Reclaiming Construction Waste

An interface for robotic stacking of irregular components in compression-only structures

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Construction and demolition activities generate approximately one billion tons of waste every year in the world. While the majority of these materials can be either reused or recycled, they are often disposed of in landfills which leads to long-term environmental issues. This thesis investigates the reuse of construction and demolition waste through robotic stacking of irregular components in compression-only structures. Previous works have emphasized the environmental and economic benefits of using as-found materials, however, the practicality of this strategy has remained low due to increased complexity of non-standard waste components and their assembly systems. This research attempts to tackle this issue by employing an adaptive and automated stacking workflow. A mechanism is designed with off-the-shelf technologies to enable a six-axis collaborative robot with perception, real-time physics simulation, and motion planning. Two compression-only structures, a column and a wall, are digitally prototyped to assess the efficiency and usability of the interface. Reclaiming waste materials through an adaptive fabrication process can benefit the construction industry by minimizing residue, reducing costs, and decreasing the environmental footprint of buildings. Moreover, this interface can be used to build durable disaster relief shelters and enable construction during expeditions to inaccessible locations.

Acknowledgements

I would like to express my sincere gratitude to my father, mother, and brother for their unwaivering support and unmeasurable sacrifice that enabled my studies.

I would like to express my deepest appreciation to my advisor, Maya Przybylski, for her guidance and patience.

Thank you to my committee, David Correa for his enthusiasm and support.

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F.1. A dry-stacked wall made of construction waste as a result of a physical experiment in this research.

#SUSTAINABLE

#CONSTRUCTION

#WASTE

#MANAGEMENT

#RECLAIM

#ROBOTICS

#FABRICATION

#COMPUTATION

#ADAPTIVE

#COLLABORATIVE

From apes to Neanderthals, to the modern man, evolution has been an inseparable part of our reality. A change that has affected our appearance, diet, and lifestyle. Over time, we have learned to communicate, gain knowledge, and pass this knowledge to others. We have learned to make tools to hunt and protect ourselves in the wild. We invented the wheel, clock, steam engine, the airplane, and computers. Robots and Artificial Intelligence are of our most recent tools, rapidly evolving and becoming more capable every day. But how do we use these modern tools? Is it possible to use these machines for creating a better future?

Advances in technology can be both scary and promising. One can imagine the world being taken over by robots as portrayed in Terminator movies [1] *or we can picture a different scenario where technology helps us build a more sustainable future, perhaps an Ecotopia* [2]*. I focus on the latter, I believe these tools can be used to resolve not all, but many of the new and old issues. In this thesis, I will be studying an old problem with a new approach, hopefully, taking a step towards a greener future.*

1. James Cameron, The Terminator, Action, Sci-Fi (Cinema '84, Euro Film Funding, Hemdale, 1984).

2. "Ecotopia," in WordSense.Eu, accessed June 4, 2020, http://www.wordsense.eu/ecotopia/.

Outline

Modern construction industry uses a significant amount of engineered and processed materials. In order to create high-performance structures, this practice consumes raw materials and energy, producing excessive amounts of waste which can be detrimental to our ecosystem. Figure F.2 portrays construction waste as a result of demolition activities.The generated construction and demolition (C&D) waste are handled through a multitude of strategies with different levels of effectiveness. In many cases, re-using waste is more environmentally-friendly than recycling, composting, incinerating, or landfilling these materials. [3] This strategy is a form of material reclamation that has been done repeatedly throughout the history for structural, cultural, and aesthetic purposes. However, using reclaimed components as the primary construction material can raise a few challenges including complex assembly systems. Thanks to the current advancements of technology, these difficulties can now be overcome. [4] This thesis investigates the possibility of reclaiming construction waste through the development of an automated design to assembly workflow that uses machine-vision, physics-simulation, and robotic manipulators to stack irregular salvaged material in a self-supporting structure.

An estimated 1.3 billion tons of waste is produced annually in the world. This amount of waste - equivalent to the weight of 10000 CN-Towers - is expected to double by the year 2025.[5] According to figure F.3, developed countries such as the United States and Canada have the highest municipal solid waste production per capita. Municipal solid waste includes materials that are disposed from homes, businesses, and construction and demolition sites. [6] A 2017 study reports that the United States have produced over 500 million tons of C&D waste while Canada has generated approximately 10 million tons of residue. [7][8] These rejected materials can be used as primary resources in a circular economy. [9]

3. Erik K. Lauritzen, Construction, Demolition and Disaster Waste Management: An Integrated and Sustainable Approach (Boca Raton: Taylor & Francis, a CRC title, part of the Taylor & Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, 2019).

4. Dirk Hebel, Marta H. Wisniewska, and Felix Heisel, Building from Waste: Recovered Materials in Architecture and Construction (Basel: Birkhäuser-Verl, 2014).

5. Hebel, Wisniewska, and Heisel, 7.

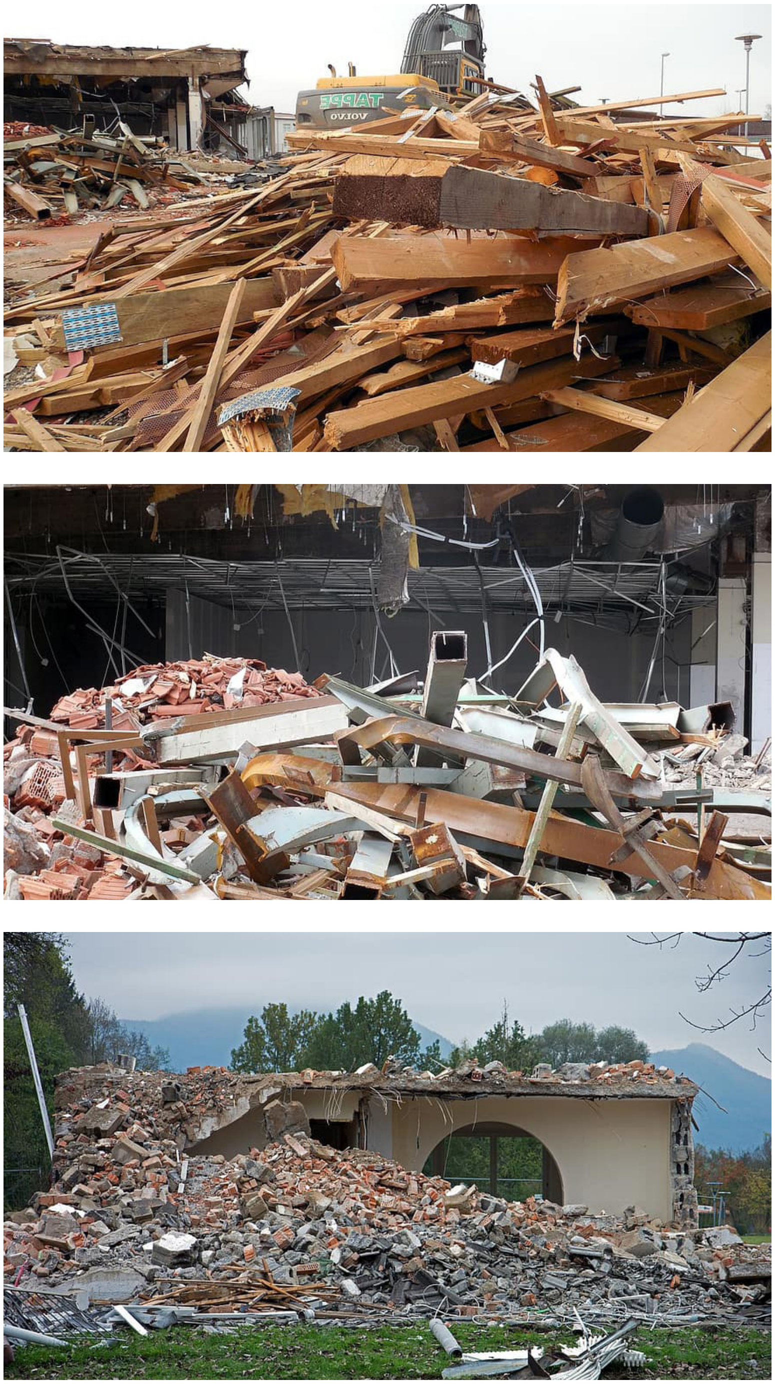
6. Environment and Climate Change Canada, "Municipal Solid Waste: A Shared Responsibility," guidance, aem, February 1, 2017, https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/shared-responsibility.html.

7. OLEM US EPA, "Sustainable Management of Construction and Demolition Materials," Overviews and Factsheets, US EPA, March 8, 2016, https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials.

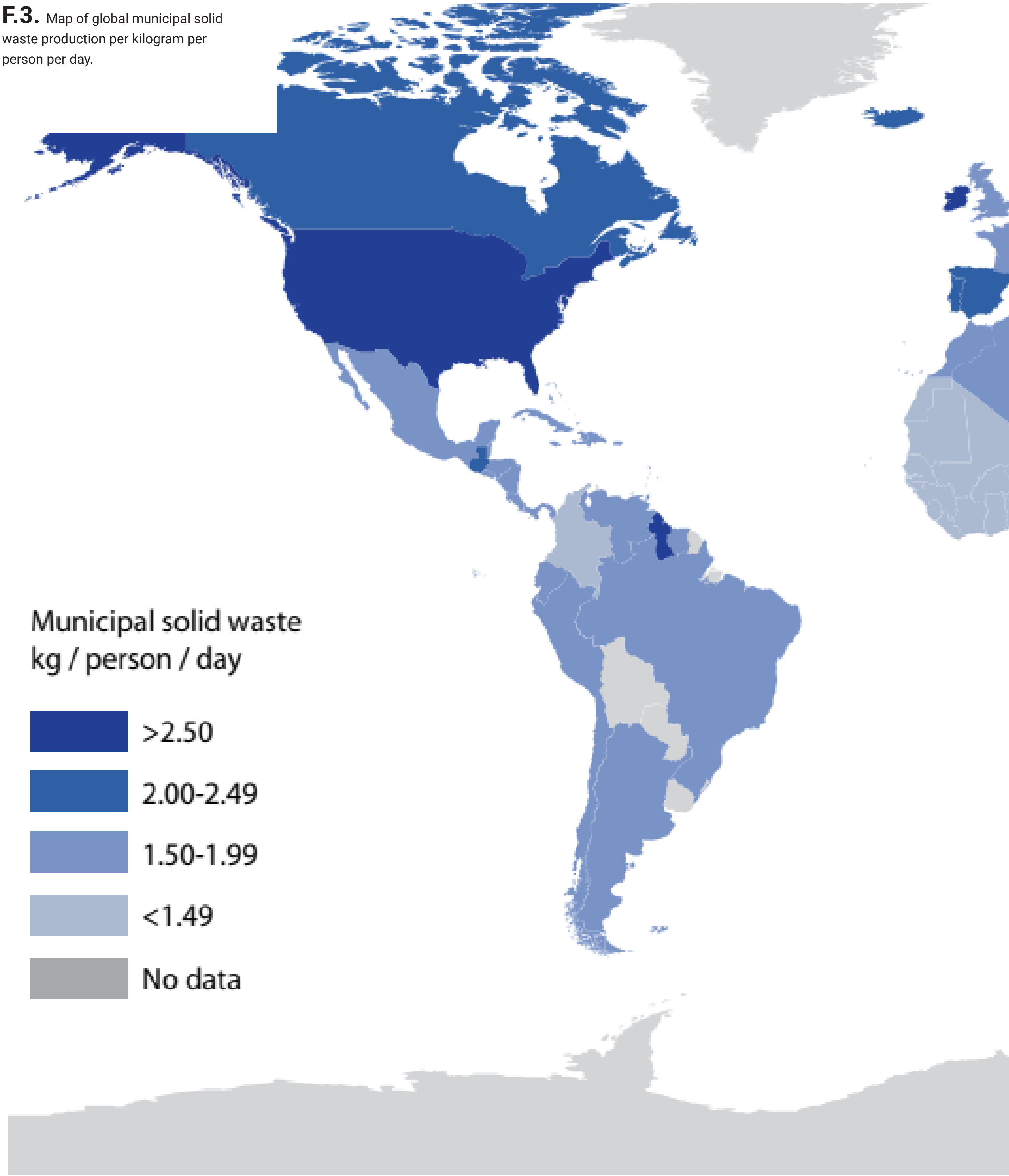
8. Statistics Canada Government of Canada, "Disposal of Waste, by Source," December 28, 2017, https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003201.

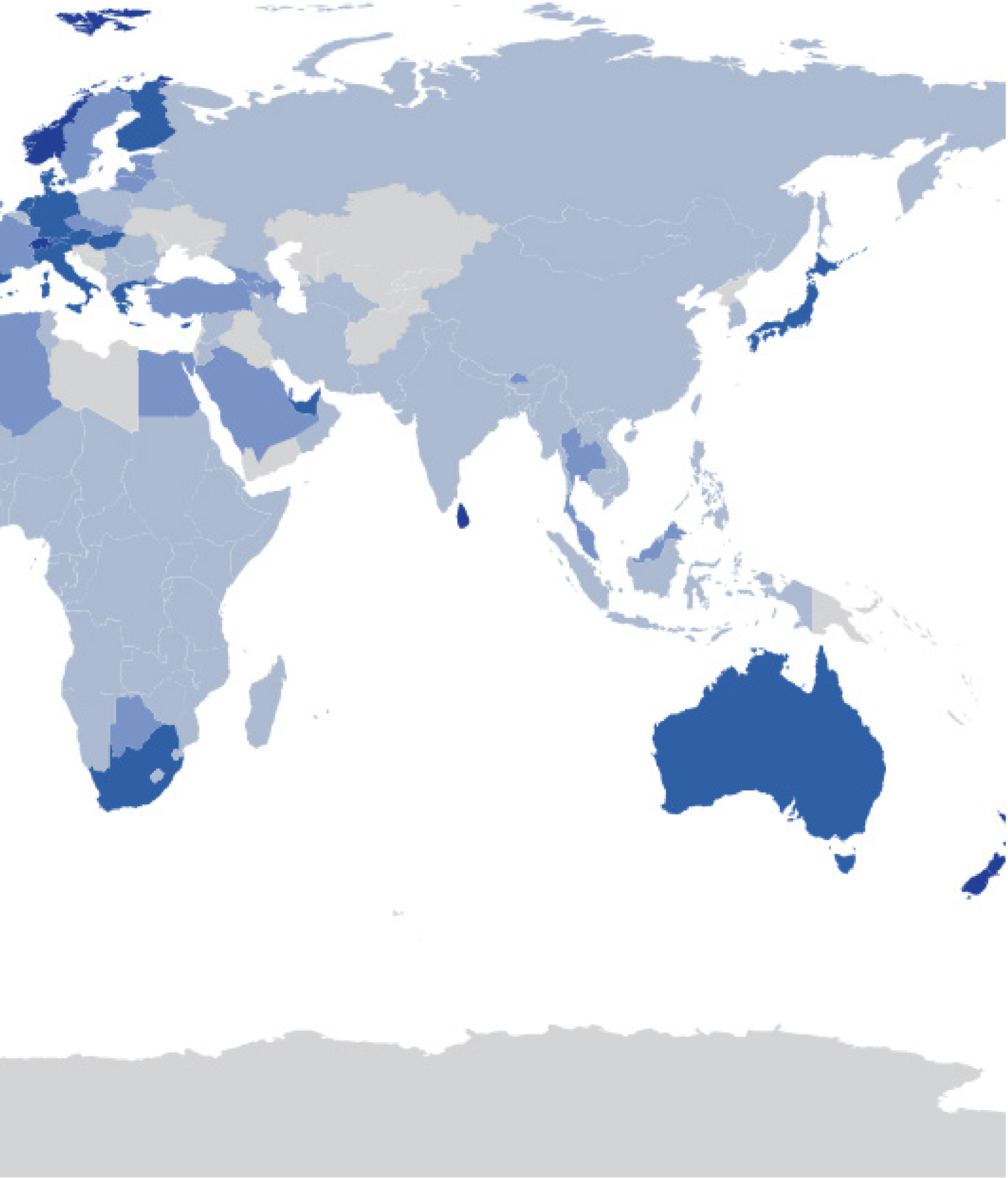
9. Hebel, Wisniewska, and Heisel, Building from Waste.

