Completions: Reuse and Object Representations

Citation for the original published paper (version of record):
Norell, D., Rodhe, E., Hedlund, K. (2020). Completions: Reuse and Object Representations. Proceedings of the 40th Annual Conference of the Association for Computer Aided Design in Architecture: Distributed Proximities, ACADIA 2020, 1: 446-455

DISTRIBUTED PROXIMITIES
PROCEEDINGS OF THE 40TH ANNUAL CONFERENCE OF THE ASSOCIATION FOR COMPUTER AIDED DESIGN IN ARCHITECTURE
VOLUME I: TECHNICAL PAPERS, KEYNOTE CONVERSATIONS

Editors
Brian Slocum, Viola Ago, Shelby Doyle, Adam Marcus, Maria Yablonina, Matias del Campo

Copy Editing
Rachel Fudge, Mary O'Malley, Paula Wooley

Graphic Identity
Adam Marcus, Viola Ago, Alejandro Sánchez Velasco

Graphic Design
Alejandro Sánchez Velasco

Layout
Carolyn Francis, Sebastian Lopez, Shelby Doyle, Adam Marcus

Printer
IngramSpark

ISBN 978-0-578-95213-0

Completions

Reuse and Object Representations

Daniel Norell
Chalmers University of Technology, Norell/Rodhe

Einar Rodhe
Konstfack University of Arts, Crafts, and Design; Norell/Rodhe

Karin Hedlund
Chalmers University of Technology

1 Completions of salvaged building elements and materials. Window frame (left), door panel (middle), and mantelpiece (right).

ABSTRACT

Reuse of construction and demolition waste tends to be exceptional rather than systemic, despite the fact that such waste exists in excess. One of the challenges in handling used elements and materials is integrating them into a digital workflow through means of survey and representation. Techniques such as 3D scanning and robotic fabrication have been used to target irregular geometries of such extant material. Scanning can be applied to digitally define a unique rather than standard stock of materials or, as in the field of preservation, to transfer specific forms and qualities onto a new stock. This paper melds these two approaches through *Completions*, a project that promotes reuse by integrating salvaged elements and materials into new assemblies. Drawing from the ancient practice of reuse known as *spolia*, the work develops from the identification and documentation of a varied set of used entities that become points of departure for subsequent design and production of new entities. This involves multiple steps, from locating and selecting used elements to scanning and fabrication. Three assemblies based on salvaged objects are produced: a window frame, a door panel, and a mantelpiece. Different means of documentation are outlined in relation to specific qualities of these objects, from photogrammetry to image and mesh-based tracing. Authentic qualities belonging to these elements, such as wear and patina, are coupled with more ambiguous forms and materialities only attainable through digital survey and fabrication. Finally, *Completions* speculates on how more automated workflows might make it feasible to develop extensive virtual catalogs of used objects that designers could interact with remotely.

INTRODUCTION

Construction and demolition waste makes up approximately one-third of all the waste generated in the European Union (EU). According to the EU Waste Framework Directive, member states shall ensure that 70% of all such nonhazardous waste is reused, recycled, or recovered (Directive 2008/98/EC). The aim is to reuse as much as possible, as reuse has an environmental advantage over recycling or recovery. Recently issued guidelines concerning demolition stress the importance of dismantling strategies to enable reuse of, for example, steel, glass, marble, wood, and window frames (European Commission 2016). Valuable elements or materials such as these should be removed before demolition, while usable but less valuable entities might be identified after demolition. Ideally, the process of reuse starts with a waste audit in which elements and materials in an existing building are inventoried. Reuse of elements is preferred over reuse of materials, as elements are of a higher order than materials. A dismantled element that cannot be reused is broken down into its constituent materials. Similarly, reuse is preferred over recycling as recycling involves wasting and reprocessing of materials. Construction waste is in this sense of a lower order, as it often consists of cutoffs and packaging.

Historically, reuse of building elements has been prompted by a scarcity of resources, as the supply of materials was conditioned by means of transport and capabilities of local craft. To reuse simply required less effort than to extract. Today, the world is full of buildings, elements, and materials. Yet reuse is still largely exceptional. One among many factors that currently conditions reuse in architecture and construction is means of representation. Methods for digital survey such as scanning make it possible to integrate an irregular stock of entities into a digital workflow for design and fabrication. Further, such means of representation grant a designer remote access to the often-unique qualities that belong to used elements and materials.

