P A P E R

Design Pedagogy: Adaptive Reuse & the Digital Twin

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With the increasing demands on integrated design, sustainability, and analysis, how can the core design studios be structured to address concerns related to context and materiality by employing a digital twin? What are some of the advantages of using *LiDAR* (Light Detection and Ranging) and photogrammetry to capture resources, and how might they facilitate our approach to design education? What are the benefits of using this technology to educate students to reuse buildings and critically and productively repurpose building materials? How considerable are the cost and time required to develop a digital twin, and what are the best practices to seamlessly interface its assets with other platforms? A *LiDAR* scan of St. Mary's church (1843) in Troy, New York, was commissioned, along with a digital twin for the second-year undergraduate design studio. The twin was shared with an allied daylighting course to examine and modify the existing daylighting conditions inside the church. The scan captured the material and ornamentation of the walls and floors, notably the stone, masonry, and wood elements, as found in the field, and helped illustrate the tectonics associated with the composite nature of the church's construction. The studio pedagogy promoted design proposals that critically engage context, adaptive reuse, daylighting, and heightened awareness of material finishes, selective demolition, and tectonics.

INTRODUCTION

This paper outlines a new pedagogical framework within the core undergraduate design studios to address aspects of the built environment that influence the design of the urban, social, material, and environmental context through the deployment of a digital twin. In order to have the students engage the context, the project posits an adaptive reuse scenario for St. Mary's Church in Troy, New York, constructed in 1843. The city's demographics and the generational shift of Troy's aging population have contributed to the contraction and shortfall of church congregations. St. Mary's is not alone; currently, an increasing number of churches in the capital region are under consideration for housing. As part of the program brief, the student teams were assigned thirty housing units and a mixed-use program that reimagines St. Mary's social and communal significance in light of its recent deconsecration. In response, students introduced various programs, including; after-school programs, dance education, a library, an urban farm and restaurant, office space, and recreational spaces. The studio used a 3d digital scan to study the entire anatomy of the church; its dimension, structure, material, and ornament, allowing students to interrogate its specific character throughout the design process. The intention of introducing the scan was not to reduce the studio pedagogy to a digital format; instead, the goal was to encourage the students to develop their proposals by visiting the church firsthand and using the scan to make large-scale physical models. With the onset of COVID-19 and the shift to remote learning in the spring of 2021, the twin became the primary resource for the studio, where site visits and the production of large-scale physical mockups were no longer tenable. Design proposals were delivered online with digital images, with most of the feedback occurring in *Miro*, a whiteboard application. For budgetary reasons, the twin is a composite of two different scanning technologies. It consists of an inherited photogrammetric model of the church's interior, generated by stitching together multiple photos to produce a mesh model, and a *LiDAR* (Light Detection and Ranging) laser scan of the exterior that the department commissioned prior to the start of the semester. The two scans were combined to produce a single resource. While definitions of digital twin vary, the following definition best describes the case study discussed in the paper.

> *...A digital twin is a digital copy of a real-world place or object. Artificial intelligence and machine learning technologies enable the creation of digital twins, which are dimensionally accurate 3D digital models that can be updated quickly to reflect changes with its physical counterpart.*[1]
>
> —Matterport- "What is a Digital Twin?"

The model produced for the studio is not the product of a fully functional digital twin since it does not receive feedback from the built environment. It is a pedagogical model that offers a glimpse into how scanning technology can be implemented to illustrate the elements of architecture, demonstrate tectonics, and introduce building lifecycle.

