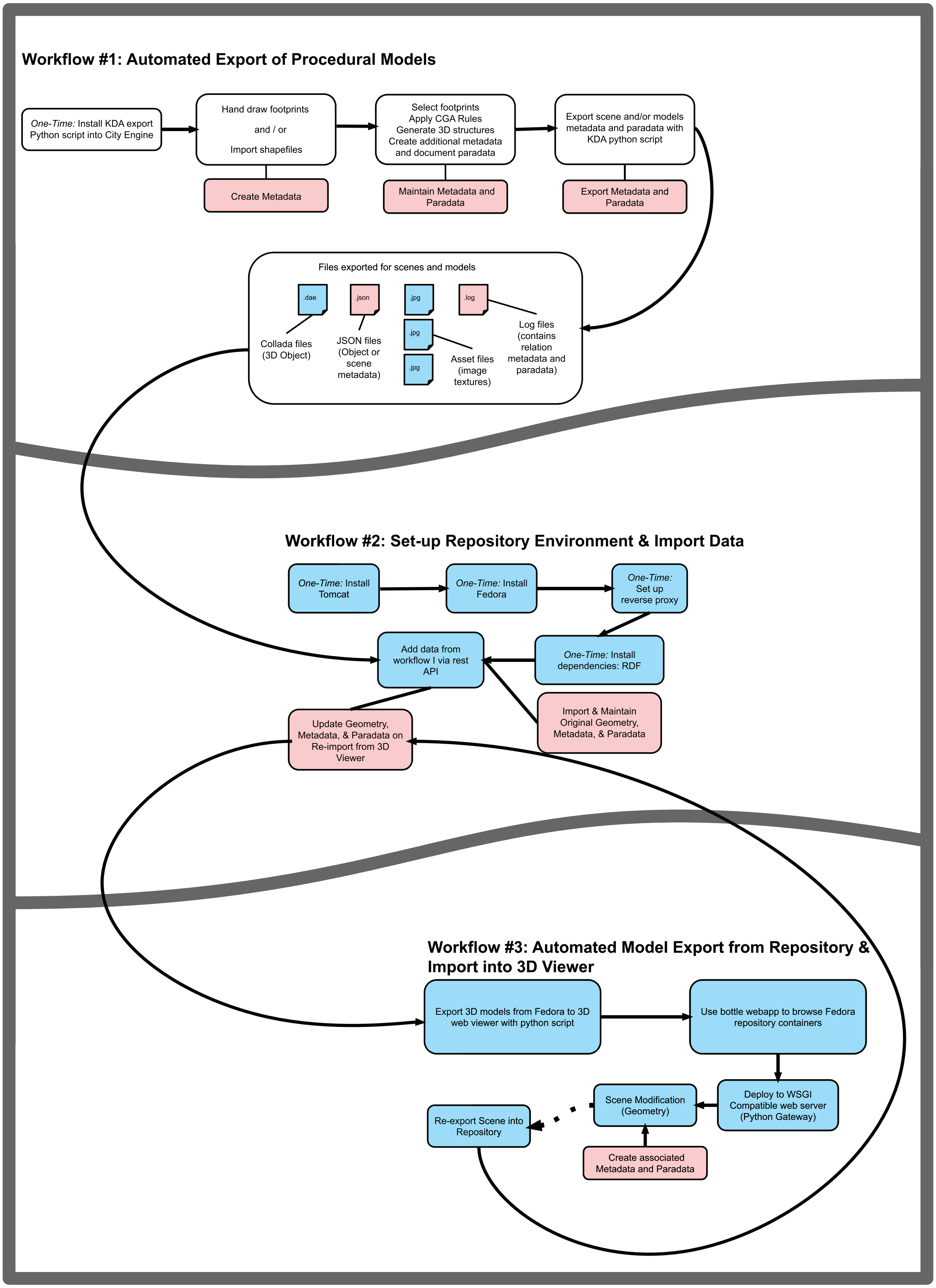

Figure 8.4. The KDA workflows shown here illustrate the steps required to reproduce and test the entire system architecture. One-time steps are only required for the initial configuration of the system and are not part of the operational workflow.