F.2. Construction & demolition waste as a global problem.



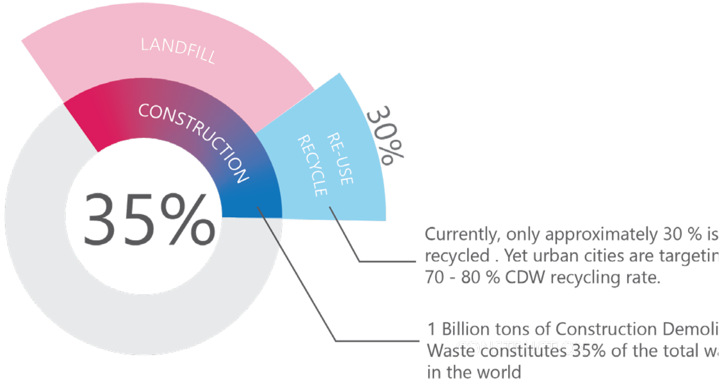
F.3. Map of global municipal solid waste production per kilogram per person per day.





The composition of this mixture varies greatly depending on the origin. Geographical location, regional construction norms, and the type of construction activity greatly influence C&D waste composition. As displayed in figure F.5, in Canada and Thailand, the majority of C&D waste is comprised of wood and concrete, respectively. [10][11] Each of these materials have a certain level of recyclability and therefore require a specific management strategy. F.6 describes the recycling potentials of each material. In general, seventy five percent of C&D waste can be reused, recycled, or used as fuel, often it is carelessly dismissed. [12] See figure F.4. As a result of such disposal, a number of environmental issues follow, including a waste of natural resources, increased transportation, reduced soil quality, and air-water pollution. [13]

With the rise of environmental concerns, numerous studies have been conducted on reducing, reusing, and recycling construction debris. Hebel, Wisniewska, and Heisel showcase numerous precedents which attempt to reuse or recycle waste in an architectural application. [14] However, many of these projects involve transferring the mix to specialized facilities for transforming the waste into a new material, increasing transportation, energy consumption, and costs.



Currently, only approximately 30 % is recycled . Yet urban cities are targetir
70 - 80 % CDW recycling rate.

1 Billion tons of Construction Demoli
Waste constitutes 35% of the total w
in the world

F.4. Construction and demolition waste recycling rate.
(data source: Jeffrey, Colin. Construction and Demolition Waste Recycling A Literature Review.
data source: Yeheyis et al. An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability)

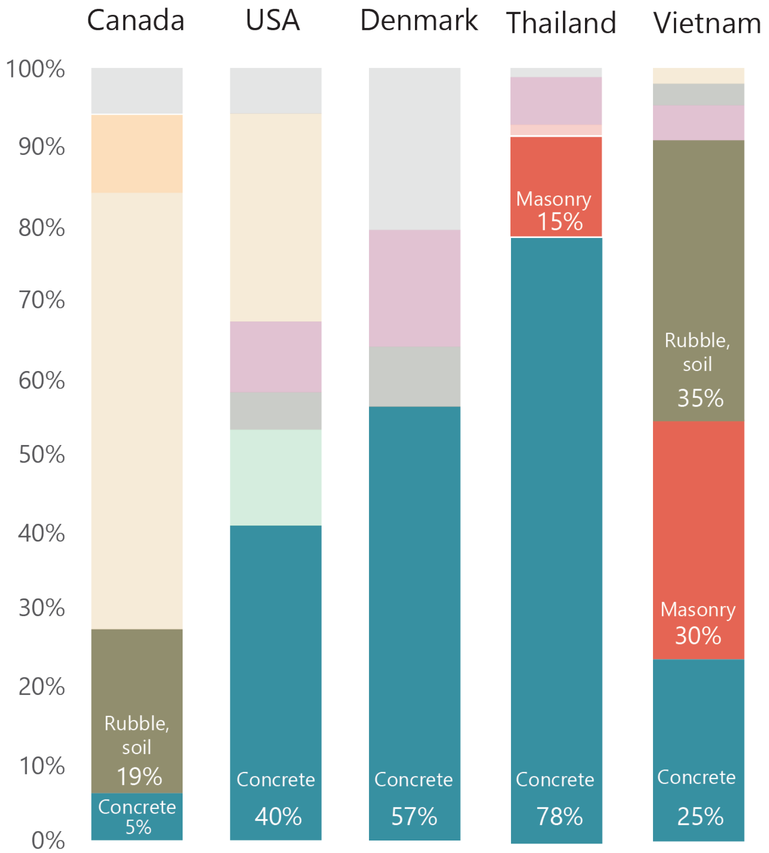
10. Muluken Yeheyis et al., “An Overview of Construction and Demolition Waste Management in Canada: A Lifecycle Analysis Approach to Sustainability,” Clean Technologies and Environmental Policy 15, no. 1 (February 2013): 81–91, https://doi.org/10.1007/s10098-012-0481-6.

11. Oyeshola Femi Kofoworola and Shabbir H. Gheewala, “Estimation of Construction Waste Generation and Management in Thailand,” Waste Management 29, no. 2 (February 1, 2009): 731–38, https://doi.org/10.1016/j.wasman.2008.07.004.

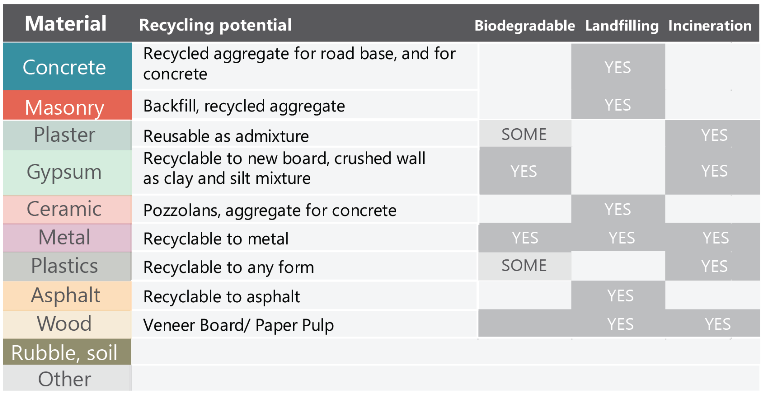
12. Lauritzen, Construction, Demolition and Disaster Waste Management.

13. Hebel, Wisniewska, and Heisel, Building from Waste.

14. Hebel, Wisniewska, and Heisel.



F.5. Construction and demolition waste composition in different countries.
(data source: Hoang et al. A review of construction and demolition waste management in Southeast Asia
data source: TRI Environmental Consulting, 2018 Construction & Demolition Waste Composition Study, Metro Vancouver
data source: Kucukvar et al. Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis)



Material	Recycling potential	Biodegradable	Landfilling	Incineration
Concrete	Recycled aggregate for road base, and for concrete		YES	
Masonry	Backfill, recycled aggregate		YES	
Plaster	Reusable as admixture	SOME		YES
Gypsum	Recyclable to new board, crushed wall as clay and silt mixture	YES		YES
Ceramic	Pozzolans, aggregate for concrete		YES	
Metal	Recyclable to metal	YES	YES	YES
Plastics	Recyclable to any form	SOME		YES
Asphalt	Recyclable to asphalt		YES	
Wood	Veneer Board/ Paper Pulp		YES	YES
Rubble, soil				
Other				

F.6. Recyclability potential based on materials.
(data source: Yeheyis et al. An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability)

This has limited the practical applications of these processes, which has led to defaulting to more conventional ways of disposal. One of the most sustainable ways of waste management is using as-found components as the primary material in a structure. This approach can eliminate or reduce the need for raw materials, processing, and transportation, resulting in reduced costs, energy consumption, and carbon-footprint. [15]

Repurposing and recycling waste material is an ancient practice. From our ancestors who used mammoth bones to construct shelters, to Crusaders who used ancient marble columns to build the *Sidon Sea Castle* in the thirteenth-century [16] to *Sayaka Ganz*, the Japanese sculptor who transforms discarded plastics into magnificent animal figures [17], we have consistently tried to find treasure in "another man's trash". F.7 portrays a shelter constructed with mammoth bones, while F.8 and F.9 display photos of *Sayaka Ganz* and *Sidon Sea Castle*, respectively.

This study argues that it might be possible to use C&D waste, as a viable construction material, with minimum modifications. These materials can be used in an architectural cycle where not only they are not removed, but they inform the structure and the design. This can help us achieve the highest levels of aesthetics and functionality for the found components. [18] In terms of aesthetic qualities, salvaged materials possess unique geometries, colors, weight, and overall, each of these elements has a distinct history.

On the other hand, as-found components are generally more durable before getting recycled. For instance, concrete loses up to one-fourth of its initial strength when recycled. [19] Similarly, the quality of recycled wood is normally lower than natural wood due to the damage to continuous wood fibers and cell chains. [20] Consequently, re-using C&D residue not only reduces costs, carbon-footprint, and material extraction, but it also provides new opportunities for novel aesthetic qualities and higher material integrity.

15. Ryan Luke Johns and Jeffrey Anderson, "Interfaces for Adaptive Assembly," in ACADIA // 2018: Recalibration. On Imprecisionand Infidelity. [Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-0-692-17729-7] Mexico City, Mexico 18-20 October, 2018, Pp. 126-135 (CUMINCAD, 2018), http://papers.cumincad.org/cgi-bin/works/BrowseTree=series=AZ/Show?acadia18_126.

16. Lauritzen, Construction, Demolition and Disaster Waste Management, 8.

17. Kristine Somerville, "Trash to Treasure: The Art of Found Materials," The Missouri Review 40, no. 3 (2017): 66, https://doi.org/10.1353/mis.2017.0040.

18. Fabio Gramazio, Matthias Kohler, and Jan Willmann, The Robotic Touch: How Robots Change Architecture (Zurich: Park Books, 2014), 385–86.

19. Sami W. Tabsh and Akmal S. Abdelfatah, "Influence of Recycled Concrete Aggregates on Strength Properties of Concrete," Construction and Building Materials 23, no. 2 (February 1, 2009): 1163–67, https://doi.org/10.1016/j.conbuildmat.2008.06.007.

20. Robert H. Falk and David Green, "Stress Grading of Recycled Lumber and Timber," in Structural Engineering in the 21st Century: Proceedings of the 1999 Structures Congress, April 18-21, 1999, New Orleans, Louisiana. Reston, VA: American Society of Civil Engineers, 1999.: P. 650-653: Ill., 1999.

F.7. Reclaimed mammoth bones were used to construct a shelter.

F.8. Reclaimed kitchenware were used to create this animal sculpture.

F.9. Reclaimed Roman columns were used in the construction of the Sidon Sea Castle.

Nevertheless, assembling a structure with scrap materials can be challenging, even for a skilled person. That is why the Architecture, Engineering, and Construction (AEC) industry often resorts to using engineered materials; these products are easier to understand and handle, contrary to found objects that can have different properties including geometry, weight, material, and color. These varying qualities results in complicated assembly systems and often compromised structural stability. Fortunately, recent advancements in robotics and computation provide an opportunity for handling irregular objects. These often non-standard and heavy elements can be easily pieced together by computers in in the digital-world similar to a three-dimensional puzzle. [21] Then, these solutions can be executed by industrial robots in the real-world, inevitably redefining the usage of construction debris in architecture.

Recognizing and handling non-standard components are studied extensively in the field of robotics. [22] *Amazon Picking Challenges* (APC) are great case studies for how robots can easily detect and manipulate their surroundings. Figure F.10 displays a robot participating in this challenge, while F.11 depicts the array of objects that were involved in the challenge. An analysis made from the first APC at the *2015 IEEE International Conference* on Robotics and Automation explains the methods used by different teams for hardware, software, and algorithms.[23] According to this paper, automating picking and placement tasks is now possible considering the maturity of the robotics field.[24] The processes in this competition could be integrated into digital fabrication in architecture, resulting in an improvisational fabrication process which is mindful of the reclaimed material.

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[21] Hebel, Wisniewska, and Heisel, Building from Waste.

[22] Johns and Anderson, "Interfaces for Adaptive Assembly," 3.

[23] Nikolaus Correll et al., "Analysis and Observations From the First Amazon Picking Challenge," IEEE Transactions on Automation Science and Engineering 15, no. 1 (January 2018): 172–88, https://doi.org/10.1109/TASE.2016.2600527.

[24] Correll et al., 172.

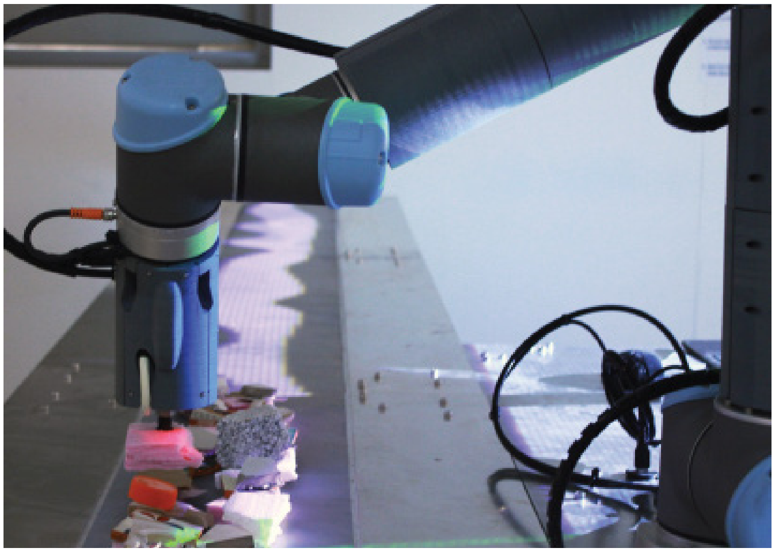
F.10. RBO team's robot participating in the first Amazon Picking Challenge.