CONTEXT: IMAGES, POINTS, MESHES, AND THE DIGITAL

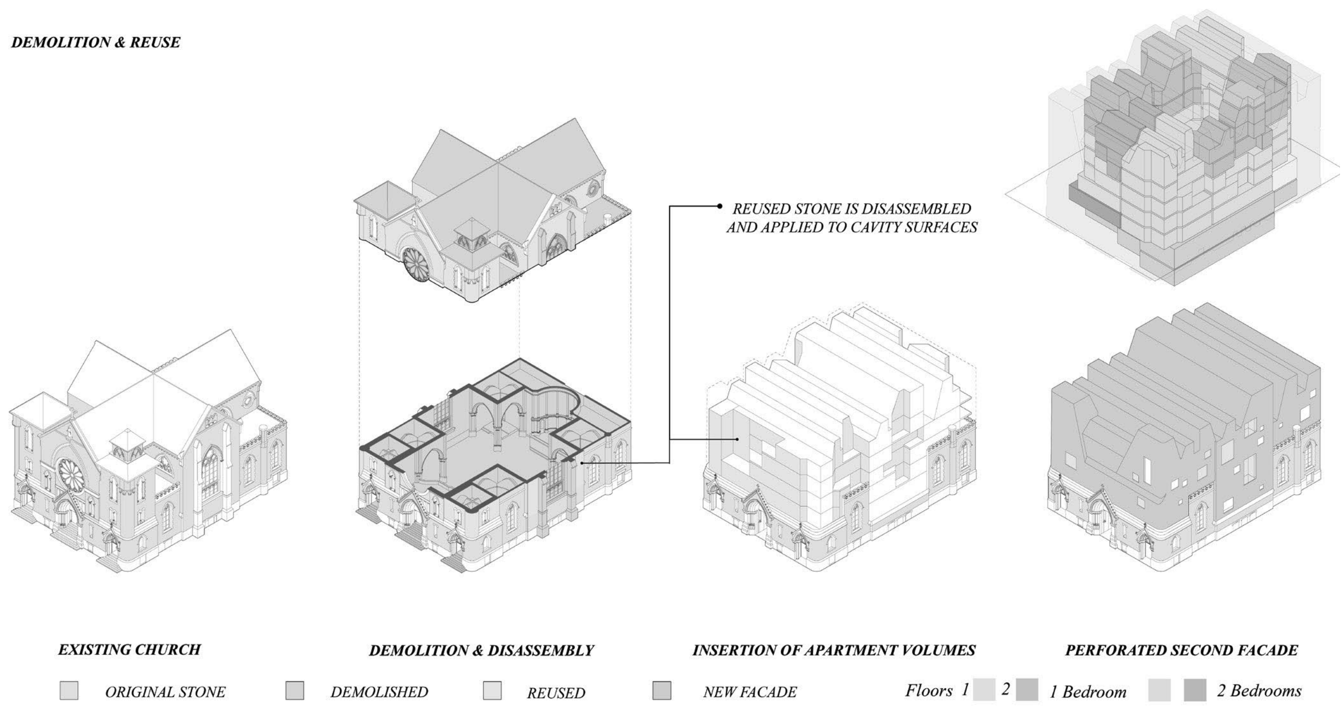

Figure 1. The selective demolition strategy involved reusing the granite facings from St. Mary's. The original granite is redeployed on the exterior balconies of the housing units. The church base houses an urban farm with a restaurant connected to the housing courtyard above. Image by Erica Eom & Sarah Weber, RPI SOA, AD4 2021.

TWIN

How architectural objects are measured and surveyed has undergone a fundamental shift in the last twenty years due to the rise of visualization techniques that prioritize the compactness of points over lines, planes, or solids.

> *In our lives, imaging is a form of photon detection. Unlike photographs, in which scenic light is made visible during chemical exposure, all imaging today is a process of detecting energy emitted by an environment and chopping it into discrete, measurable, electrical charges called signals, which are stored, calculated, managed, and manipulated, through various statistical methods.*[2]
>
> —John May- *Signal. Image. Architecture.*

The use of disconnected points, or point clouds, and their reconstruction as meshes, has introduced new regimes that challenge orthographic measurement as a primary tenet of architectural representation.

> *...the 1990s saw the development of several new ways to create points, including 3D scanning and particle-based physics simulations. In some cases these point sets included connectivity information, but in other cases they did not, leading to so-called point cloud data. Finally, new techniques had been invented for discretely approximating the operators of differential geometry, enriching the set of operations that could be applied to point-based representations of surfaces.* [3]
>
> —Marc Levoy- "The Early History of Point-Based Graphics"

In order to reconstruct an object's surface, one can start with several measuring techniques, for example, laser range finding, photogrammetry, or stereo or 3D scanners, which provide basic information about the location of points in space. Concerning these points, the term 'cloud' refers to the dense collection of points containing three or four coordinates, x, y, and z, plus color data, in relation to the point of origin. While points are common to most CAD packages, architectural software is often ill-equipped to reconstruct surfaces from a point cloud. The transfer of point data into a surface or a solid requires it to be processed into a 3d mesh. Similar to the resolution of a 2d image, the fidelity of a 3d object varies according to the density of the points used to register it.