Data Preservation (CS3DP) and the Library of Congress on Digital Stewardship of Intrinsic 3D Data. These projects showed how a repository approach could be customized to better match libraries' requirements and skillsets, providing a pathway to promote preservation and access efforts beyond individual projects. While we selected Fedora based on the expertise available in our project team, any widely used repository could be used for this part of the infrastructure, chosen based on locally available skillsets and requirements. Following the same logic of building on existing capacity and infrastructure in the libraries community, the project team chose to implement the Research Description Framework (RDF) as part of its metadata strategy because it is widely employed as a key component of linked data in the libraries and archives communities.

Considerations for File Type Support and Metadata Schema

In selecting a 3D file type to support the KDA infrastructure, we reviewed the requirements of archaeologists and heritage practitioners against the affordances of specific formats. Different 3D geometry file types (for example, X3D, COLLADA, OBJ, PLY) allow for the storage of various kinds of information. Some formats maintain strict standards, only allowing specific kinds of information to be included, while other formats are more permissive. Many popular 3D file formats support inclusion of basic metadata such as creation date, number of 3D points, or polygons. However, they typically do not support incorporation of more complex metadata or paradata about modeling choices. As discussed above, in the context of procedural modeling these more complex metadata and paradata are important for scholarly reuse and reinterpretation. Documenting multiple relationships between components in 3D scenes was also a key requirement of the KDA infrastructure because scene-level relationships are integral to procedurally generated models (Figure 8.5.). Additionally, 3D procedural models typically have numerous associated source files and involve many modeling choices; therefore, it was equally important to plan for large paradata files.

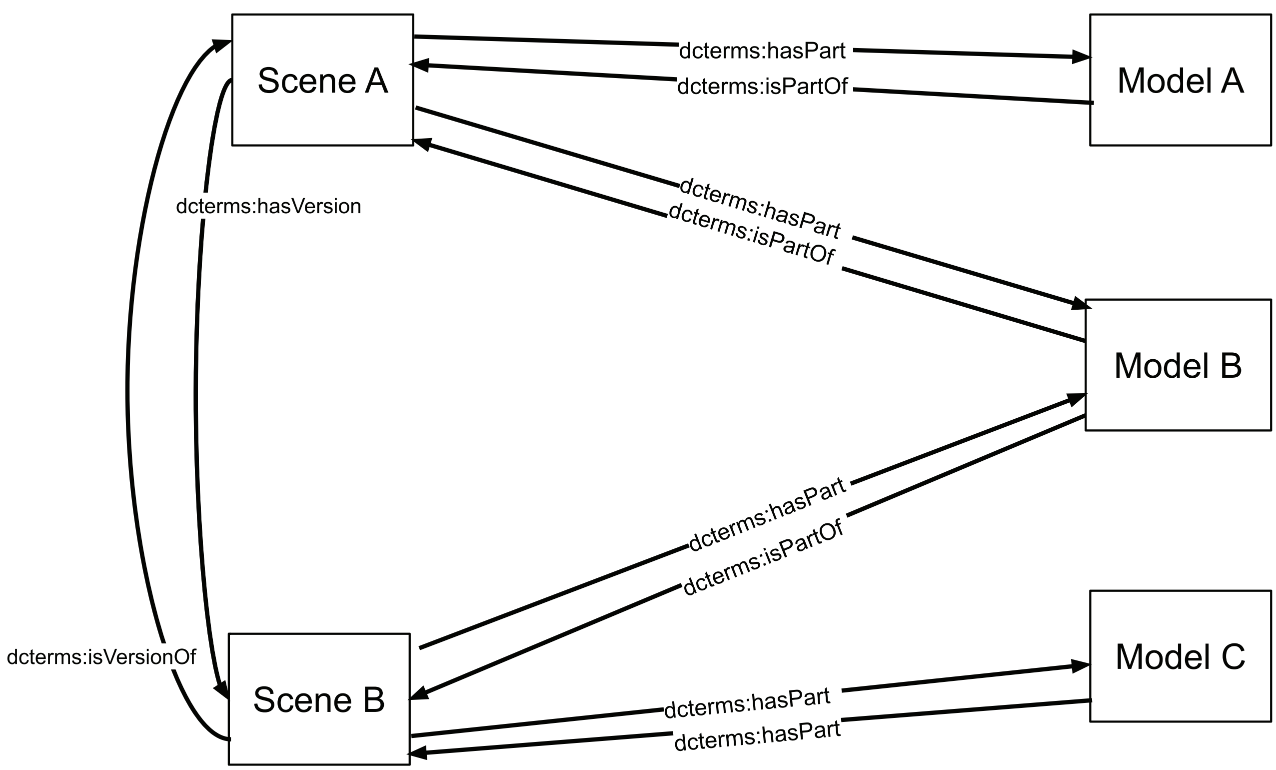

Figure 8.5. Metadata capturing the relationships between scenes and their components across multiple iterations are essential for tracking the reuse of components, which is integral to the practice of procedural modeling.