F.11. Different items used in the first Amazon Picking Challenge.

F.12. Wood Chip Barn project by Design + Make Group.

F.13. Granular aggregation is used in Rock Print project to create self-supporting structures.

F.14. Interfaces for Adaptive Assembly attempts to construct a wall with as-found objects.



There is a vast body of research on employing computation and robotics in architecture. Nevertheless, most of these studies take a pre-deterministic approach; machines are programmed to materialize a zero-tolerance design and components are engineered to fit. While this process enables magnificent structures, it significantly increases resource extraction, energy consumption, and waste production. [25] Little research has been conducted on robotic fabrication using found objects, a bottom-up approach leading to a sustainable materially-informed design.

The *Woodchip Barn* project by *Design + Make Group* is a good example that strategically uses as-found materials in fabrication. As observed in figure F.12 this structure is built with minimally engineered pieces of woods. [26] Other examples of using non-standard components in robotic fabrication include the explorations undertaken by *Gramazio Kohler Research* team at ETH, Zurich. *Rock Print* , displayed in figure F.13, capitalizes on material aggregation strategies to create reversible load-bearing structures, while the *Autonomous Stone Stacking* takes a different approach by attempting to stack rock pieces to form a tower. [27] *Interfaces for Adaptive Assembly*, depicted in figure F.14, is yet another attempt at using salvaged materials. This project, which is at the time the closest study to this thesis, utilizes machine-vision to analyze reclaimed objects, then assembles them in a path. [28]

[25] Johns and Anderson, "Interfaces for Adaptive Assembly," 2.

[26] Pradeep; Dailami Devadass, "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) ISBN 978-0-692-77095-5] Ann Arbor 27-29 October, 2016, Pp (CUMINCAD, 2016), http://papers.cumincad.org/cgi-bin/works/paper/acadia16_206.

[27] Gramazio, Kohler, and Willmann, The Robotic Touch.

[28] Johns and Anderson, "Interfaces for Adaptive Assembly."

This thesis conducts physical and digital experiments to develop an intelligent system for automated assembly of construction and demolition waste in compression-only structures. See figures F.15 and F.17. A mechanism is designed for perception, physics simulation, and motion planning to enhance the abilities of a six-axis robotic arm. Next, physical prototypes of a column and a wall are made to help develop and understand a generative algorithm. Afterwards, a number of structural and operational objectives are defined in a comprehensive scoring system to create a digital prototype of the mentioned structures. The digital prototype is constantly checked in a real-time rigid-body simulation to ensure structure stability. The results are used to inform the movements of the industrial robot and the construction of the structures. Finally, structure height, structure porosity, and the number of used waste components is compared with the number of dismissed waste components to determine the efficiency of the interface.

The tools employed to develop this integrated design-to-assembly workflow could be categorized into hardware and software. As the hardware, one Core i-7 windows computer, one Universal Robots UR10, one Robotiq 2F-85 gripper, two RGB-D sensors, and one Arduino microcontroller. a custom end effector is fabricated for grasping irregular objects. A photo of the Robotiq 2F-85 gripper can be seen in figures F.16 and F.18. The software operates in two separate platforms, a Python script and a Grasshopper definition. Python, Open-CV, and Point Cloud Library (PCL) are used to process the collected visual data, while Grasshopper, PhysX, and Machina are used to calculate the solutions, simulate the results, and communicate commands to the robot over Transmission Control Protocol (TCP).

This research faced a few challenges in the process. Assembling irregular objects in a self-supporting structure is a computationally expensive task which becomes more complex as the number of objects increase. In algorithm design, this problem is classified as a non-deterministic polynomial-time problem. [29] Developing an online optimization method in Grasshopper 3D was the next computational obstacle. At this time, many of the optimization tools available for Grasshopper 3D perform through a separate interface, which eliminates the possibility real-time optimization. optimization, and

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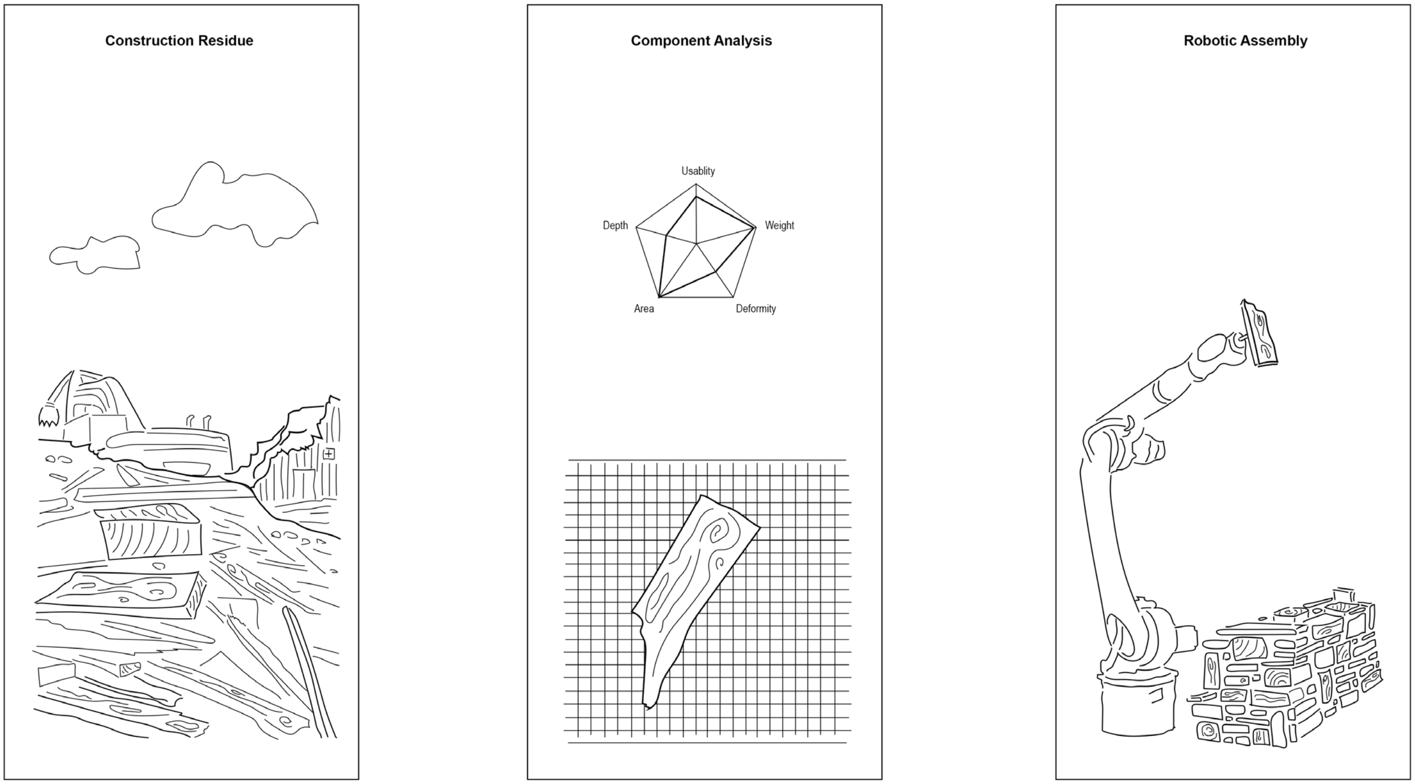
[29] Steven S. Skiena, The Algorithm Design Manual (London: Springer, 2010).



Construction Residue

Component Analysis

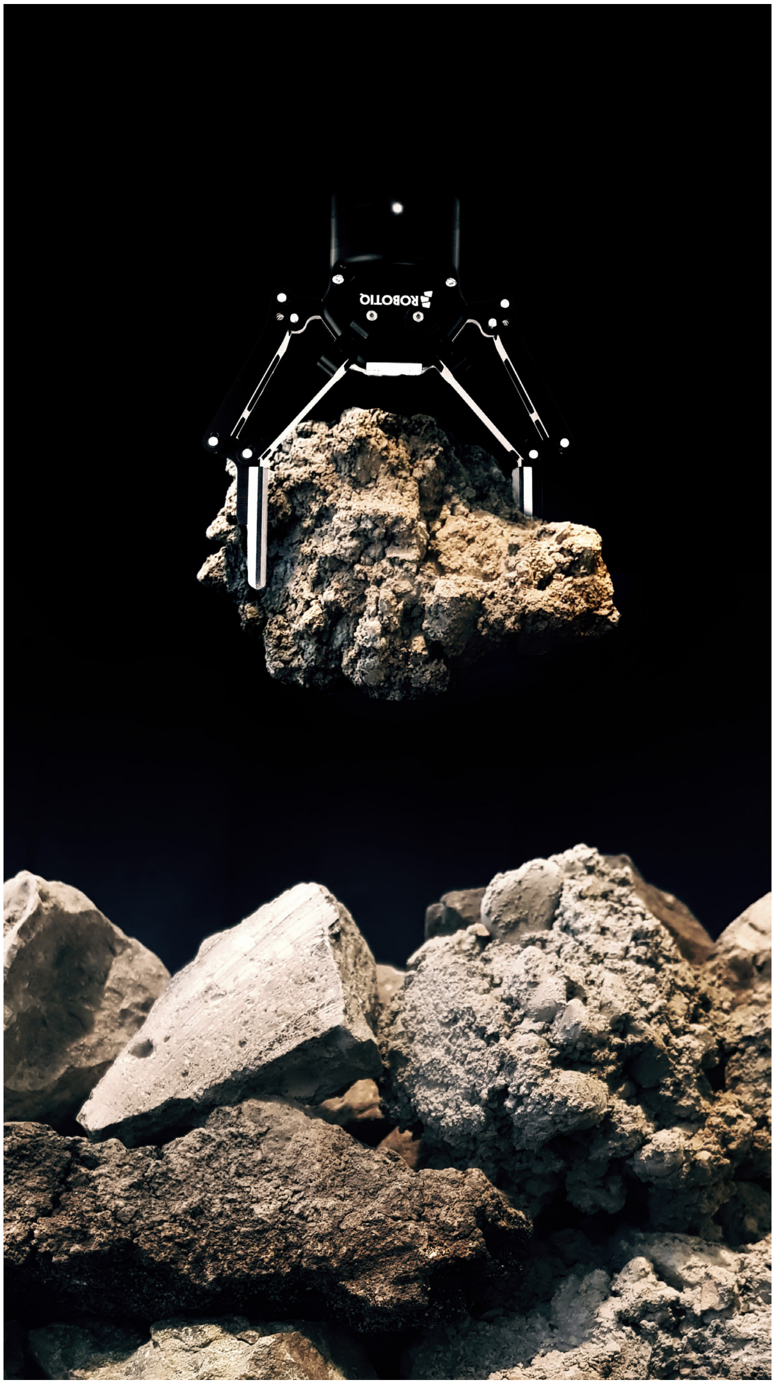
Robotic Assembly

F.15. Robotic construction process. Ultimately, robots can use C&D waste to build on-site.

resolving issues regarding an inefficient physics simulation. Another hindrance to this research was caused by the unfortunate circumstances created by the COVID-19 pandemic resulting in the termination of access to digital fabrication facility. This unprecedented situation changed the course of this thesis; construction of a physical prototype was no longer possible and this research had to focus more on the computational aspect of this robotic system.

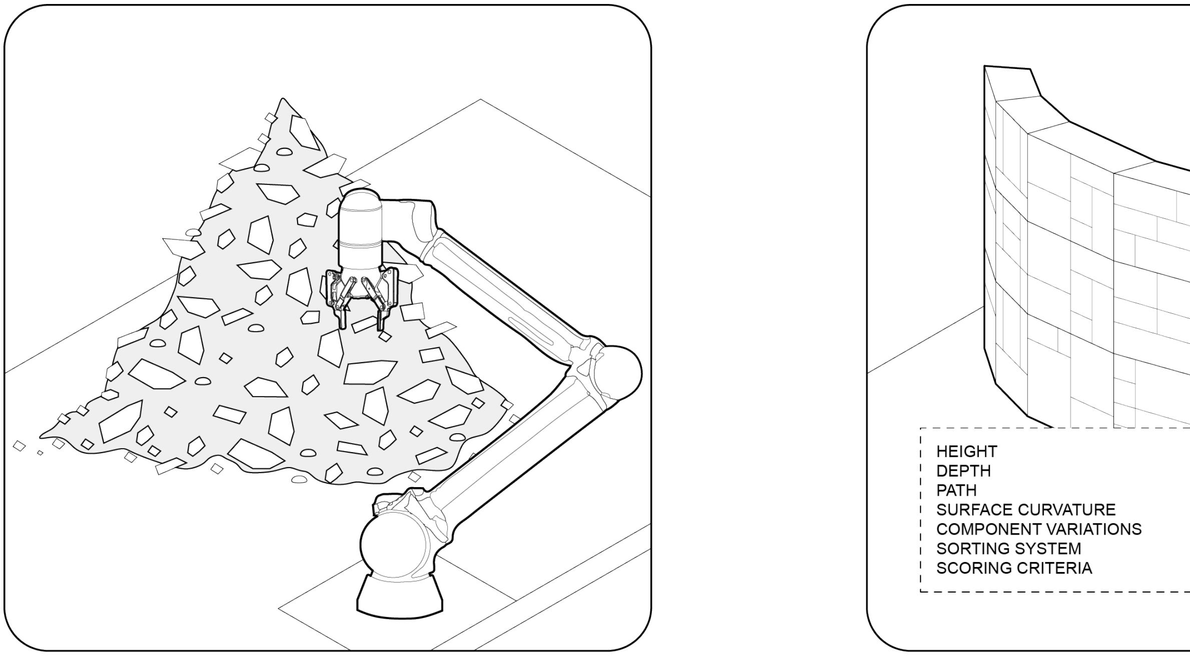
There are many aspects of this interface that can improved. The scope of this study only allowed rigid-body simulations, therefore, limiting the assembly techniques to aggregation. A more advanced simulation can enable construction of compound structures. Additionally, the development of a custom gripper can greatly benefit object handling and lift the current geometric restrictions. Moreover, the singularity and the immobility of the robotic arm greatly reduces deployability. Integrating a moving base and multiple robotic agents could increase the construction speed and bring it closer to real-world applications. Lastly, machine-vision is currently used to analyze new objects and does not track the components after they are place in the structure, meaning that there is no self-monitoring function which can lead into a divergence between the physical and digital models.