In targeting issues of reuse and representation, this paper brings together methods from two lines of research. First, digital survey and fabrication of nonstandard materials, and second, experimental preservation of artefacts. Through the design project *Completions*, the paper proposes an approach to reuse where building elements and materials are integrated into new assemblies by means of 3D scanning and computer numerically controlled (CNC) fabrication. By surveying and "completing" elements and materials found in a state of disrepair with adjoining parts, the research focuses on two aspects: first, the fidelity as well as the residual effects of scanning as a means of survey, and second, the pairing of used and adjoining elements, including fabrication as well as the transfer of qualities between them. Drawing from the ancient practice of reuse known as *spolia*, the work develops from the identification and documentation of a varied set of objects that later become points of departure for subsequent design and production of new entities.

NONSTANDARD MATERIALS AND REMATERIALIZATION

Standard materials as well as readily available products are typically made available to a designer through online catalogs. The catalog grants remote access to entities in it through images, graphics, and data, and these allow an architect to integrate qualitative as well as quantitative aspects of objects into drawings and models, often including digital models complete with material finishes. Similarly, a building element for reuse must be surveyed and documented before it can be incorporated into a digital workflow. Its dimensions are typically both given and nonstandard, and additionally, its architectural qualities may go beyond what can be captured with conventional digital modeling.

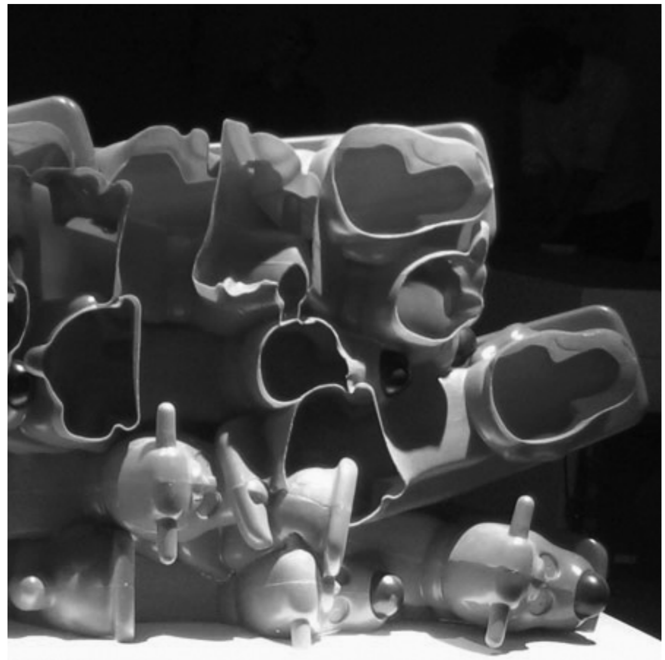
The challenges that pertain to material standards have not gone unnoticed within the realm of digital practice. A large swath of work has focused on overcoming limitations of a standardized stock of materials by using fabrication to produce "nonstandard architectures" from standard materials such as bricks, lumber, or sheet materials. More recently, architects have turned representation and fabrication processes onto extant and nonstandard materials, often with the aim of harvesting and manipulating specific qualities that such material may possess. This entails a larger shift in mindset, from considering materials as an abundant and malleable resource to considering them as a limited and specific set of entities that come with properties and character. Two approaches can be outlined in relation to these recent developments.

One line of inquiry seeks to expand the repertoire of materials and effects available by integrating a unique and often irregular stock of materials into a digital workflow. Greg Lynn's pioneering "Recycled Toy Furniture" used 3D scanning to capture a stock of used plastic toys (Lynn 2009). The scanned toys were assembled by digitally positioning and rotating them in relation to each other so that intersections could be obtained, and fits between entities were accommodated through Boolean operations and robotic carving (Fig. 2). Several recent projects have similarly used structured light scanning or photogrammetry to document entities such as tree branches (Devadass et al. 2016), concrete rubble (Clifford and McGee 2018), or bamboo sticks (MacDonald, Schumann, and Hauptman 2019) for the purpose of fitting them to each other. Such workflows tend to be optimized in relation to a particular logic of fabrication and assembly, based on, for example, nodal joints or masonry logics. While these projects all have advanced the use of scanning in relation to a unique stock of materials, none of them target reuse of building elements or materials.