The use of meshes presents significant challenges for beginning students. First, meshes require unique file management and workflows, given that they are typically in the form of patches or open solids. Meshes typically represent the surfaces of a building

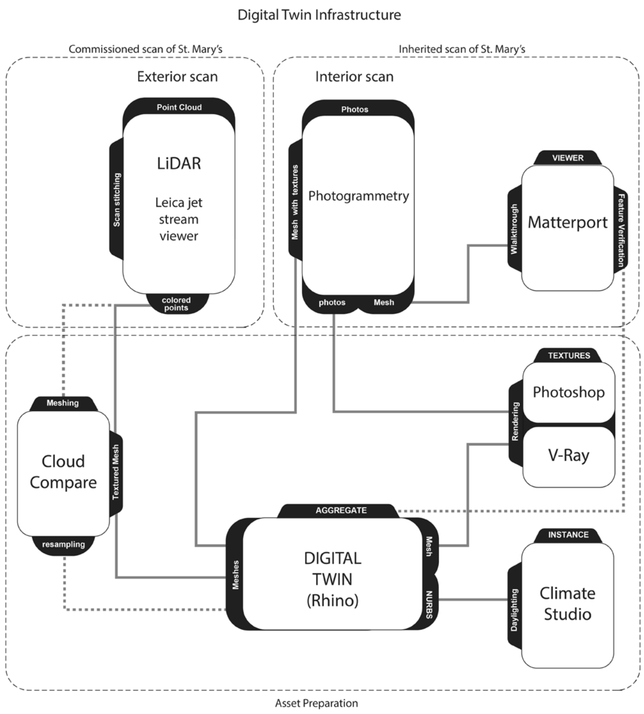

Figure 2. The Digital Twin infrastructure. The table tracks the data flow from the *LiDAR* point cloud scan and the photogrammetric scan to the different software platforms employed in the design studio. Table by author, 2021.

rather than discrete building elements that are commonly associated with solid modeling. The process of sorting the mesh into discrete objects is called semantic subdivision, and it represents an ongoing challenge in the field of computer vision. The second confusion arises concerning architectural scale. Typically, the disciplinary progression of architectural scales, from large to small scale, provides a structured path for design. A point cloud of a building represented through a higher or lower degree of resolution, where the architectural surface is visible to the same degree, overshadows the idea that design is a progression from lower degrees of resolution to higher degrees of refinement. Third, 3d scanning prioritizes resolution over dimension. A point cloud can be resampled or downsampled to produce a lower resolution model, which is helpful to the designer, but this requires other means and methods to extract critical building geometry. The process requires the filtering or sampling of the point cloud in order to remove extraneous information. Finally, the result of combining an interior scan with an exterior scan does not fully capture what lies within the walls, floors, and thickness of the building. Scanning reveals the *poché* as the occluded space that lies between the rooms. Andrew Saunders describes this aspect of the point cloud, writing, "To view the inside from the outside and the inside turned out paints a completely new understanding of the total working of the interior volume as a whole."[4] Now, it is possible to place the viewer inside the poché, behind the wall surface, where the scanner cannot reach.

The term 'digital twin' requires further context.

> *…the basic concept of the Digital Twin model has remained fairly stable from its inception in 2002. It is based on the idea that a digital informational construct about a physical system could be created as an entity on its own. This digital information would be a "twin" of the information that was embedded within the physical system itself and be linked with that physical system through the entire lifecycle of the system… The PLM or Product Lifecycle Management in the title meant that this was not a static representation, but that the two systems would be linked throughout the entire lifecycle of the system. The virtual and real systems would be connected as the system went through the four phases of creation, production (manufacture), operation (sustainment/support), and disposal.*[5]
>
> —Dr. Michael Grieves- "Origins of the Digital Twin Concept"

A twin may be derived from a 3d scan or originate as a 3d model. Digital twins have also led to significant advances in historic preservation and restoration. In architecture, digital twins collect data for post-occupancy evaluation, building forensics, and remote sensing, giving rise to a feedback loop and the ability to forecast improvements between the actual building and its virtual counterpart. For the studio, the information is the point cloud, the digital assets derived from it, including their reuse and partial disposal. In this case, the twin is employed to expand the student's sensibility for what exists in an actual building, including those aspects of the 'real' architecture which are typically added to the digital model, namely, color, material, finish, detail, aging, tectonics, and thickness as they exist in the field. The twin was introduced to promote collaboration allowing the model to be used to validate daylighting scenarios using other platforms. Over time, the objective is to introduce new learning objectives and promote integrative thinking by collecting data from the

Figure 3. *Matterport* screen capture of St. Mary's. The photogrammetric scan is accessible in a virtual viewer, enabling students to understand color, material, finish, take measurements, and make interactive walkthroughs of any room. Virtual model by Owen Bush & Scan2Plan, 2021.