Using robotic fabrication technologies to reclaim construction waste, as depicted in F.16, can have many applications in the architecture, engineering, and construction industry. In a conventional construction scenario, a robotic system to repurpose construction waste decreases construction waste production, reduces material and labor costs, and limits the environmental footprint of our buildings. In addition, this strategy enables rapid construction of durable emergency shelters. Another application of this system is building structures in remote areas, such as Mars, where transporting materials is nearly impossible. Lastly, this bottom-up design and assembly process creates new possibilities for architects and engineers for aesthetics and functions which are directly informed by materials.



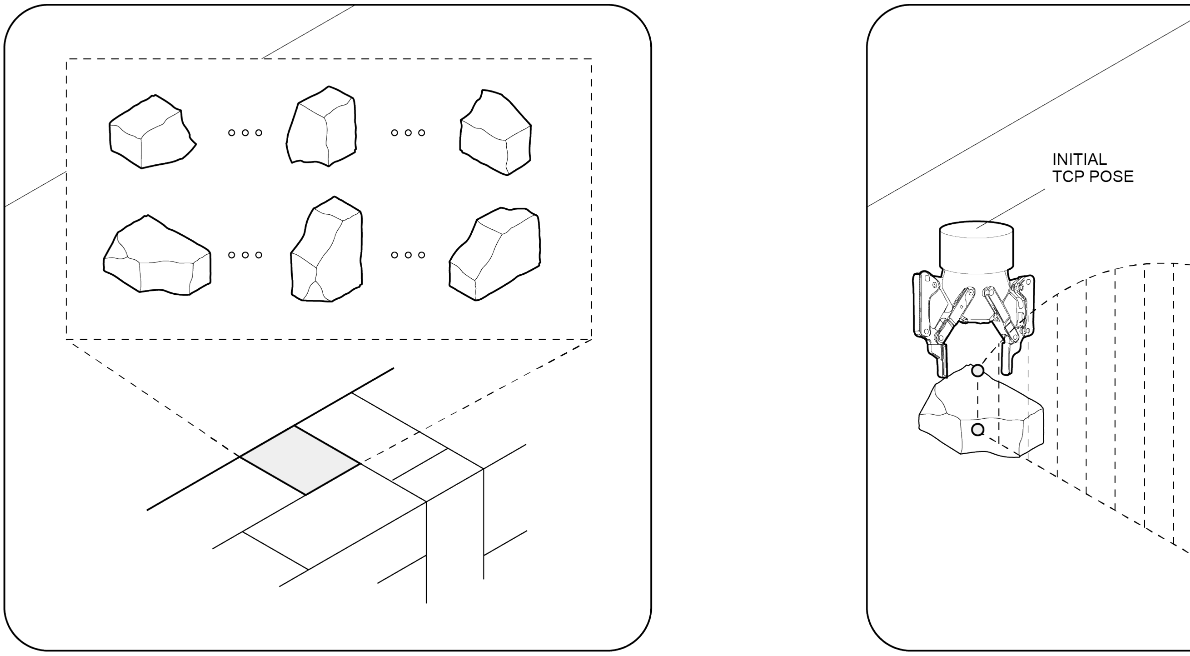
F.16. An abstract photo of Robotic Stacking of Irregular Components in Compression-only Structures.

F.17. Process diagram.



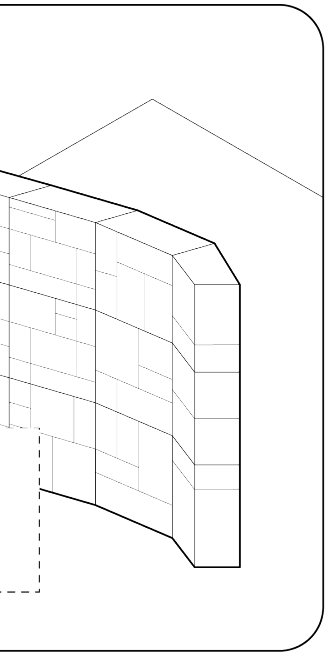
Construction Waste as Building Material

Setting Desig

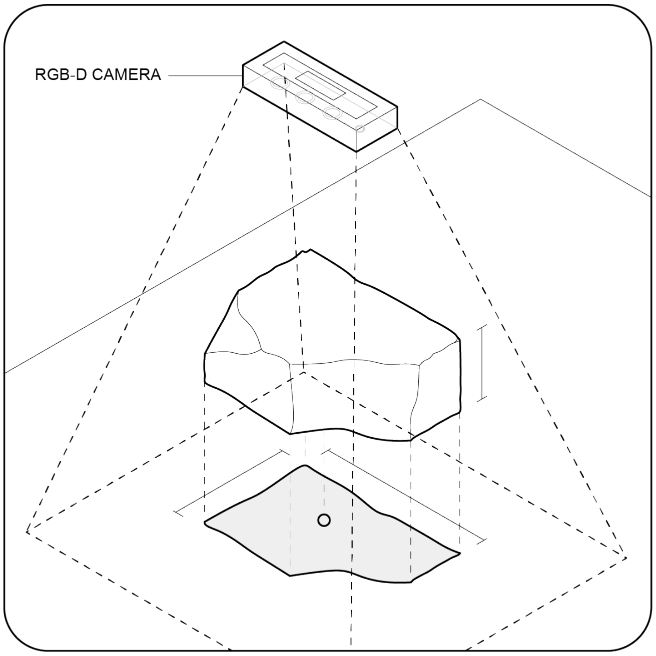


AI Calculates Best Object & Target Pose

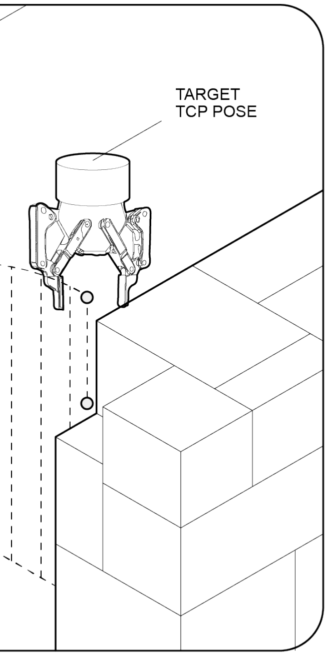
Path Ge



gn Parameters



Object is Scanned and Analyzed



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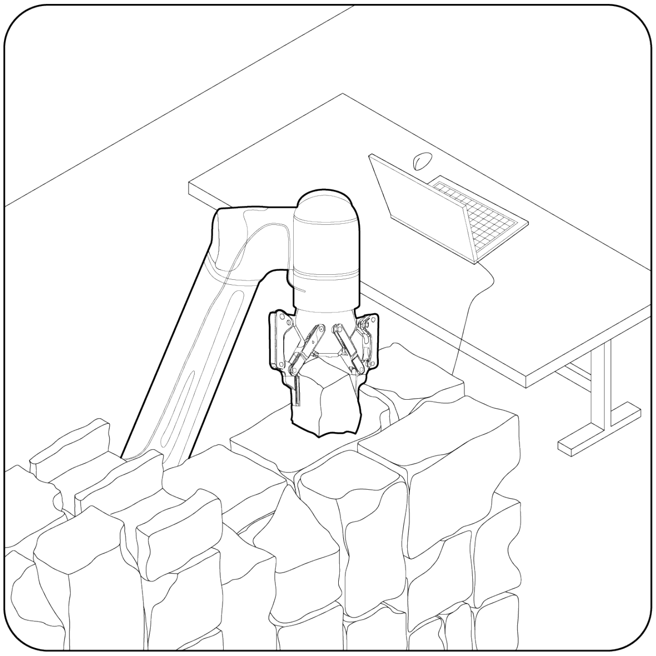
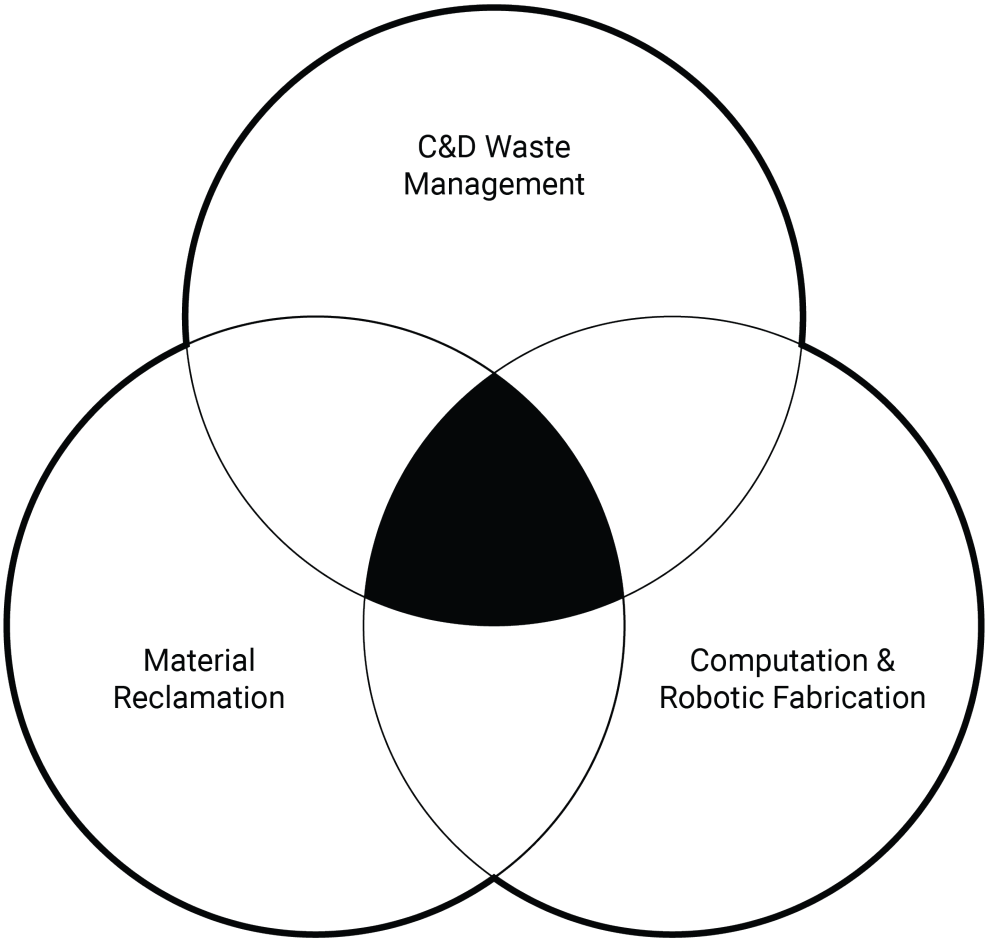


Robot Places Object

F.18. Piece of rubble grasped by Robotiq 2F-85 gripper.

Scope

The theoretical frameworkof this research, as seen in figure F.19, is based on the intersection of construction and demolition waste management, material reclamation, and robotic fabrication. More specifically, rubble is studied in the C&D waste management field due to its large amounts and lower recyclability rate. In terms of material reclamation, salvaging materials for sustainability and structural properties are targeted. Using as-found components for their aesthetic properties and cultural significance is not the primary concern of this research. Finally, online robotic stacking is employed in the robotic fabrication field. This method is different than offline robotic stacking, in which all objects are scanned prior to design generation, then robot proceeds to build the structure. Refer to figure F.20 for the scope diagram.



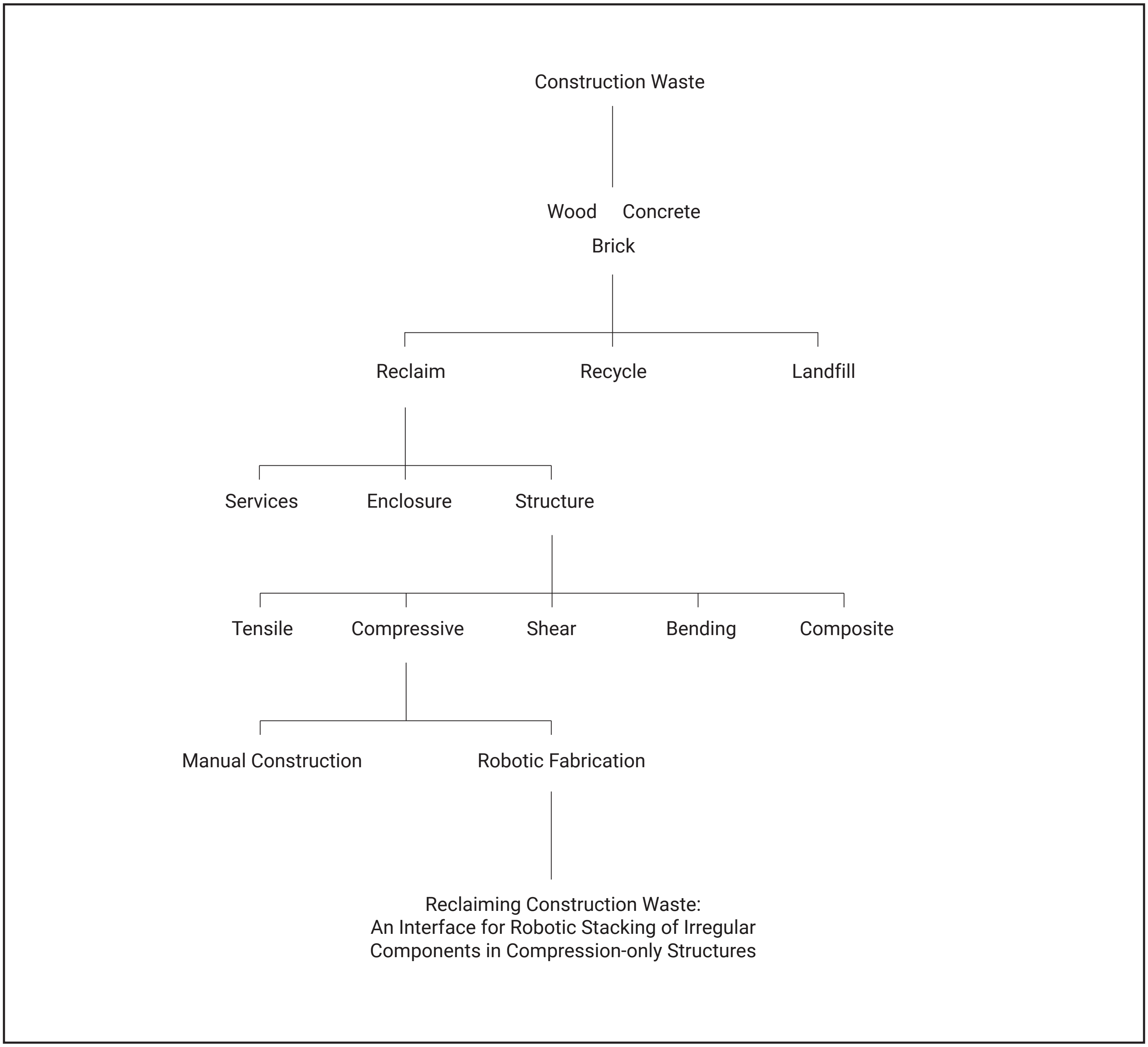
F.19. Theoretical framework.