The scanning process's ability to capture and transfer finer nuances in form, texture, and color is of varying relevance in this type of work. In Lynn's project, scanning is used to mine and expose formal features belonging to the toys. In Brandon Clifford's and Wes McGee's "Cyclopean Cannibalism" masonry wall, on the other hand, scanning is used to define a stock geometry based on concrete rubble into which a new geometry can be fitted. This results in all surfaces of the rubble being carved, thus limiting the visual impact of captured forms on the end result.

Particular techniques for representation can be leveraged against the need for visual and dimensional apprehension and a specific fabrication process. Photogrammetry, the technique used in the research presented here, captures overall geometry as well as texture and color, making it ideal for identifying marks and signs of age. However, the resulting geometry does not come with a set scale, and it tends to be slightly less reliable in its overall measurements compared to laser scanning. Further, specifics of geometry, surface finish, or just the sheer quantity of material might make scanning impractical or too data intensive to use. For planar elements such as sheets, or linear elements such as sticks (MacDonald, Schumann, and Hauptman 2019), photography and edge detection through image processing have instead been used to obtain a two-dimensional outline of an element.

Another line of inquiry involves scanning for rematerialization, or transfer, of forms and qualities from an existing entity onto a new stock. In adaptive reuse, laser scanning is typically used to acquire a model of buildings for the purpose of fitting new elements to unique existing elements through fabrication (Buthke et al. 2020). Recent examples of experimental preservation, such as work in the exhibition *A World of Fragile Parts*, curated by Brendan Cormier (Cormier and Thom 2016), use scanning and fabrication to document and reproduce significant artefacts. Work by David Gissen or Factum Arte complements traditional conservation of such artefacts with the production of replicas. These projects employ techniques and methods that can be used towards representing, mending, or extending used elements and materials. The scanning process's ability to capture and transfer finer nuances of form, texture, and color is essential to this category of work.



2

3

2 Greg Lynn FORM, Recycled Toy Furniture, 2008.

3 Spolia columns and entablature in Santa Maria in Trastevere, Rome, 1140–1148.

While informed by both categories, our work takes a different approach, in which the identification and scanning of a varied set of used elements and materials becomes a point of departure for subsequent design and fabrication of new entities that are combined with the used ones. Our focus has not been on developing a system for a specific type of element or material but rather on developing a workflow that can harvest a multitude of qualities of used entities.

SPOLIA: INCONGRUOUS ASSEMBLIES

The practice of reuse can involve an opportunistic outlook in which used building elements and materials are explored for qualities that may go beyond their intended use. Such "creative" reuse of building elements and materials may not be systemic or institutionalized today, but this has not always been the case. In the late Roman Empire, marked by economic downturn, a practice of reuse emerged that came to be known as *spoliation*. Spolia were building elements sourced from antique buildings in a state of disrepair that were fitted with other parts in the construction of a building on a different site. As Maria Fabricius Hansen (2015) explains, this resulted in a peculiar synthesis of old and new where aesthetic variation was favored over uniformity. Surprising and sometimes incongruous combinations of pieces from different sources were assembled intentionally, and the design and crafting of new pieces were often influenced by the characteristics of the spoliated ones (Fig. 3).

Remarkably, this practice of reuse was state-sanctioned, and legislation suggests that Romans viewed the city as a common material repository, where materials would circulate between buildings. Reuse was regulated based on civic needs with the aim of making the most of material resources and minimizing the need for transportation. According to Joseph Alchermes (1994), The Code of Theodosian (389 AD), for example, protected public buildings from ruination for private purposes. Other laws limited new construction if there was a need to repair old but well-functioning public buildings. When new construction was necessary, the state would often allocate materials for reuse rather than allocate funds. Sourcing of elements and materials within local geographical regions was supported with storage facilities that could house significant structural or decorative elements in transit between buildings (Alchermes 1994).