We also considered interoperability across systems as essential to support reuse.[1] In selecting a file format for use in the KDA infrastructure, these were the primary considerations, together with current levels of use in the procedural modeling and wider digital archaeology user communities. X3DOM meets some but not all of these requirements. It provides capacity for embedding complex scene information and paradata into the models and provides useful support for archiving 3D data. However, many commonly used 3D visualization software tools are not compatible with X3DOM or do not facilitate reading its paradata. Further, the X3DOM format is not widely used in the cultural heritage and archaeology communities. In contrast, the OBJ format is widely used in the archaeological community as a 'standard' format and is compatible with most major open-source software packages and scripting routines. However, while suitable for tracking single structures, OBJ does not support complex scene hierarchies, which are essential to procedural modeling applications.

In contrast, the COLLADA (DAE) format, an XML-based schema, enables data transfer among 3D digital tools and supports rich metadata and paradata for both objects and within scene hierarchies. It is widely used in the archaeological and cultural heritage communities. This format captures more information about geometry and materials within a scene, including textures, lighting, and camera angles. Moreover, COLLADA permits more detailed object descriptions than OBJ. This additional information becomes useful for 3D data reuse, particularly in capturing modeling choices, tracking changes, and ultimately facilitating citability. We selected this format because, as discussed above, it best matched the infrastructure's requirements.

Together with the use of the COLLADA format, the project team chose to use a JSON sidecar file to maintain core metadata for each modeled scene. While it is technically possible to embed metadata in the COLLADA file, the sidecar JSON metadata file aids ingest and portability within the Fedora Repository. More broadly, this design choice maximizes interoperability with other library-based institutional infrastructures, as JSON or XML metadata files are widely used in these contexts.

We considered two metadata models for the schema of these sidecar files, the CIDOC CRM (CIDOC Documentation Standards Working Group 2018) and the Europeana Data Model (EDM) (Europeana Foundation 2018), because these models are widely used in cultural heritage contexts. The EDM was selected because it is flexible and incorporates some of the properties of Dublin Core and CIDOC CRM (Doerr and Theodoridou 2011, Stead and Doerr 2015), as well as Web Ontology Language (OWL), Friend of a Friend (FOAF), Simple Knowledge Organization System (SKOS), and other metadata models. Its support for describing relationships among objects, scenes, and files is also beneficial. This design choice reflected our prioritization of interoperability with metadata schemas used in diverse institutional contexts.

Design Choices for the Viewer

The KDA repository outputs and ingests models through an online, open-source 3D viewer, extracting them from and redepositing them into its repository. Initially, two related web-based 3D viewers already used in the heritage community were considered for the infrastructure, with the aim of building on existing research efforts and favoring tools already in use by the broader community: the ADS 3D Viewer (https://archaeologydataservice.ac.uk/research/3DViewer.xhtml, Galeazzi et al. 2016) and the 3DHOP viewer (http://3dhop.net/, Potenziani et al. 2015). On close inspection of their functionality, these tools were not easily adaptable to meet the KDA infrastructure's needs. Specifically, the infrastructure needed to store information on complex 3D scenes, including information on the relationships between reused 3D sub-components (that is, models), as discussed above (Figure 8.5.).

While the ADS 3D Viewer supported the import of OBJ files, commonly used in procedural modeling, it did not natively support COLLADA. 3DHOP natively supported PLY and while it was possible to modify the code to enable the import of COLLADA and subsequent conversion to PLY, this process added complexity as well as challenges for reuse of derivatives in other platforms. On this basis, the project team chose to develop a simple 3D Viewer using three.js (three.js Community 2018), which natively supports COLLADA, to test the workflows and infrastructure. The prototype viewer (Figure 8.6.) is available at https://cdrhsites.unl.edu/keeping-data-alive/fedora-viewer.html.