Figure 4. A detail of the front facade of St. Mary's Church. Left, the painterly appearance of the colored point cloud. The *Cloud Compare* interface allows the points to be enlarged for viewing. Right, the facade details after reconstruction in the Rhino model. The point cloud of the exterior was sampled at different thresholds and used to make a NURBS model for *Rhino* and *Climate Studio*, 2020. Image by the author.

field. Additional development is needed to incorporate building sensors that would enable a feedback loop to demonstrate the relationship between the building's form, and its environment.

TEARING DOWN: SPOLIA AND REUSE

The information, detail, and resolution revealed through *LiDAR* technology transforms how we understand the architectural context. Contextualism, and contextual architecture, is now a principle of design in which a structure is not only designed in response to its specific urban and natural environment but, more precisely, to the elements that constitute its anatomy. The digital twin exposes the diversity of materials and objects, which are the by-products of a building's lifespan once demolished. According to the art historian Dale Kinney, "Recent studies of *spolia* have emphasized the connotative traces of the word's original meaning, "spoils" or war booty, an extension from "hide," the skin that is stripped away from an animal as armor is stripped from a defeated opponent."[6] The parallel here between the building's hide is relevant given that the laser can only obtain information at the surface while particular areas remain occluded from the scanner. Kinney continues, "The columns, capitals, friezes, and other embellishments that might be taken are generically designated by their material (marmora) or function (ornamenta, ornatus). Theoretically, there was a verbal category *spoliabilia*, but apparently the word was rarely used."[7] This civic network of *spoliabilia* was part of an effort to establish a reserve of ornaments and materials that could be repurposed when the imperial stone quarries could not meet demand.[8] Occasionally, stonework was repurposed for a different function, and as Kinney shows, there are ingenious examples of statuary being reversed and recut.[9] The significance of *spoliabilia* is its development into a civic and aesthetic enterprise. In cases of reuse, digital scanning provides a new medium to address many of the same concerns for reusing buildings and the potential to survey and ultimately salvage architectural materials. The twin made it possible to critically reflect on removing materials and the consequences of two seemingly innocuous keystrokes, *Backspace* and *Delete*. The premise of architectural *spolia*, or more generally, *spoliabila*, served as a framework for the studio to strategize the reuse of the church and its materials (Figure 1).

The renowned fixer and right to repair advocate Kyle Wines writes on the importance of repair culture and the need to understand how consumer objects operate internally so that we can fix them. He writes, "Taking apart the past and reassembling it for future generations is a question of empathy."[10] The twin provides a valuable real-world scenario and a multi-layered context for the studio. One takeaway from using the twin in the studio was not what it did well but instead the opportunity to learn from what it did poorly. For example, the lobby floor is positioned almost five feet above the sidewalk. Originally it was designed with stairs leading away from all of the exits, including stepped passages to the sanctuary. Accessibility became a problem for everyone to solve. The array of terraced floors, handrails, steps, baseboards,

Figure 5. The housing addition atop St. Mary's church includes a perforated rainscreen and light monitors. The balconies and alcoves are finished with the repurposed stone facings from the church. Image by Erica Eom & Sarah Weber, RPI SOA, AD4, 2021.

and thresholds demonstrate the idea that design negotiates multiple systems, including the need for accessibility. A similar learning opportunity arose concerning the functionality of the existing egress stairs to meet the new occupancy load and their fixed locations outside the sanctuary's walls. These constraints help to focus the learning objectives. Additionally, the twin was configured into elements to allow students to work intensively within the model to address the architectonics and the physical seam that exists in the church between the masonry and wood construction.