The technical challenges involved in spoliation included transport and handling, and machinery for lifting and transporting massive blocks of stone had to be invented. The structural integrity of the stone was an issue, but mostly in relation to handling during construction, when fracturing might occur. Spolia is noteworthy in the context of digitally enabled reuse because of the pairing of playful, ad hoc aesthetics with the implementation of systems for sourcing, distributing, and assembling used elements and materials. The inventive combinations of found and new entities promoted through spoliation point to new and untapped opportunities for reuse offered by means of digital survey and production.

4

5

6

4 Suggested workflow for reuse of building elements and materials.

5 Fragments of window frames at demolition site.

6 Door panel on display at reuse market.

COMPLETIONS

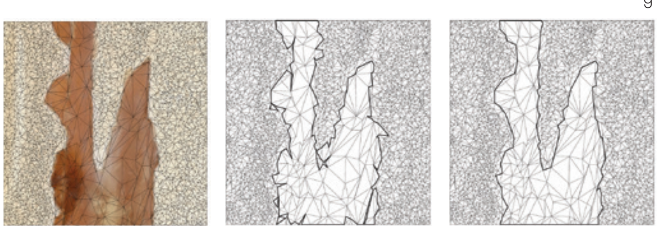
Completions is a response to technical as well as aesthetic issues surrounding contemporary reuse of building elements and materials. While the project promotes a systematic workflow, it challenges a prevailing systems aesthetic in digital practice that relies on repetition of self-similar components. It develops an alternative design position based on the act of repairing, adjusting, and assembling—a formal and material vocabulary that can negotiate fractures, missing parts, patina, misalignment, and abrupt cuts, etc. The three *Completions* pieces described in this section were conceived to reflect this position.

The process of reuse amounts to a workflow (Fig. 4) with an extended engagement with a stock of materials, often beginning with visits to local outlets for used or wasted materials (Figs. 5, 6). Once a stock has been defined, methods for survey and fabrication need to be continuously tuned in relation to varying forms and qualities. The stock establishes an economy of means as well as an element of serendipity that conditions much of the subsequent work.

7

8

9



10

7 Photogrammetry scanning process to obtain a closed mesh model. Greenscreen photograph of window frame.

8 Geometry of window frame obtained with photogrammetry (cropped). Closed mesh model with image map.

9 Flatbed scanning of sawn-off ends of window frame for extraction of profile vector drawings.

10 Polygonal face selection methods for tracing of boundaries on door panel: Reduced colored mesh obtained with photogrammetry (left). Selection of faces based on face area (middle). Selection of faces based on color (right).

Stocking Up

Collecting a stock of used or discarded materials and building elements is not trivial, since reuse in the design or building industry is not generally implemented and relies on a variety of independent actors. Generally speaking, three categories of entities can be defined in relation to how construction and demolition waste is handled (European Commission 2016). Each category was considered in the sourcing of material for *Completions*. *Stripping* is the dismantling of more valuable elements and materials before demolition, and such elements may end up for sale in various local outlets. *Scavenging* is the separation of less valuable elements and materials after demolition, and this kind of waste typically goes to recycling stations. *By-products* are leftover materials from manufacturing and construction processes, such as cutoffs and packaging. By-products or elements that are located through scavenging are often damaged and destined for lower-order recycling, recovery, or landfill.

Used objects for completion were located through a series of stock visits to different outlets (Figs. 5, 6). Objects were selected based on qualities such as size (manageability), form (linear, surface, mass), materiality (texture, color, signs of age), and identity (recognizable as a particular material or type of element). One side of a door panel with panel moldings was bought from a reuse market. Part of a wooden window frame was salvaged from a demolition site. A visit to a stone manufacturer gave access to fractured cutoffs from marble sheets. The selected pieces were understood as incomplete fragments rather than as whole objects.

Survey and Postprocessing

Different approaches to documenting each piece were taken depending on the condition it was in, and on its overall geometry, from 3D scanning with photogrammetry to 2D tracing.