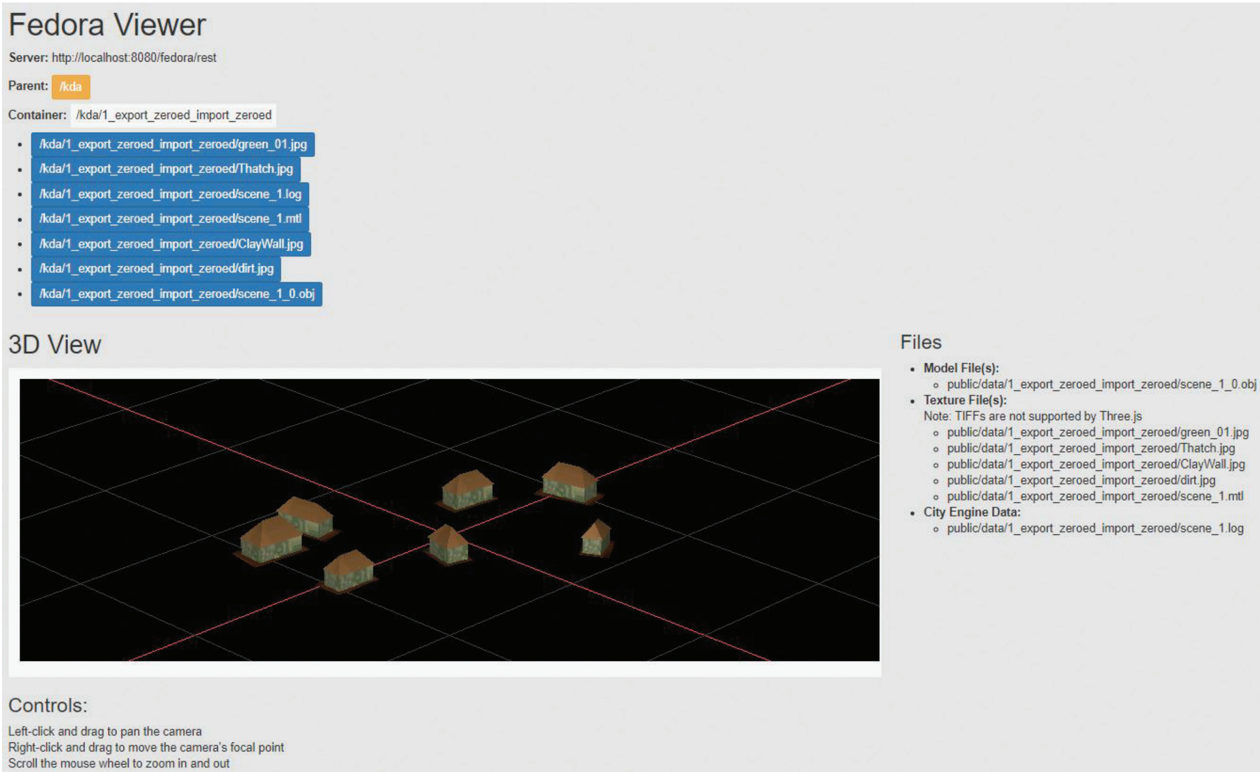

Figure 8.6. The prototype Fedora Viewer, showing linked files, metadata and paradata containers, and the visual rendering of a procedurally modeled scene.

Reflecting on the KDA Infrastructure Design

In designing and developing the KDA infrastructure, beyond tackling the various practical and technical challenges sketched above, we chose to reflect seriously on the main research and practice aims of procedural modeling in archaeology, and their convergences and divergences with those of communities working with reality-captured 3D and CAD/BIM-modeled 3D. As noted above, by surveying the literature, we identified core research aims that included exploring possible past urbanisms, conducting digital experiments on the make-up and experience of past places, and using these experiments to reflect on how societies shaped these modeled places. A proper evaluation of how the KDA infrastructure enables practitioners to meet their research aims must await its full development and a period of active use. Therefore, at present, we focus our evaluation on how the design enables the pursuit of the communities' practice-oriented aims: generous reinterpretation, reflexive strategies of collaboration, and engagement with the biographies and intellectual legacies of digital things. All of these depend on the capacity of the infrastructure for 1) recognition of contributions to research through the provision and reuse of 3D model components and 2) increased visibility of the connections between different procedural modeling experiments.