Structure

This thesis is structured into six chapters, with each chapter divided into two to five sections. Each chapter starts with a title page which describes the title, the topics covered in the chapter, and the chapter number. The next pages include a spread image, ten keywords, and a general introductory text. This piece of text is formatted differently than the rest of the book to emphasize its introductory nature. In this book, the citations are done according to the seventeenth edition of Chicago Manual of Style. [30] The sources for all the drawings are listed in the list of figures section on page viii.

The first chapter is Introduction, which includes the outline, scope, and structure of this thesis book. The next three chapters – Construction and Demolition Waste, Reclaimed Materials, Digital Fabrication - cover Literature Review. The Construction Waste chapter includes sections Source, Management, and Recycling methods which discuss the origin of the construction waste problem, its severity, and the conventional recycling methods. The Reclaimed chapter portrays precedents of waste reuse for its cultural significance, material sustainability, aesthetic properties or structural qualities. Digital fabrication studies different projects that employed robotic fabrication strategies with irregular objects. The fifth chapter, Methodology, describes the steps in the development of an intelligent system for the robotic stacking of a compressive structure. Material study, mechanism design, machine vision, and algorithms are all covered in this section. The Conclusions and Insights chapter discusses the contributions, challenges, applications, and further developments of this research. Finally, this book concludes with Letters of Copyright Permission, Bibliography, Appendices, and Glossary as Back Matter.

30. The University of Chicago Press Editorial Staff, The Chicago Manual of Style, 17th Edition (Chicago: University of Chicago Press, 2017).



F.20. Scope diagram.

CONSTRUCTION WASTE

- Source & Composition
- Management Strategies
- Recycling Methods
- Conclusion

B

F.21. Mismanagement of construction and demolition waste can contribute to a variety of long-term environmental problems.

#CONSTRUCTION

#DEMOLITION

#WASTE

#RECYCLE

#REUSE

#MANAGEMENT

#SOURCE

#COMPOSITION

#CARBON FOOTPRINT

#ENVIRONMENT

Each year in Canada, approximately nine million tons of construction and demolition waste is produced. [31] *This amount of waste is generated due to execution errors, inappropriate management, design changes, and residues from raw materials.* [32] *This mix consists of valuable components such as masonry, drywall, wood products, and concrete. Study shows that 75% of the construction debris can be either reused or recycled.* [33] *However, these materials are commonly entered into a linear process instead of a metabolic cycle, resulting in burial or incineration of these substances which has a devastating impact on the environment. This chapter studies the roots of this problem, common solutions, and how design can alleviate this problem. Historical and modern instances of waste reuse through art and architecture are introduced. Then, the challenges and opportunities of using reclaimed materials are discussed.*

[31] Yeheyis et al., "An Overview of Construction and Demolition Waste Management in Canada."

[32] Yeheyis et al.

[33] Yeheyis et al.

Source & Composition

Constructing our built-environment consumes nearly one-third of the world's resources. [34] This activity also produces a great amount of unwanted materials referred to as construction and demolition waste. Annually, nearly 9 million tons of C&D waste is produced in Canada, while the world generates about 1.3 billion tons of municipal solid waste. [35] [36] Researchers expect a significant increase in the waste production across the world as infrastructures become obsolete. Figure F.22 illustrates a global map of waste production across the globe. According to this illustration, the United States and Canada are among the highest producers of solid waste in the world, which underlines the importance of studying C&D waste and its management.

C&D waste includes the residue generated through all stages of construction, renovation, and demolition. This waste can be categorized as either physical, solid waste, or non-physical, time and budget. [37] This matter originates from a variety of construction activities, for instance, small home renovations and large-scale urban developments both produce waste. [38] The cause factors of this problem are poor project management, design mistakes, improper material handling, and unplanned alterations in planning and design. [39] A study by *Nagapan et al.* reports that design change, improper material storage, and careless handling are the top three contributors to waste generation in the construction industry. [40] In addition to the previous causes, natural and man-made disasters can generate great amounts of waste. Depending on the type and the severity of the incident, disaster waste can be significantly greater than the annual waste productions of the region. [41]

34. Yeheyis et al.

35. Yeheyis et al.

36. Hebel, Wisniewska, and Heisel, Building from Waste.

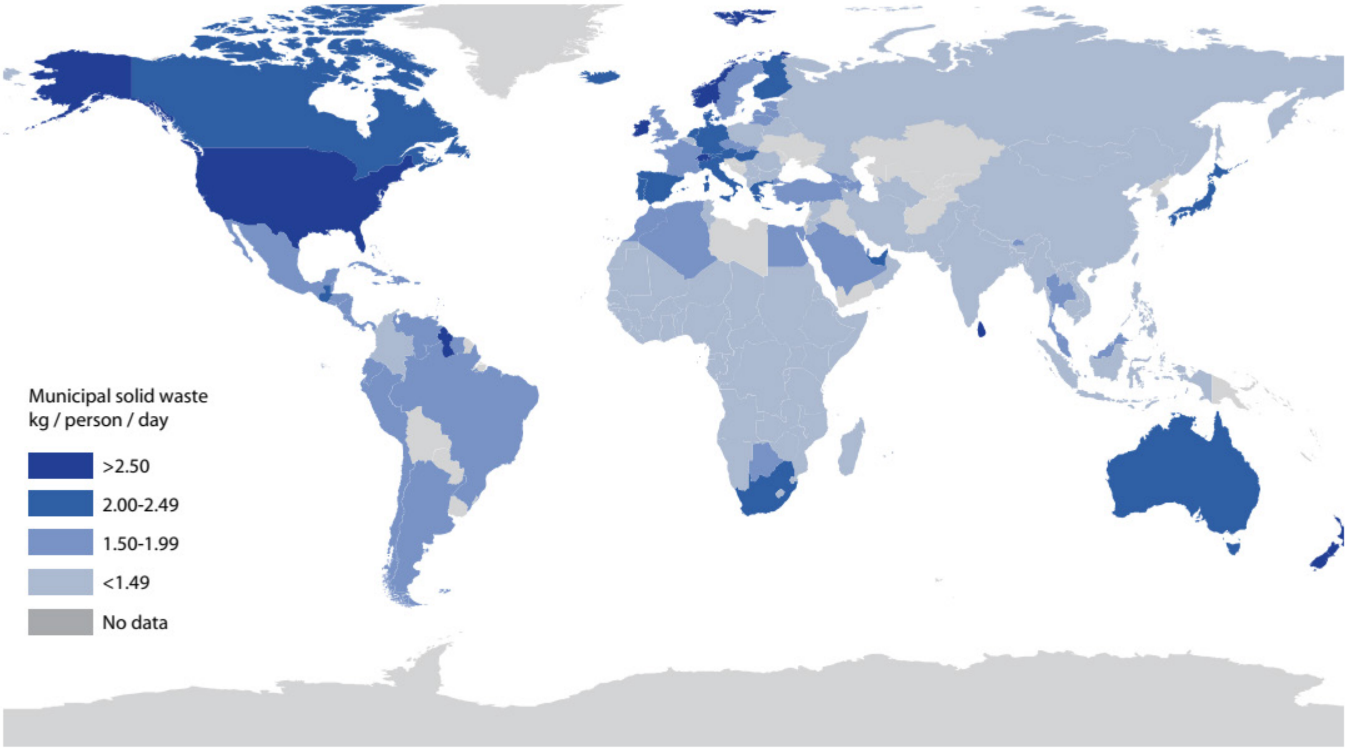
37. Sasitharan Nagapan, Ismail Abdul Rahman, and Ade Asmi, "Factors Contributing to Physical and Non-Physical Waste Generation in Construction Industry," International Journal of Advances in Applied Sciences 1, no. 1 (2012): 1–10.

38. Statistics Canada, "Waste Management Industry Survey: Business and Government Sectors, 2010 - ARCHIVED," August 21, 2013, https://www150.statcan.gc.ca/n1/en/catalogue/16F0023X2013001.

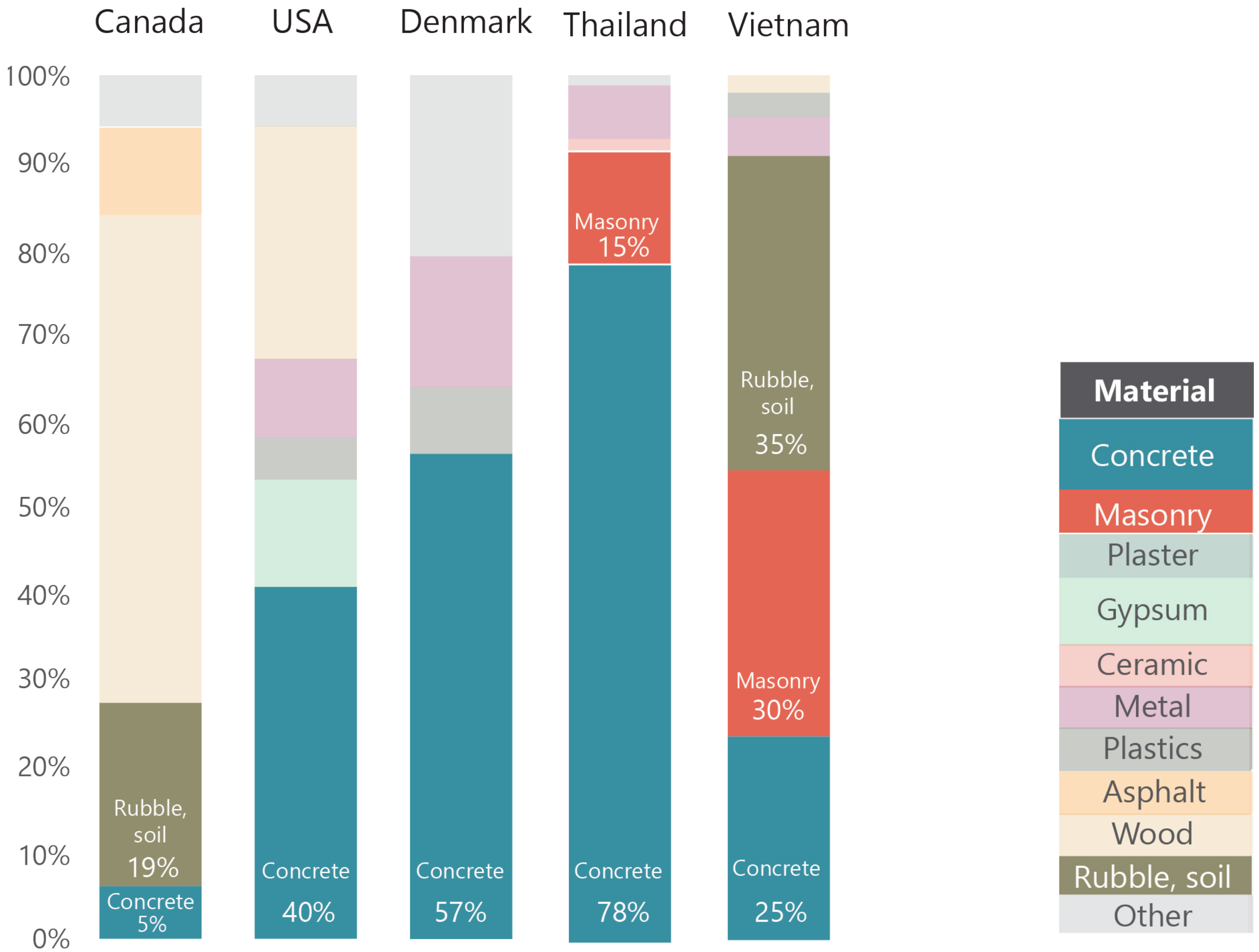
39. Yeheyis et al., "An Overview of Construction and Demolition Waste Management in Canada."

40. Nagapan, Rahman, and Asmi, "Factors Contributing to Physical and Non-Physical Waste Generation in Construction Industry."

41. Charlotte Brown, Mark Milke, and Erica Seville, "Disaster Waste Management: A Review Article," Waste Management 31, no. 6 (June 1, 2011): 1085–98, https://doi.org/10.1016/j.wasman.2011.01.027.



F.22. Map of global municipal solid waste production per kilogram per person per day.



F.23. Construction and demolition waste composition in different countries.
(data source: Hoang et al. A review of construction and demolition waste management in Southeast Asia
data source: TRI Environmental Consulting, 2018 Construction & Demolition Waste Composition Study, Metro Vancouver
data source: Kucukvar et al. Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis)

According to figure F.23, The waste composition differs based on the prevalent construction materials in each region. In Canada, the majority of this mixture consists of valuable components such as masonry, drywall, wood products, and concrete. Insulation, paper, plastics, metals, and other materials compose only a small fraction of the C&D waste. [42] Additionally, waste composition varies depending on the type of construction activity (construction, renovation, or demolition). In Canada, wood and rubble account for more than half of the construction waste produced during the construction phase, while these two materials make nearly three quarters of the mixture during the demolition phase. As demonstrated, Canada produces more wood than any other type of waste, contrary to many other countries which produce more concrete and rubble. [43] In general, concrete, masonry, and rubble account for a great amount of C&D waste produced in the world. [44]

Our planet has limited amount of natural resources and the growing population increases the need for more construction activities, therefore, more C&D waste. These materials which are generated as a result of construction, renovation, or demolition of a building, have different properties. For instance, timber, metals, and concrete have different levels of biodegradability, rigidity, and potential for incineration. It is imperative to understand the nature of these materials in order to dispose or recycle them. Mismanagement of the C&D waste can increase costs, greenhouse gas emissions, time requirements, and overall, cause a number of environmental issues. [45] Consequently, appropriate management strategies are necessary for a sustainable construction practice.