For the purposes of scanning, objects were photographed against a green screen and rotated incrementally to achieve

11 Window frame: Isometric of digital model obtained with photogrammetry (top left). Door panel: Elevation of digital model obtained with photogrammetry (right). Marble sheets: Elevation of photographed sheets assembled into mantelpiece, with trimmed parts indicated with dashed lines (bottom left).

a set of images that covered all areas of their surface (Fig. 7). Prior to photogrammetric processing, the green pixels were removed from each image through semi-automatic masking. This method meant that entire objects could be scanned in one session, eliminating the need to combine point clouds that result from scans of different sides of objects (front, back, top, bottom). In addition, it eliminated the typical interference from the background surface that objects are resting on, making it possible to process the point cloud into a closed mesh geometry (Fig. 8).

For some entities, such as the cutoff marble sheets, 3D scanning proved to be cumbersome. While photogrammetry can aptly capture the coarsely textured surface of a fractured edge, the smooth planar surfaces might have problems registering accurately due to glare. In these cases, more appropriate and resource-efficient methods for documentation were considered. Marble sheets were photographed in an elevational view and edges were subsequently extracted as vector drawings with image processing. Similarly, dimensions and profiles of the sawn-off ends of the window frame were obtained using flatbed scanning (Fig. 9).

In other cases, fabrication and finishing processes required that visually distinct regions on surfaces were identified. Dark areas of worn-off paint on the door panel could be separated from the scanned mesh using polygonal face selection methods (Fig. 10). Initial tests using area-based selection of faces in the scanned mesh were abandoned in favor of color-based selection that produced more accurate results. Using these techniques, locally damaged, blemished, or otherwise distinct regions could be identified and taken into consideration in further work.

These ways of representing objects couple visual and dimensional aspects, thereby forming a basis for both design and fabrication. They grant remote access to qualities such as materiality and patina that otherwise tend to elude standard means of architectural representation.

12 Completion of salvaged window frame. CNC-routed solid pine wood.

Modeling and Fabrication

Three pieces were developed based on the window frame, the door panel, and the marble sheets. The design of these pieces was guided by the identity and the state of disrepair that the collected pieces were in. Taking cues from spolia, the completions balanced dutiful mending with add-ons playfully conceived in the manner of an exquisite corpse.

A set of curves derived by connecting edges on two of the window frame's sawn-off ends created a sweeping figure that seamlessly bridged between those ends (Fig. 11). Some of the edges stemmed from the original profile of moldings, while others came from intersections with random fractures where the piece had broken during dismantling. The smooth, interpolated surfaces of the completing piece were both continuous and at odds with the rough materiality of the reclaimed piece (Figs. 1, 12).

The other, missing side of the door panel was added by creating a mirrored replica of the original (Fig. 11). Using the mesh geometry acquired with scanning, a new door panel was fabricated that included worn-off paint and other damages inflicted on the original during its past life. As a residual result of the scanning process, a slight geometrical noise traveled across its smooth white surfaces, making them less crisp and legible than on the original. Because of the symmetry with the completing piece, the status of the spots with worn-off paint seemed to shift, from accidental marks to intentional and ordered articulation (Figs. 1, 13).

The marble sheet cutoffs amounted to a collection of fragments that did not suggest a specific object. By considering straight edges and fractured edges of the sheets, a puzzle of matching edges was created in the form of a mantelpiece (Fig. 11). A few cuts were placed in order to improve the fit between adjacent pieces. Some cuts were straight, while others followed the irregular edge of an existing crack so that a tight fit with a fractured edge of another sheet could be obtained (Figs. 1, 14, 15).

13 Completion of salvaged door panel. CNC-routed solid pine wood.

The process of survey and fabrication made it possible to create seams and formal continuities between and across pieces, and in addition to create new pieces that mimicked the found ones by using the scanned mesh as a basis for fabrication. Materials and fabrication principles were kept consistent within each of the three completed pieces. CNC-routed massive pinewood was used for the window frame and the door panel, and the stone fragments were cut with a waterjet.

By completing it, a used or salvaged object is turned into a new enigmatic entity that seems to be neither wholly repurposed nor newly manufactured. The authentic qualities belonging to these objects, such as materiality, wear, and craft, are paired with more ambiguous forms and materialities only attainable through digital survey and fabrication. The completions playfully adopt the identity or function of a found object while simultaneously suggesting new unexpected possibilities. They depart from a selection of objects but do not end in readymades or as mere agglomerations of such objects.