Encouraging Generous Reinterpretation

The motivations of reuse practices vary significantly between 'reality-captured' 3D, CAD/BIM-modeled 3D, and procedural-modeling 3D communities, respectively focused on accurate reproduction and ownership, communicating certainty and interpretation transparently, and generous reinterpretation as defined by Sullivan (2020). In reality-captured 3D practice, reuse is strongly aligned with reproduction of object geometry and material appearance in order to faithfully recreate object shape. While reinterpreting the meaning or context of the digital thing is definitely an important part of reality-capture workflows, this reinterpretation takes place outside the core archival infrastructure. Thus, workflows developed by the digital standards and good practices community as embodied by, for example, the London Charter, CARARE, and 3D-Coform, do not account for reinterpretation practices (see a recent review in Rahaman and Champion 2019 for discussion of aims and practices and gaps between them). Reinterpretation is an added layer of practice, the requirements of which are driven by a different community of actors. The debates in reality-capture 3D practice have centered on ownership and stewardship of digital things (for example, Magnani et al. 2018, Santana Quintero et al. 2019, Ulguim 2018—as cited above) and around authenticity and aura (Jeffrey 2015, Jensen 2018b, Jones et al. 2018, Kenderdine and Yip 2018). These debates testify to a strong concern with accurate reproduction of form in the context of reuse (though see Dawson and Reilly 2019 for a creative counterpoint and some intentional rule breaking).

In this context, archaeologists have discussed ownership and access, stewardship, and interpretation of digital 3D objects in relation to contested or competing narratives. The debate centers on who tells the story of an object through digital platforms, who owns it and manages the right to its reproduction, and by whom it can and should be found and accessed. Given the very real political and emotive issues surrounding ownership, power, colonial legacies, and representation in which digital reality-captured 3D models have found themselves entangled (for example, Colley 2015, DeHass and Hollinger 2018, Nicholas 2016, Stobiecka 2020, Thompson 2017), encouraging reinterpretation in the central infrastructures that house the digital things becomes fraught. Intentionally or not, the communities engaged in the design of centralized infrastructures and workflows for this kind of 3D data have focused on the faithful reproduction of digital objects, making them findable and accessible, and maintaining referential links with their physical counterparts. The core infrastructures, repositories, archives, search tools, and workflows to produce descriptive metadata and standards for formats, in focusing on findability, accessibility, and preservation, have largely maintained a neutral position amid the often heated debates about the sticky business of reinterpretation of digital things (for further discussion of these complexities, see Eric Kansa, chapter 9 in this volume).

CAD/BIM 3D modeling sits in a different position within archaeology and heritage practice (Beacham 2011, López et al. 2018, Pfarr-Harfst 2016, Simeone et al. 2019). Infrastructures and workflows to support the association of paradata have been a primary concern for this community because while some aspects of the geometry and materials of these models essentially attempt to approximate the physical objects, and therefore share goals with reality-capture 3D, many represent hypothetical reconstructions and interpretations. The use of paradata to explain the modeling choices and processing behind the hypothetical and interpretive elements of these models, and to distinguish between these and the reality-reproducing elements, clearly focuses on supporting reinterpretation (Bentkowska-Kafel et al. 2012, Brusaporci 2017). However, the requirements of this reinterpretation practice are distinct from those of procedural modeling. A reinterpretation in a CAD/BIM context is a largely self-contained product, reconstructing a complete entity or world in the tradition of reconstructive illustration or physical modeling (Frischer and Dakouri-Hild 2008, Hodgson 2004; Moser 2012 and Molyneaux 2013 on the history of illustration and images including reconstructions in archaeology). Paradata documentation focuses on making a strong and nuanced argument through the reconstructed model and on maintaining and communicating intellectual rigor in this process. Therefore, the primary concern within the CAD/BIM community developing paradata infrastructures is to explain and communicate the interpretive choices made by individual modelers or modeling teams, rather than foregrounding connections between different reconstructions of the same entity.