42. Yeheyis et al., “An Overview of Construction and Demolition Waste Management in Canada.”

43. Yeheyis et al.

44. Yeheyis et al.

45. Lauritzen, Construction, Demolition and Disaster Waste Management.

Management Strategies

Sustainable C&D waste management is a crucial step to protect our natural and built environment. This practice can help reduce the financial, social, and environmental impacts of C&D waste. [46] Moreover, proper waste management can facilitate emergency responses after a disaster. [47] Therefore, it is imperative to study waste management strategies, see figure F.24. Primarily, there are four common types of waste management strategies: waste reduction, recycling, incineration, and safe disposal. [48] However, these methods are not all equally effective for all situations and materials. The most effective of these strategies are the ones which replace the linear process of waste discharge with a metabolic cycle whereby the refuse is treated as a resource. As illustrated in figure F.25, waste management systems have different levels of efficiency; reusing buildings is the most sustainable, in contrary to the disposal or special treatment of materials which are the least efficient. [49]

The first step of construction waste management is reducing. This is a preventive method which optimizes material usage and minimizes waste generation. For instance, a modular design or procurement of design rules can reduce the amount of refuse produced in the process. Reusing and recycling are the next two steps in C&D waste management. Reuse refers to a metabolic cycle of implementing the refuse as resources for the same purpose. Recycling, however, refers to the gathering and the transformation of the unwanted materials into new products. Contrary to reusing which is often on-site and does not require special facilities, recycling often needs additional resources, energy, and transportation to off-site locations. Metals, glass, and wood are a few of the materials which are often recycled. [50]

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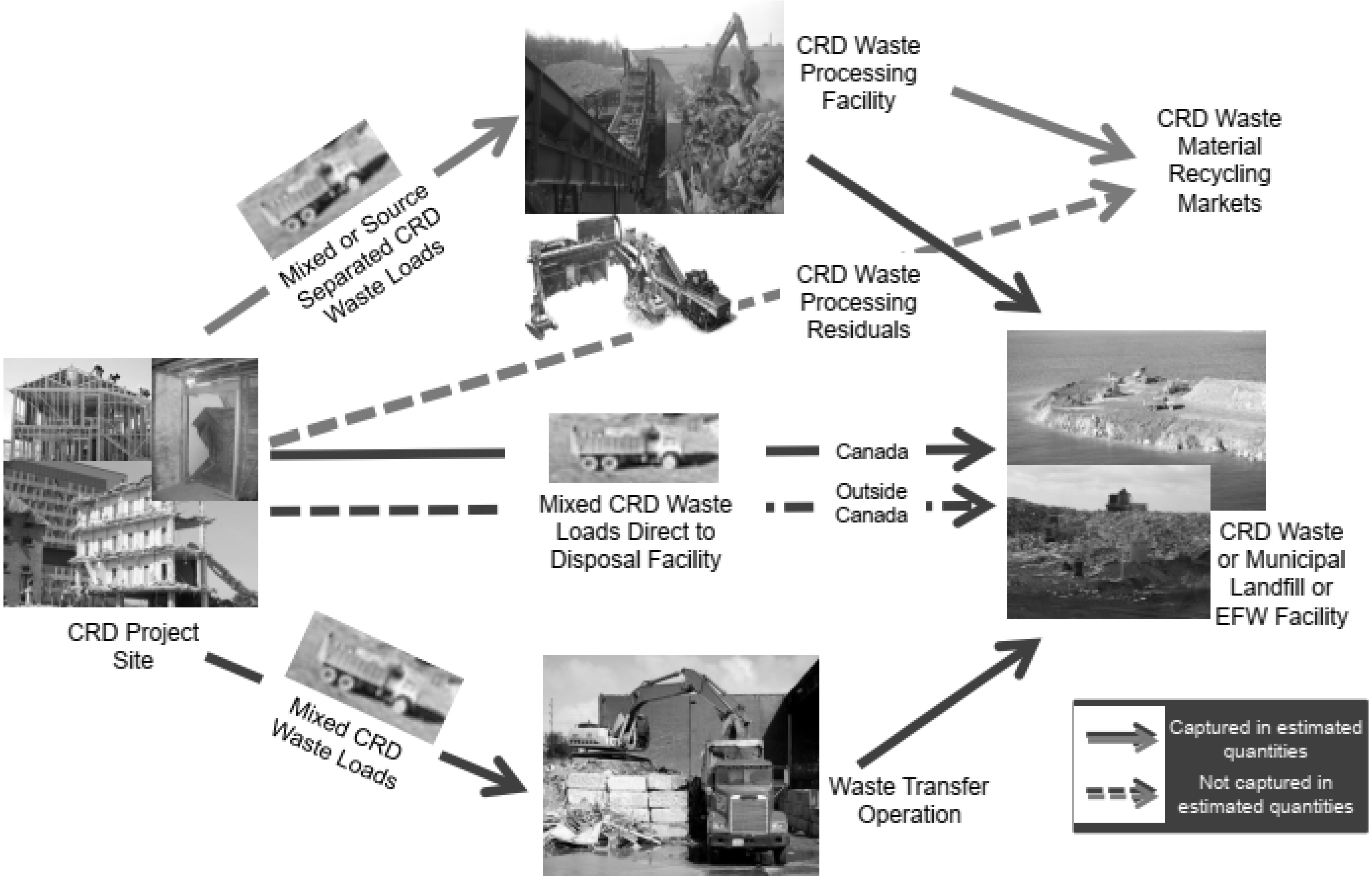
46. Yeheyis et al., "An Overview of Construction and Demolition Waste Management in Canada."

47. Brown, Milke, and Seville, "Disaster Waste Management."

48. N. Marchettini, R. Ridolfi, and M. Rustici, "An Environmental Analysis for Comparing Waste Management Options and Strategies," Waste Management 27, no. 4 (January 1, 2007): 562–71, https://doi.org/10.1016/j.wasman.2006.04.007.

49. Lauritzen, Construction, Demolition and Disaster Waste Management.

50. Yeheyis et al., "An Overview of Construction and Demolition Waste Management in Canada."



F.24. Existing construction and demolition waste management system.

Composting is the next system which can be used to deal with biodegradable wastes such as wood, cardboard, and gypsum board. If oxygen is introduced to this process, water and carbon dioxide are produced. Incineration is another waste management approach whereby waste is burned and converted to energy. Nevertheless, this approach has its drawbacks as it contributes to greenhouse gas emissions. Therefore, incineration is often recommended for the management of hazardous waste materials. [51] The last and the least sustainable means of waste management is landfilling. This method involves burying the C&D waste under the ground which can create significant environmental and financial problems in the long term. [52]

Decreasing waste generation via reducing, reusing, and recycling are often the first choice in waste management. These options are followed by incineration to produce energy, composting, and safe discharge. [53] Mismanagement of C&D waste can lead into major long-term environmental issues. Greenhouse gas emissions, soil pollution, and shortage of landfill are a few outcomes of inappropriate waste management. This research argues that the 3R methods, reducing, reusing, recycling should be prioritized over the other options. However, these strategies should not be evaluated without the consideration of waste materiality. Therefore, the following section studies the common waste management methods for rubble.

Recycling Methods

Concrete, masonry, steel, wood, and glass are the main elements in C&D waste. The majority of these materials are recyclable or reusable. Concrete is often crushed and recycled as aggregate or backfill. Bricks are either crushed or reused as new bricks. Steel is often melted and recycled in the production of new steel profiles. Wood and glass are also reused instead of new materials. Where recycled, wood is turned into other timber-based products whereas glass is used in insulation products. [54] With wood as the exception, none of these materials are biodegradable or can be used for incineration to produce energy. [55] See figure F.26.

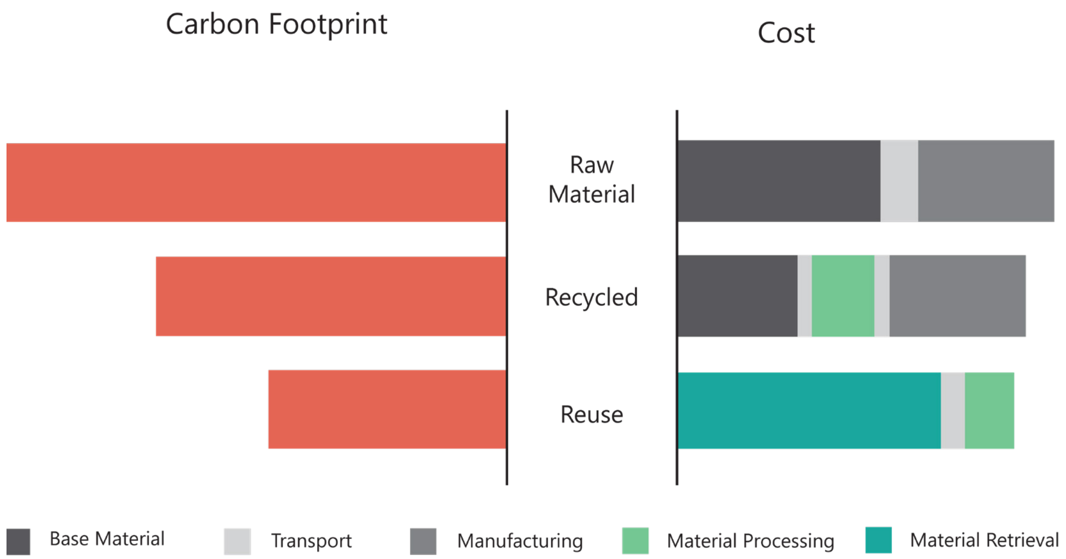
51. T Sabbas et al., “Management of Municipal Solid Waste Incineration Residues,” Waste Management 23, no. 1 (January 1, 2003): 61–88, https://doi.org/10.1016/S0956-053X(02)00161-7.

52. Yeheyis et al., “An Overview of Construction and Demolition Waste Management in Canada.”

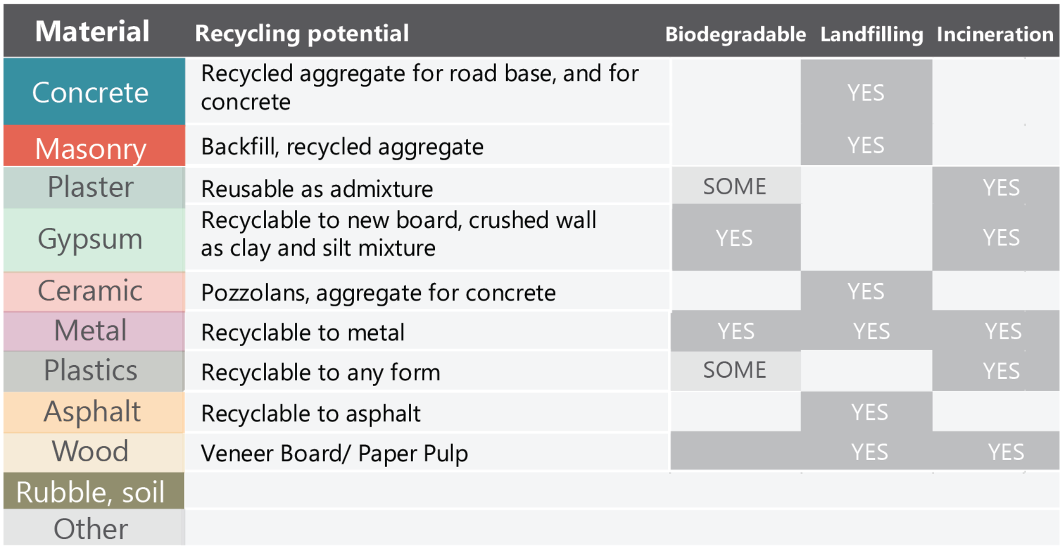
53. Marchettini, Ridolfi, and Rustici, “An Environmental Analysis for Comparing Waste Management Options and Strategies.”

54. Lauritzen, Construction, Demolition and Disaster Waste Management.

55. Yeheyis et al., “An Overview of Construction and Demolition Waste Management in Canada.”



F.25. Cost and carbon footprint comparison for different waste management strategies.
(data source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Environment)



Material	Recycling potential	Biodegradable	Landfilling	Incineration
Concrete	Recycled aggregate for road base, and for concrete		YES	
Masonry	Backfill, recycled aggregate		YES	
Plaster	Reusable as admixture	SOME		YES
Gypsum	Recyclable to new board, crushed wall as clay and silt mixture	YES		YES
Ceramic	Pozzolans, aggregate for concrete		YES	
Metal	Recyclable to metal	YES	YES	YES
Plastics	Recyclable to any form	SOME		YES
Asphalt	Recyclable to asphalt		YES	
Wood	Veneer Board/ Paper Pulp		YES	YES
Rubble, soil				
Other				

F.26. Recyclability potential based on materials.
(data source: Yeheyis et al. An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability)

Concrete accounts for more than half of the construction and demolition waste. Considering the large volume and the extremely high recycling potential of concrete, reusing this material can save approximately 1 billion tons of resources annually. [56] Experts suggest that existing concrete structures should be repurposed instead of demolished. If the building is made with pre-fabricated elements, these components should be used in a new construction. If the previous options are not available, concrete should be crushed and used as recycled aggregate or backfill. [57] Economic, material quality, and environmental factors are essential in prioritizing these strategies.

Masonry, bricks, and tiles are common construction materials around the world. The recycling methods of masonry is similar to that of concrete. Bricks and tiles should be either reused, crushed and recycled for new products, or used as backfill. The strength of recycled masonry is in most cases lower than a newly manufactured unit. Additionally, recycled masonry becomes more expensive than a factory-produced unit when manual processing and cleansing are required. [58] As a result, old masonry units are often used as façade covers, interior decorations, and repair of old buildings. [59]

While all types of construction and demolition waste can be problematic for the environment, this thesis choses to study rubble due to a number of reasons. Rubble, which is available in large volumes, can be neither incinerated, nor composted. The heaviness of this mixture increases the difficulty of material collection and transportation, deterring humanitarian aid in times of disaster. Production of these materials often requires natural resources and releases carbon dioxide into the atmosphere. Therefore, reusing debris with minimal modifications takes priority over crushing these materials to use as backfill.

56. Lauritzen, Construction, Demolition and Disaster Waste Management.

57. Lauritzen.

58. Lauritzen.

59. Daniel; Reitz Baerlecken, “Junk: Reuse of Waste Materials,” in Achten, Henri; Pavlicek, Jiri; Hulin, Jaroslav; Matejovska, Dana (Eds.), Digital Physicality - Proceedings of the 30th ECAADe Conference - Volume 2 / ISBN 978-9-4912070-3-7, Czech Technical University in Prague, Faculty of Architecture (Czech Republic) 12-14 September 2012, Pp. 143-150 (CUMINCAD, 2012), http://papers.cumincad.org/cgi-bin/works/U=&P=http/Show?ecaade2012_280.

Conclusion

In the architecture, engineering, and construction industry, building with engineered materials is common practice. The manufacturing of these components generally requires a great amount of natural resources. Nevertheless, transforming these materials to their base components is either challenging or impossible. [60] Additionally, the need for construction is expected to increase considering the growing population of the earth, aging of the built-environment, and the rising number of natural disasters. Consequently, it is imperative to tackle this issue by forming collaborations between waste and construction industries, viewing C&D waste as resource rather than a worthless material, and studying the state-of-the art recycling strategies. [61]

According to *Lauritzen*, five design principles should be followed for a sustainable construction. First, reusability should be considered in material selection. Second, the design should address the lifetime of the building. Third, the architecture should corelate to its context. Fourth, connections should be designed for not only assembly, but also disassembly. Lastly, a plan should be devised for the deconstruction of the structure. [62] These principles help create a sustainable cycle of resource-to-waste-to-resource instead of a linear process of resource-to-waste. In this approach, waste is reclaimed as the primary material for the construction of a new structure, reducing resource and energy consumption, expenses, and waste production. This approach is particularly beneficial after a disaster when transportation is disrupted and access to new resources is limited.