SCANNING AND THE DIGITAL TWIN

For budgetary reasons, a pre-existing photogrammetric interior scan was combined with a new *LiDAR* scan of the exterior. Both scan formats have benefits and drawbacks. Due to the laser, the resolution and color data obtained by the *LiDAR* scan make it superior when capturing the topography of complex surfaces. The resulting point cloud provides superior levels of resolution for the church's ornaments, windows, and stone coursing, even capturing the distortion and settlement of the roof and the exterior walls. While the *LiDAR* scan captures color data, the resulting textures can be 'foggy' when baked into textures maps, and they lack the clarity of the photogrammetric textures (Figure 4). Alternatively, photogrammetry uses a camera to capture high-resolution images of the surfaces that can be processed into a mesh using photo stitching software.[11] This scan was compiled in a 3d viewer enabling students to take a virtual tour through the building interior using a browser in *Matterport* (Figure 3). While photogrammetry does not capture topographic variations like a *LiDAR* scan, it is superior at capturing photo-realistic images of the finishes throughout the church. In preparation for the renderings, the students worked together. They divided up the exterior surface of the church to prepare photographic textures in *Photoshop* before mapping them back onto an instance of the twin. The registration of the photographs with the 3d scans changed the student's attitude toward the elevations, enabling them to work on the window surrounds, apertures, and coursing rather than tracing or imaging the orthographic projections in *Rhino.* Consequently, there was considerably more care and attention directed toward the materiality and resolution of the envelope when paired with the existing facades. Here additional skills were provided in allied courses to address more advanced texturing methods to handle recessed alcoves, ornament, and material transitions.

The exterior *LiDAR* scan of St. Mary's Church was acquired in a single day using a portable Leica digital scanner positioned around the church. The site presented two specific challenges. An aerial drone was used to capture the roof while shrubs and the neighboring building occluded some portions of the building. The individual scans were then stitched together by the vendor and delivered as a single point cloud containing 39 million data points, spaced roughly 1/16 of an inch apart and saved in LGS format. The Leica Jetstream Viewer was used to preview the cloud (Figure 2). The entire cloud was exported as a LAS file to *Cloud Compare*, an open-source 3d point cloud processing software, for trimming and cleanup.[12] Next, the points were grouped into smaller batches for processing. Several tests were run to determine the minimum number of points needed to provide a sufficient level of clarity to the edges of the building's geometry. The cloud was resampled to roughly 8.5 million points. A Poisson reconstruction was used to produce a mesh with roughly 11 million faces, the mesh normals were unified, and a space-filling function was used to fill the holes in the mesh. Once the file was imported to *Rhino*, it was used as a reference to model the individual parts of the building and verify key building dimensions. The modeling proceeds according to how many components are required. For pedagogical purposes, all window details and their surroundings, moldings, tracery, gutters, statuary, ornaments, stairs, structural walls, partitions, and floors were remodeled as NURBS geometry and organized by layer in *Rhino* according to the various systems.

The elements provided a firsthand opportunity to introduce students to the practice of organizing an architectural project file and how to share files in a team. Before the project commenced, the following concepts were introduced; 1. A point of beginning in both the plan and the section, along with the primary elevation datums, and 2. A classification system for organizing and hiding all of the different objects in the building. The time investment required to produce the twin was significant, lasting six weeks before a complete building model of the interior and exterior was ready (Figure 5). There were two significant challenges during the modeling phase. The first involved the alignment of the interior photogrammetric mesh with the exterior *LiDAR* data. Precise alignment was challenging given that there was no way to align the scans geometrically. Alignment was determined using the widows, and this resulted in several mismatches. Secondly, as is typical, information was missing in the blind spots between the two scans, and it was not possible to make a site visit due to the pandemic. Contents of the walls and floors had to be speculated upon based on the building materials. However, the scan made it possible to deduce the nature of most of the hidden construction. The roof trusses were not part of the scan, and they were constructed and later added to the model. The building was presented to the students as a composite. Consisting of a masonry base and two masonry towers, a wood roof, plaster interiors, and an exterior compromised primarily of granite facing and carved stone. With this came the design challenge to selectively remove no more than thirty percent of the church and reuse as much of the material as possible.

Design and simulation typically demand different file structures. Careful planning and selecting the most suitable format can maximize cross-platform exchanges. As a result, the studio employed two types of twins; digital twin instances (DTI) and a digital twin aggregate (DTA).[13] The aggregate comprises multiple instances that consist of smaller components; structure, datum, ornament, finishes, and work points. The twin makes it possible to export resources from the aggregate to develop a design infrastructure that has feelers across the curriculum. The compactness of the model is one of the pedagogical benefits of investing in the cost and time that comes with making a twin. The model requires additional investment and a multi-year plan to expand the applications of the twin from year to year. A twin instance was used to perform a daylight analysis on the church in an allied environmental course. This cross-curricular alliance requires extra time and resources before the exercise can commence. The DTA is a mesh model, and *Climate Studio* requires a NURBS model instance. This required extra modeling time and troubleshooting before it was shared with the teams of students. Once the file resources are in place, they can be shared between courses from year to year to investigate different types of simulations. Preparing a NURBS instance with considerably less detail reduces the processing time for daylight analysis, but it requires the proper wall depth. For analysis purposes, portions of data from both the interior and exterior scan were joined to achieve a watertight wall section that precisely captures the different thicknesses of the church's exterior. It is important to remember that instances need to be constructed to be deployed as a design tool rather than a dead instance. Editable models ensure that the model can be easily modified to test different daylighting scenarios.