The procedural modeling community uses 3D model components to manifest different hypothetical reconstructions, with only an indicative relationship to the geometry of any physical thing. Its core work involves iterative experimental generation of complex models made of collections of 3D components. The redeployment of the 3D components and the implications of their reuse in different modeling exercises and outputs is central to this community's practice. The reinterpretation of the potential roles and affordances of the individual 3D model components is significant in this community of practice, and thus connections through shared 3D components are a primary concern. To access digital data typically refers to the ability to discover, examine, and retrieve 3D models (Landi et al. 2020, Mons et al. 2017). However, for the data to be meaningfully 'accessible' for procedural modeling, we need to add to this 'definition' the capacity to reuse the data in multiple ways (Albrezzi et al. forthcoming, Moore et al. forthcoming, Richards-Rissetto forthcoming, Wilkinson et al. 2016).

The design of the KDA infrastructure responds to this need by emphasizing citability and providing tools to support this practice. Citability is closely tied to generous reinterpretation in that it foregrounds connections between ideas and credits the intellectual legacy of a model's other uses. The primary functions of reality-captured 3D are to provide a digital archival copy and to support the study of the digital entity, as one would study the physical object (through techniques such as metric analysis). To fulfill these functions, the primary FAIR requirements are that it must be findable and accessible. In contrast, the primary FAIR requirements of a procedural model component are that it be reusable and interoperable. Consequently, the real aims and value of citations are different. In the first, the primary goal of citation is reference to the originating entity. In the second, it is about creating connections through citation that build a network of intellectually generous connected reinterpretations. Procedural modelers using model components benefit from generous reinterpretive practices because documenting connected reuse, via paradata, adds to the informational value, legitimacy, and interest of the models.

Enabling Reflexive Strategies of Collaboration

Our reflections on the role of citability and generous reinterpretation within procedural modeling practice suggest that infrastructures and workflows need to prioritize reflexive strategies of collaboration (Wright and Richards 2018). Considerations of the value added by collaborations are of primary concern because the 3D model components derive value foremost from their connections to and iterative reuse in other models. Enabling an intentional, self-conscious, reflexive, collaboration strategy, in this light, becomes a primary aim of this community's infrastructure and workflows, aligned with calls for reflexive practice in digital archaeological work (for example, Berggren et al. 2015, Boyd et al. 2021, Wilkins 2020).

Using easily modifiable sidecar paradata and metadata files, supporting large paradata files to allow unlimited additions to the chain of documented reuse, and versioning the paradata file encourage iterative collaboration between teams and support this reflexive mode of collaboration. The exposure of paradata on reuse through 3D viewers and as a downloadable file, and its prioritization within infrastructure design, promotes an intentional and self-conscious practice, in which considerations of the value of the connections between uses of a 3D model are foregrounded.

While sharing some aspects with collaboration in CAD/BIM modeling, we highlight important differences that lead to slightly different infrastructural requirements. Collaboration in CAD/BIM modeling takes place most frequently within a team coming to a collective interpretation, which is encapsulated in a single set of paradata associated with a specific version of the 3D model (Banfi et al. 2018 and Logothetis et al. 2017 specifically discuss collaboration in heritage BIM work). In this practice, the output of a closed circle of collaboration is a finished set of paradata tied to the 3D model that is its intellectual product. While the ability to view and ingest paradata is important for both groups, the ability to re-edit and add to paradata is not a priority for CAD/BIM modeling practice, while it is essential for procedural modelers.

The requirements and affordances are even further from those of reality-capture 3D practice. In this context, the initial collaborative stage of work largely precedes a model's entry into the digital infrastructures and workflows. It takes place during the creation of the 3D geometric model itself, as teams often work together to digitally capture an object. A separate collaboration may take place outside the bounds of core archival infrastructures during reinterpretation by a group of external users (for example, as in DeHass and Taitt 2018). This is primarily a practice of collaboration around the digital 3D model, rather than *through* the model. In current practice, the results of these later collaborations are treated as separate from a theoretically 'neutral' 3D model and consequently not widely integrated into the metadata or other documentation of the model itself, a situation that is not unproblematic.