RESULTS AND DISCUSSION

The results of the *Completions* project form a basis for further research on productive means of representation for integrating extant material into digital workflows.

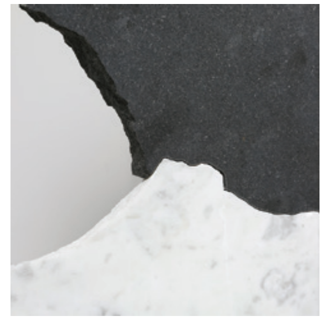
While *Completions* promotes reuse of building elements, it simultaneously recognizes difficulties associated with such practice. In principle, if an element is reused repeatedly, it will slowly be exhausted to a point where it is reduced to its material. Wear as well as damage inflicted during stripping or demolition will eventually cause deterioration. A completion can make it possible to reuse an element or piece of material that would otherwise go to lower-level recycling, recovery, or landfill. Such a process might require the injection of new material into the stream, but this injection can be weighed against the amount of material that would otherwise have been wasted.

The exactitude and rich materiality of models obtained with scanning can provide an alternative to the “layers of abstraction” that, according to Maarten Gielen of reuse practice Rotor, come with typical CAD drawings (Borasi, Gielen, and Pantazis 2018). The scanning process, unlike the eye of a human conducting a survey, does not discriminate between categories of objects or between what has been intentionally designed and what is circumstantial. It simply captures an object in the state in which it is found, including color and texture. This ability to “see” objects devoid of human preconception resonates with a speculative reuse practice that seeks to go beyond the reduction of waste by mining used objects for their qualities and transferring these qualities into new entities. In addition, scanning can distance an object from its original context and function, thereby opening up alternative possibilities for use and interpretation.

Further research will combine visual qualities acquired with photogrammetry with cross-sectional assessment in order to detect fractures or other defects that could affect structural capacity. Examples of nondestructive assessment methods used today include industrial radiography and ultrasonic testing (mainly for steel constructions) and resistograph inspections (for wood). The virtual model of a salvaged object could be informed by this kind of data in order to simulate its structural capacities.

The research presented here amounts to an approach and a workflow as well as a few design pieces. A systemic application of principles outlined in this paper will require further research regarding the representation and indexing of used entities. Developing more robust workflows for scanning could make it feasible to develop

14



15

14 Marble sheet cutoffs assembled into mantelpiece.

15 Detail of fit between fractured edge (white) and edge cut with waterjet (black).

extensive virtual catalogs of used elements that architects could interact with remotely during the design process. In order to be searchable, such catalogs might benefit from the automatic recognition of different types of objects, their features, and constituent materials. Deep learning is currently applied to classify images and video based on architectural elements that they depict (e.g., Kim, Song, and Lee 2019). Overall, these further developments might in turn allow for the design and coordination of larger assemblies where a multitude of elements and materials are combined.

CONCLUSIONS

Completions explores the potential of digital technology for reuse by coupling photogrammetry with fabrication. The aim is twofold: to reduce waste by intercepting existing streams of elements and materials, and to mine such elements for their architectural qualities. The project targets three categories of entities from construction and demolition processes, including elements and materials that result from stripping and scavenging, as well as manufacturing by-products. Methods for representation and fabrication are adopted and fine-tuned in relation to the specific geometries, features, and state of each type of element or material. The work presented is a first test of an approach that brings together methods and thinking from digitally enabled reuse as well as from experimental preservation of artefacts.

Targeting reuse through means of representation can be viewed as an attempt to challenge larger ingrained habits of architectural design. Point clouds, meshes, and image maps obtained with scanning place unique characteristics of objects at the center of the designer's attention. These means of representation assign as much weight to qualities such as materiality, texture, and color as they do to overall form or proportion, properties that architectural representations normally foreground.

ACKNOWLEDGMENTS

This research is funded by the ARQ Foundation, C-ARC at Chalmers University of Technology, and Konstfack University of Arts, Crafts and Design. *Completions* was designed by Daniel Norell and Einar Rodhe, in collaboration with Karin Hedlund. The project was fabricated with the support of workshops at Chalmers and Konstfack. The authors wish to thank the anonymous reviewers for valuable comments.