60. Baerlecken.

61. Lauritzen, Construction, Demolition and Disaster Waste Management.

62. Lauritzen.

RECLAIMED MATERIALS

- Hisotry
- Architecture
- Conclusion

C

F.27. Reclaimed materials create unique textures and design.

#Found Materials

#Salvage

#Reuse

#Recycle

#Design

#Materiality

#Texture

#Reclamation

#History

#Architecture

“Reclaimed materials are considered to be any materials that have been used before either in buildings, temporary works or other uses and are re-used as construction materials without reprocessing. Reclaimed materials may be adapted and cut to size, cleaned up and refinished but they fundamentally are being re-used in their original form.”[63] *Using reclaimed materials is as ancient as architecture dating back to half a million years ago; a structure discovered in a Japanese construction site that is believed to have been made by Homo erectus.* [64] *These ancient people used the materials found in their surroundings, such as stones and wooden sticks to construct shelters. Another example of material reclamation is the blanket fort, also known as pillow fort or sheet fort. For a number of people, this is one of their earliest architecture and repurposing projects. In this scenario, none of the elements are designed for creating an architectural quality, yet they are creatively used in the shape of a structure. This research suggests that construction and demolition waste can be used in the same manner, as the primary element to build novel structures.*

[63] “Reclaimed Construction Materials,” accessed June 28, 2020, http://www.greenspec.co.uk/building-design/reclaimed-materials/.

[64] “BBC News | SCI/TECH | World’s Oldest Building Discovered,” accessed June 28, 2020, http://news.bbc.co.uk/2/hi/science/nature/662794.stm.

History

Reclaiming, scavenging, repurposing, or reusing, this is an act frequently accomplished throughout history. Humans utilized found materials to construct shelters, creating various forms of materially-informed architecture, such as mammoth bone huts, igloos, and pit-houses. Processing raw materials into unrecognizable forms and transporting them across the globe is only prevalent in the modern age. Nevertheless, more recently, artists like *Sakaya Ganz*, *Hendrick Kerestens* and many others have started reclaiming the waste of our consumerist society, redefining the meanings of these components in their masterpieces. [65] While leveraging engineering capabilities enables us to transform all materials, natural properties of locally available components should not be neglected.

It is estimated that our ancestors used mammoth bones to construct shelters over 12,000 years ago. See figure F.28.[66] Instances of material reclamation can be found at all periods; *Sidon Sea Castle*, shown in figure F.29, is a structure in Lebanon built in the thirteenth century. In this building, ancient marble columns were repurposed in the form of a wall-anchoring system. Construction of the *Charlottenburg Museum* in Copenhagen is another example of a historic material reuse. Masonry from the *Kalø Castle*, Denmark, was used to construct this seventeenth-century museum. [67] In another example, the *Bottle House* was built in 1926 using 50,000 glass bottles, eliminating the difference between residue and resource. [68]

Scavenging found materials is not limited to the architectural realm. Painters, sculptors, and photographers also redefine secondhand materials in different ways. Prominent artists such as *Pablo Picasso* and *Marcel Duchamp* turned pieces of papers, cloths, wood, and other waste into masterful collages. Continuing the trend of reusing materials, Japanese-born *Sayaka Kajita Ganz* builds animal sculptures with discarded household plastics; *Hendrik Kerstens* captures portrait photographs which illustrate the excessive production of waste in our society. [69] Another contemporary instance of turning junk into a structure is the *Cathedral of Junk* at Texas, US, where *Vince Hannemann* has built a fortress in his backyard with castaway objects. [70]

65. Somerville, "Trash to Treasure."

66. Baerlecken, "Junk."

67. Lauritzen, Construction, Demolition and Disaster Waste Management.

68. Hebel, Wisniewska, and Heisel, Building from Waste.

69. Somerville, "Trash to Treasure."

70. "Cathedral of Junk," Atlas Obscura, accessed June 29, 2020, http://www.atlasobscura.com/places/cathedral-junk.

F.28. Reclaimed mammoth bones were used to construct a shelter.

F.29. Reclaimed Roman columns were used in the construction of the Sidon Sea Castle.

Reusing discarded materials in a new cycle can have a number of implications. Artworks created with waste materials often criticize the consumerist society of today and signify the importance of recycling, whereas the ancient instances of material re-use often have environmental and structural motifs. A question might arise for many people about the practicality of waste reclamation for everyday use. To answer this question, we should note that with the advent of the modern-day sustainable architecture, many practices moved towards more efficient, environmentally-friendly, and economic materials. *D. Hebel, M. Wisniewska,* and *F. Heisel* study numerous products manufactured with waste in their book *Building from Waste: recovered materials in architecture in construction* [71]

Architecture

There is an on-going body of research on the use of recovered materials in the construction industry. As mentioned in page 40, these waste materials are either reused or recycled. The main difference between these two strategies is the amount of processing needed before using the repurposed element. Generally, the less material-engineering is applied, the more sustainable the element will be. *Ningbo Historic Museum* by *Wang Shu*, *Head in the Clouds Pavilion* by *STUDIOKCA*, *Hanil Visitors Center* by *BCHO Architects*, and *Nepalese Emergency Shelters* by *Shigeru Ban* are examples of waste re-use. On the other hand, *Artek Pavilion* by *Shigeru Ban* and *Hy-Fi Pavilion* by *The Living* are two instances of waste recycling.[72] [73] Figure F.30 displays polyethylene terephthalate (PET) bottles which are designed to be more than plastic containers; figure F.31 illustrates roofing products produced by recycling discarded tetra pak cartons.

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71. Hebel, Wisniewska, and Heisel, Building from Waste.

72. Hebel, Wisniewska, and Heisel.

73. “How to Make a Facade with Recycled Materials: 16 Notable Examples,” ArchDaily, September 30, 2018, https://www.archdaily.com/896930/how-to-make-a-facade-with-recycled-materials-16-notable-examples.

F.30. Polyethylene terephthalate (PET) bottles are designed to serve as bricks after their intial use.

F.31. Discarded tetra pak cartons are recycled to manufacture roofing products.

There are five main reasons why waste materials are reclaimed: Cost effectiveness, sustainability, functionality, cultural significance, and aesthetic qualities can be a driving factor in selecting salvaged objects over new ones. Normally, using found objects eliminates the need for transportation and excessive raw material processing, resulting in reduced total costs. Due to the carbon emission of manufacturing new products, re-using old items is highly eco-friendly. Moreover, certain as-found materials show a higher structural capacity than their recycled counterpart. Another reason why reclaimed materials are used in arts and architecture is related to the life-time and the apparent background of the object; the reclaimed material, in a sense, “tells a story.” Lastly, the unique aesthetics of these components creates possibly interesting textures and patterns. Figure F.32 pictures a few examples of material reuse in architecture.

Conclusion

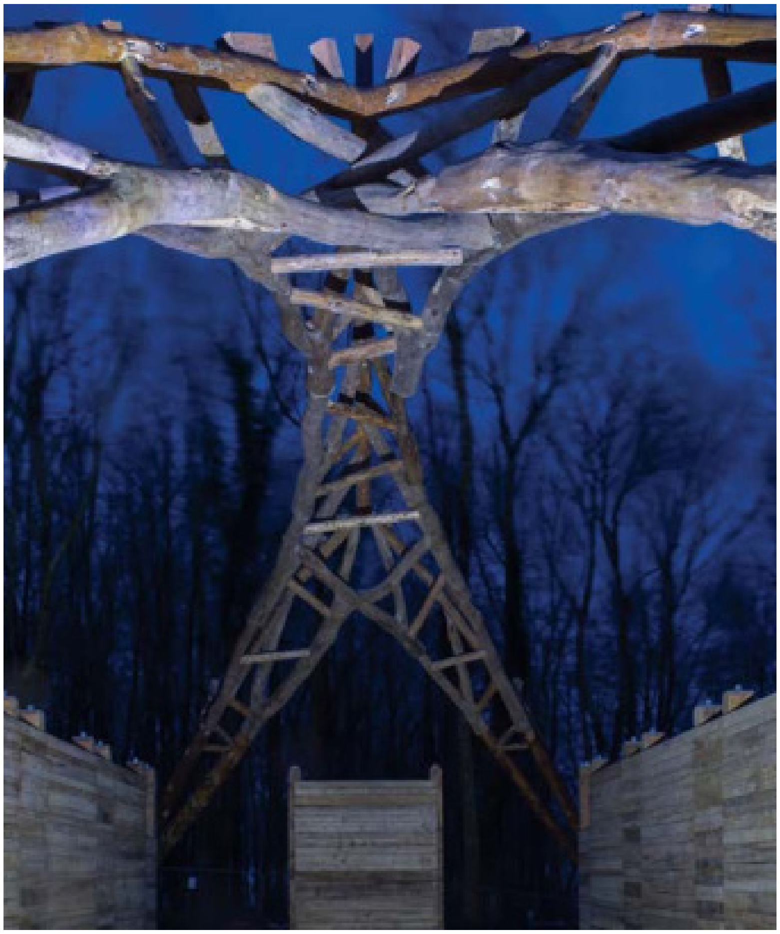
Reclaiming materials has been taking place in every stage of human history. Wood and stone have been continuously used to construct shelters with little manipulation. However, breaking pieces of rock into appropriate sizes has required excessive force and energy. Moreover, the weight of this material has increased the difficulty of transportation. As a result, recovering construction, demolition, and specifically disaster rubble has proved to be an environmentally sustainable and economically reasonable choice. [74] Although material reclamation can be beneficial, it might present a number of challenges. A portion of the materials can be contaminated with toxic elements. Additionally, recovered components, in most cases, do not possess the structural integrity of a recently manufactured unit. Lastly, these non-standard elements have varying geometries which make assembly particularly challenging.

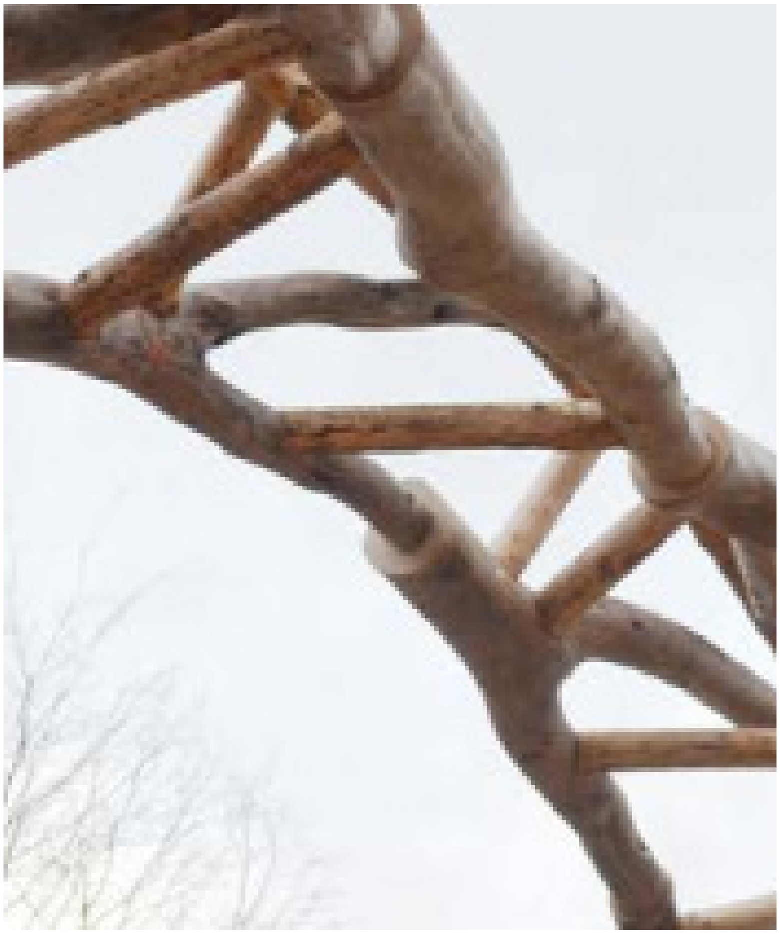
The issues of handling non-standard components can often be alleviated with off-the-shelf technologies. For example, machines can be used to detect and separate toxic materials, and estimate the properties of each component. These devices can analyze rubble and devise structurally-informed assembly systems similar to a game of “Tetris” where objects with different shapes and forms are stacked on each other.[75] This strategy can be an ideal solution for the construction of durable shelters as it can decrease the required man power, accelerate construction, re-use rubble from the surrounding, and protect humans. To realize this possibility, state-of-the-art technologies and fabrication techniques for handling irregular objects are studied in the next chapter.