CONCLUSION

The initial investment of time and expense to develop a digital twin is significant. Acquiring the scan, preparing the model assets, constructing the textures, and preparing the necessary instances for analysis and fabrication require considerable resources and skills. However, once completed, the twin can evolve with the curriculum to address new concepts over several years. A digital twin is indispensable as a medium for making observations concerning the layers of construction within a building. The twin provoked curiosity about the church's construction and the need for a better understanding of the assemblies and the layering of primary, secondary, and tertiary layers of construction. Scanning provides a level of realism and specificity to the building's materiality, structure, color, and finish that is engaging to the students and unrivaled in its detail. The integration of the twin in the second year of the BArch program ultimately led to a richer and more diverse set of projects. The context played a decisive role in the student's decision-making, including strategies for daylighting, accessibility, egress, testing various housing typologies, adaptive reuse, and selective demolition. The twin's presence, the inability to make physical models due to COVID-19, and the fixed footprint of the church resulted in the students spending less time modeling and more time working through the design of the housing using two-dimensional plans.

Design pedagogy must acknowledge that these technologies have surpassed orthographic drawing in their ability to represent a building, and core education needs to address the shift. Teaching students to design by sampling information already demands a new set of foundational skills, and it has begun to provide a new career path for young architects. Finally, the ornate construction of St. Mary's and the level of detail of the twin make it possible to introduce the students to a multitude of non-standard window and stone details that would have been otherwise impossible. With the increasing emphasis on integrative thinking, embodied energy, and environmental analysis, the roles of a digital twin, will continue to expand in practice and academia as a means to reimagine how we manage, design, and repurpose architectural resources in the future. The reality that we can capture a complete building from the environment is a critical step forward in reimagining a buildings' design for disassembly. These affordances should be at the forefront of how we share information across academia, building science and the profession.

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ENDNOTES

1. "What is a digital twin?" Matterport, accessed February. 27, 2022, https://matterport.com/what-digital-twin.
2. John May, *Signal. Image. Architecture*. (New York: Columbia Books on Architecture and the City, 2019), 45.
3. Marc Levoy, "The Early History of Point-Based Graphics", in *Point-Based Graphics,* (Amsterdam: Morgan Kaufmann, 2007), 16. Accessed online February 28, 2022, https://folk.uib.no/zir001/files/pointclouds/%5BGross%20 2007%5D%20Point-Based%20Graphics%20(Book).pdf.
4. Andrews Saunders, *Baroque Typologies*, (Modena: Palombi Editori, 2018), 61.
5. Michael Grieves, "Origins of the Digital Twin Concept," (2016), 2-3, accessed February. 27, 2022, 10.13140/RG.2.2.26367.61609.
6. Dale Kinney, "'SPOLIA. DAMNATIO' AND 'RENOVATIO MEMORIAE.'" *Memoirs of the American Academy in Rome* 42 (1997): 117–48. https://doi.org/10.2307/4238749.
7. Kinney, "'SPOLIA. DAMNATIO' AND 'RENOVATIO MEMORIAE,'"121.
8. Kinney, "'SPOLIA. DAMNATIO' AND 'RENOVATIO MEMORIAE,'"124.
9. Kinney, "'SPOLIA. DAMNATIO' AND 'RENOVATIO MEMORIAE,'"118.
10. Kyle Wiens, "The Repair Revolution," in *Things Come Apart: A Teardown Manual for Modern Living*, by Todd McLellan, (London: Thames & Hudson, 2014), 40-42.
11. Regarding the theoretical differences between photogrammetry and laser scanning, see Michael Young, *Reality Modeled After Images: Architecture and Aesthetics after the Digital image*, (New York: Routledge, 2022), 55-60.
12. "Cloud Compare User Manual v2.61," accessed online, October 8, 2021, http://www.cloudcompare.org/doc/qCC/CloudCompare%20v2.6.1%20-%20User%20manual.pdf.
13. Grieves, "Origins of the Digital Twin Concept," 4.