REFERENCES

Alchermes, Joseph. 1994. “Spolia in Roman Cities of the Late Empire: Legislative Rationales and Architectural Reuse.” *Dumbarton Oaks Papers* 48: 167–178.

Borasi, Giovanna, Maarten Gielen, and Konstantinos Pantazis. 2018. ”Specifying from a Broader Catalogue.” Canadian Centre for Architecture, September 19, 2018. https://www.cca.qc.ca/en/articles/issues/24/into-the-material-world/53665/specifying-from-a-broader-catalogue.

Buthke, Jan, Niels Martin Larsen, Simon Ostenfeld Pedersen, and Charlotte Bundgaard. 2020. “Adaptive Reuse of Architectural Heritage.” In *Impact: Design With All Senses, Proceedings of the Design Modelling Symposium* (Berlin 2019), 59–68.

Clifford, Brandon, and Wes McGee. 2018. “Cyclopean Cannibalism: A Method for Recycling Rubble.” In *ACADIA 2018: Recalibration: On Imprecision and Infidelity [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Mexico City, Mexico, 18–20 October 2018, edited by P. Anzalone, M. del Signore, and A. J. Wit, 404–413. CUMINCAD.

Cormier, Brendan, and Danielle Thom, eds. 2016. *A World of Fragile Parts*. London: V&A Publishing.

Devadass, Pradeep, Farid Dailami, Zachary Mollica, and Martin Self. 2016. “Robotic Fabrication of Non-Standard Material.” In *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines [Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Ann Arbor, MI, 27–29 October 2016, edited by K. Velikov, S. Ahlquist, M. del Campo, and G. Thün, 206–213. CUMINCAD.

Directive 2008/98/EC. The European Parliament, Council of the European Union. Article 11.2. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN.

European Commission. 2016. EU Construction & Demolition Waste Management Protocol. https://ec.europa.eu/docsroom/documents/20509/attachments/1/translations/en/renditions/native.

Fabricius Hansen, Maria. 2015. *The Spolia Churches of Rome*. Translated by Barbara J. Haveland. Aarhus: Aarhus University Press.

Kim, Jinsung, Jaeyeol Song, and Jin-Kook Lee. 2019. “Approach to Auto-Recognition of Design Elements for the Intelligent Management of Interior Pictures.” In *CAADRIA 2019: Intelligent & Informed, Proceedings of the 24th Conference for Computer-Aided Architectural Design Research in Asia* - Volume 2, 785–794.

Lynn, Greg. 2009. “Recycled Toy Furniture.” *Architectural Design* 79 (2): 94-95.

MacDonald, Katie, Kyle Schumann, and Jonas Hauptman. 2019. “Digital Fabrication of Standardless Materials.” In *ACADIA 19: Ubiquity and Autonomy [Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)]*, Austin, TX, 21–26 October 2019, edited by K. Bieg, D. Briscoe, and C. Odom, 266–275. CUMINCAD.

IMAGE CREDITS

Figure 2: © Greg Lynn FORM.
Figure 3: © Camilla Borghese.

All other drawings and images by the authors.

Daniel Norell is Senior Lecturer in architecture at Chalmers University of Technology and cofounder of Norell/Rodhe. His design work and research, often undertaken with Einar Rodhe, focus on reuse, representation, and material agency. Their research has received support from the Swedish Research Council, C-ARC, and Architecture in the Making at Chalmers, the ARQ Foundation, and the Swedish Arts Grants Committee.

Einar Rodhe is an architect and Senior Lecturer in interior architecture and furniture design at Konstfack University of Arts, Crafts and Design, and cofounder of Norell/Rodhe. The work of Norell/Rodhe has been exhibited at Venice Architecture Biennale, Yale University School of Architecture, Oslo Architecture Triennale, and Arkdes, Sweden’s National Centre for Architecture and Design.

Karin Hedlund is a member of the research group Chalmers Architecture + Computation, cofounder of hedlund/ekenstam, architect at White Arkitekter and a returning workshop leader at the Architectural Association. Hedlund has received funding from the ARQ Foundation, Barbro Osher Pro Suecia Foundation, Carl Larsson Foundation, and FFNS SWECO Foundation. Her design work and research focus on reuse, representation, robotics, and material agency.