Supporting Engagement with Biographies and Intellectual Legacies of (Digital) Things

The development of infrastructures and workflows to support object biographies for digital 3D models exist across all the communities of 3D archaeological practice. In the reality-capture 3D community, this is reflected by considerable investment in the development of infrastructures for data sharing (Galeazzi et al. 2016, Scopigno et al. 2017). A common approach is to provide DOI-like citations for the digital 3D models and embed in their metadata references to the connected physical objects (for example, the Smithsonian's 3D digital portal, OpenContext and ADS integrations of 3D viewers, investment in the development of the 3D-HOP framework, and ARIADNE's Visual Media Service). The referential metadata in these infrastructures links the biographies of the physical and digital objects. The ability to cite the object in literature outside the infrastructure reflects the community's concern for its intellectual legacy, in the sense of its impact on scholarship about the object in its digital incarnation. The development of infrastructures that encourage the explicit citation of its digital incarnation is particularly interesting as a practice when we consider that an author could cite the physical object. Encouraging citation of the digital incarnation and the physical object through it hints at the promotion of a distinct intellectual legacy for the digital 3D model as an entity, much as casts in cast galleries become quasi-independent heritage entities (Juckette et al. 2018, Rabinowitz 2015).

The CAD/BIM modeling community's tight integration of the paradata and model geometry encourages engagement with the biography of the object by making the commentary on its creation fully integrated into the format of its expression of its digital shape and material properties. The two, literally designed as part of the file structure, cannot be separated, as they are a key component of the community's paradata infrastructure. This choice, in contrast to the sidecar-style paradata file selected for the KDA infrastructure, speaks to the strong emphasis on object biography in the CAD/BIM modeling community of practice. KDA design choices, which enable reflexive collaboration for procedural modelers, also support the CAD/BIM community's aim to reveal and encourage engagement with intellectual legacies. However, here the engagement is active, and the priority is making intellectual legacies open and extensible, aligned with the community's emphasis on adding value to models through reinterpretation. The design of infrastructures and workflows consequently prioritizes interoperability of paradata as well as ease of viewing and iterative modification.

In procedural modeling, KDA's emphasis on practice that automates aspects of the process of tracking changes, inputs, and decisions reflects the expectation of ongoing contributions to the 3D model components' biographies and the tracking of their evolving legacies. The infrastructure aims to support ongoing engagement with such practice by making the basic mechanistic aspects of the work automated. KDA is not suggesting full automation; human attention is still essential. Rather we advocate the incorporation of automated processes and checks into the workflows as fundamental aims for the infrastructure. The high level of effort involved in constructing rich biographies and tracking dense legacies could discourage practitioners; however, the inclusion of automated tracking mechanisms in the infrastructure could lessen such efforts and support the importance of iterative engagement with 3D models within the community's practice.

Conclusions: Designing New Affordances

In the digital era, our interactions with technology are mediated by the varying properties of hardware, software, data types, user interface design (UI), user experience design (UX), and workflows that shape our practices, which in turn impacts not only our interpretations, but more importantly the potentiality of our interpretations (Ingold 2018:41). Since Gibson (1977) and Norman (1988), diverse disciplines ranging from narrative studies to design studies to archaeology have employed the affordance concept (albeit in varying ways and not without debate, for example, Webster 1999) as a theoretical framework for research and practice (Backe 2012, Copplestone and Dunne 2017, Forte 2016, Gillings 2012, Ingold 2018, Llobera 1996).

In the KDA project, we focused on the potential opportunities and hindrances afforded by infrastructures and workflows for 3D procedural modeling, taking up the call of Perry and Taylor (2018) and long-term advocacy by Huggett (for example, 2015; 2020) to engage in a reflexive process to theorize our digital research practices. This process of reflexive exploration focused our attention on how procedural modelers work with 3D models through the infrastructure and what they considered important or valuable. It highlighted the need to look beyond the engagements of individual modelers with data, metadata, and paradata and account for the strongly collaborative and interactive character of this community's practices. To truly support these collaborative practices, looking forward we must build infrastructures that afford and encourage their users to engage with one another, as well as the 3D models, metadata, and paradata they create.

Authors' Statement

Heather Richards-Rissetto led the KDA Project and Rachel Opitz contributed to the KDA Project's design. Karin Dalziel, Jessica Dussault, and Greg Tunink carried out the practical development of the KDA architecture and contributed to drafting the description of the KDA architecture in the article. Rachel Opitz and Heather Richards-Rissetto conceived the chapter, led the writing of all sections other than the KDA architecture description, and edited the chapter.

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Note

1 https://guides.archaeologydataservice.ac.uk/g2gp/3d_2-3

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