74. Hebel, Wisniewska, and Heisel, Building from Waste.

75. Hebel, Wisniewska, and Heisel.

F.32. Examples of material reuse in architecture

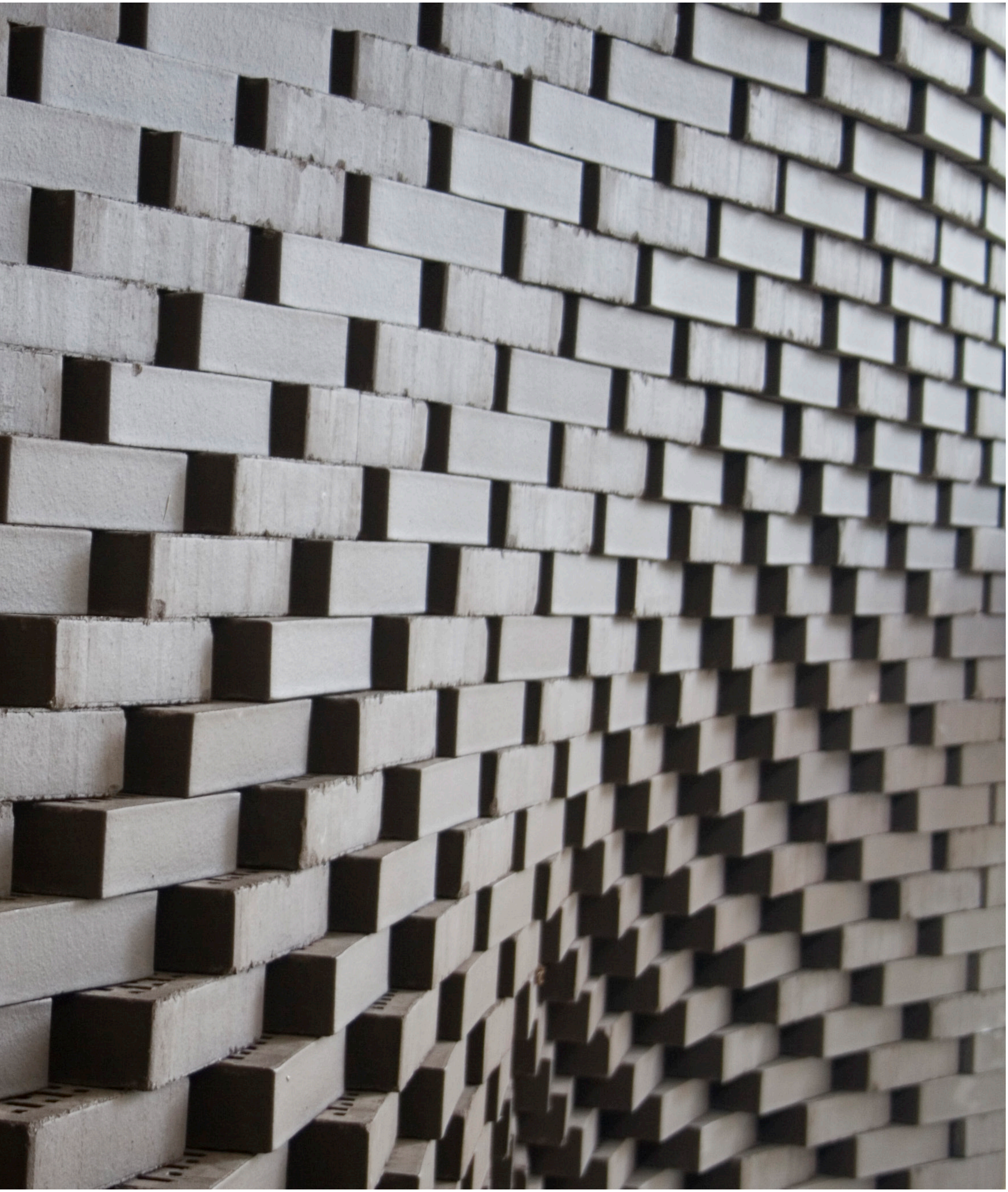


DIGITAL FABRICATION

- Background
- Robotic Fabrication
- Computation & Robotics
- Conclusion

D

F.33. Structural Oscillations project developed by Gramazio Kohler Research, ETH Zurich.



#DIGITAL
#FABRICATION
#BUILD
#PARAMETRIC
#ROBOTIC
#ADAPTIVE
#COLLABORATIVE
#ARCHITECTURE
#COBOT
#CONSTRUCTION

Architecture, similar to every other profession, has been subject to changes caused by technology over time. For example, the advent of computer-aided design in the mid-1960s transformed draftsmanship, design, and engineering. Construction documents became more precise, project management more efficient, and calculations easier. The recent improvements in the computations and robotics have enabled another great change in the AEC industry. Structures which were previously impossible or difficult to construct can now be built with high precision. This has unlocked endless opportunities for highly customized designs in which every component is unique. A few of these fabrication methods include additive manufacturing, subtractive manufacturing, and adaptive assembly. In the following chapter, state of the art projects in the field of Digital and Robotic Fabrication are studied.

Background

The advent of advanced manufacturing devices has played an important role in the architecture industry. In the past twenty years, making devices such as CNC machines, 3D printers, Laser and Waterjet cutters, and many other fabrication technologies have revolutionized the way we design and materialize our built-environment. [76] Complex designs, which were previously only possible in the digital world, are now fabricated with high precision. Nowadays, experts from all over the world study the application of these methods in the construction industry. The Institute for Computational Design (ICD) at the University of Stuttgart, *Gramazio and Kohler Research* group at ETH, *Design + Make Group* at the Architectural Association, and *Mediated Matter Group* at MIT are a number of researchers in the field of digital fabrication.

Among all the possibilities in utilizing digitally-driven devices for making, this thesis is particularly focusing on robotic construction. Traditionally, robots have been used in the automotive industry to automate repetitive tasks, however, these modern devices have been recently employed by designers, architects, and builders. According to *M. Daas and A. Wit*, robots in architecture can play either of the following roles: design, fabrication, construction, and operation. In the design process, these machines inform, analyze, and prototype. In the fabrication process, robots are used to produce mass-customized elements off-site, as opposed to the construction process where robots work on-site alongside humans. See figure F.34. In the operation process, robots accomplish a task with a low to high level of autonomy. [77]

Digital fabrication technologies, like any other tools, present both benefits and drawbacks. Using these modern systems allows for higher precision, increased design complexity, reduced production time, lower error rate, and mass-customization of the elements. Personalizing products leads into a “limited edition” or “one-of-a-kind” mentality, elevating sense of ownership and design value. On the other hand, many digital fabrication mediums use standard materials before customization.

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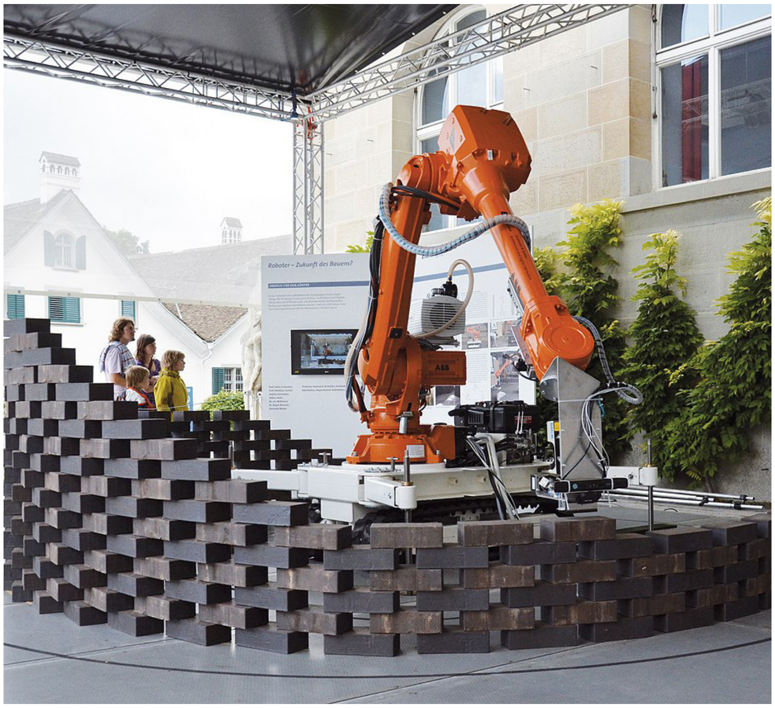
76. Mahesh Daas and Andrew John Wit, eds., Towards a Robotic Architecture (Novato, CA: ORO Editions, 2018).

77. Daas and Wit.

F.34. Endless wall project by Gramazio Kohler Research, ETH Zurcih.



This process can cause increased embodied-energy and reduced resource efficiency. Moreover, the "zero tolerance" approach of these devices might decrease the appreciation for naturally- and locally-available materiality. [78] [79]

Despite the numerous design possibilities, high precision, and reduced operation costs unlocked by digital fabrication, these processes are often unmalleable and unsustainable. Even though these machines enable infinite material customization to fit the design, it is essential that the material morphology and behavior are balanced against design considerations. [80] Instead of customization of standardized materials, which is often wasteful, the machine's ability to handle a variety of geometries should be capitalized. The variations found in raw and recovered materials should replace the artificial variations created by machining. To that end, an adaptive interface is needed; capable of improvisation based on materiality, structural goals, and aesthetic requirements.

[78] "The Pros and Cons of Digital Fabrication," Shield Casework (blog), July 16, 2015, https://www.shieldcasework.com/pros-and-cons-of-digital-fabrication/.

[79] Daas and Wit, Towards a Robotic Architecture.

[80] Johns and Anderson, "Interfaces for Adaptive Assembly."

This robotic system, capable of scanning physical objects and making informed decisions, falls under the Information-Tool-Technology category described by Schindler. According to this researcher, there are three complementing waves in processing technology: hand-tool-technology, machine-tool-technology, and information-tool-technology. Hand-tool-technology is the first wave which involves manual handling and modification of materials using a certain tool. The second wave is the machine-tool-technology; this is where machine undertakes the manufacturing tasks which previously were done manually. In this phase, thermal or kinetic energy is used to produce mechanical energy. The third wave of processing technology, information-tool-technology, uses information, material, and energy to drive the fabrication process. In this scenario, the user often designs the process rather than the final outcome. [81]

Robotic Fabrication

Many experts are studying the use of found materials in digital fabrication. *Greg Lynn* studied the intersection of recycled materials, digital design, and fabrication in the project *Blob Wall*. *Design + Make Group* at the Architectural Association explored the use of natural timber in the construction of the *Wood Chip Barn*.[82] *Gramazio and Kohler* continuously researched the use of robotics in construction; *Rock Print* studies the Jammed Architectural Structures and Rubble Aggregation focuses on stacking of irregular components.[83] *Interfaces for Adaptive Assembly* by *Johns and Anderson* studies an interactive robotic interface for stacking found materials.[84] Other notable examples of robotic fabrication are *The Resolution Wall, On-site Robotic Construction*, and *The ICD Aggregate Pavilion 2018*. [85] [86]

The *Wood Chip Barn*, a project by *Design + Make Group*, is a good example of using found materials in a structure. This design is comprised of twenty unique Y-shaped pieces of wood which are assembled into a structural truss. See figure F.39. First, digital models of these elements are created through photogrammetry, then, the position of each element is calculated and optimized.

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81. Christoph Schindler, “Information-Tool-Technology: Contemporary Digital Fabrication as Part of a Continuous Development of Process Technology as Illustrated with the Example of Timber Construction,” in Proceedings of the 27th ACADIA Conference, 2007.

82. Devadass, “Robotic Fabrication of Non-Standard Material.”

83. Gramazio, Kohler, and Willmann, The Robotic Touch.

84. Johns and Anderson, “Interfaces for Adaptive Assembly.”

85. Gramazio, Kohler, and Willmann, The Robotic Touch.

86. “ICD Aggregate Pavilion 2018 | Institute for Computational Design and Construction | University of Stuttgart,” accessed July 1, 2020, https://www.icd.uni-stuttgart.de/projects/icd-aggregate-pavilion-2018/.

F.35. Granular aggregation is used in Rock Print project to create self-supporting structures.

Next, milling toolpaths are generated for minimal machining. Finally, these forks are assembled in the form of a truss. As a result of this work flow, cheap wooden forks shape an aesthetically pleasing and structurally sound construct. [87]

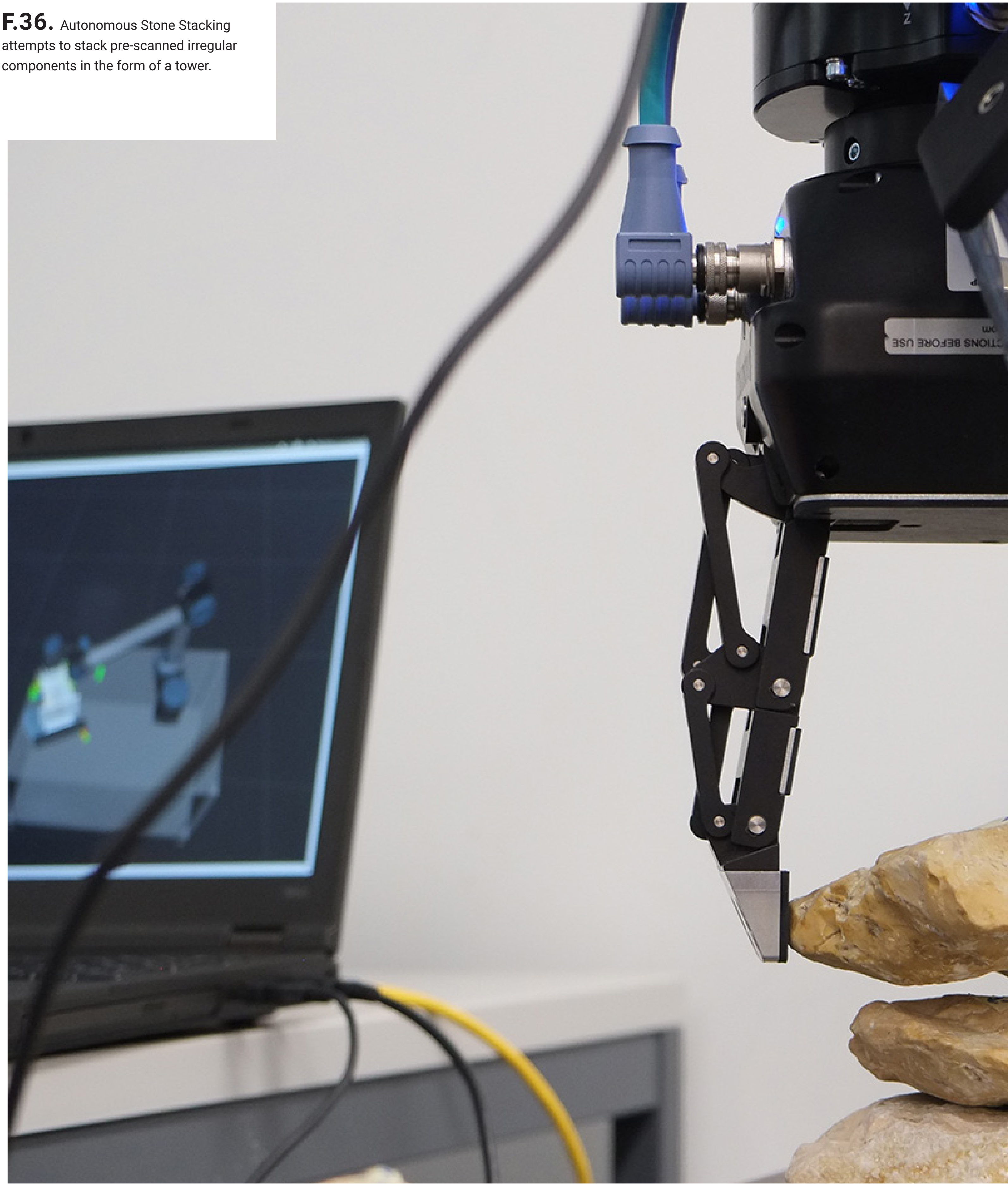
Gramazio Kohler Research group at ETH Zurich and the *Self-assembly Group* at MIT worked together on developing the *Rock Print* project, figure F.35. In this architectural installation, low-grade granular objects are jammed into reversible load-bearing structures. This process involves an innovative type of granular construction without the need for curing. This 3D rock printing method enables a variety of environmentally-friendly load-bearing structures which are assembled and disassembled by robots. Adaptability and being originated from material logic are two clear advantages of this research project. However, there are existing challenges in algorithms, physics simulation, and robotic fabrication workflow, which is inevitable in any novel research project. [88] [89]

[87] Devadass, “Robotic Fabrication of Non-Standard Material.”

[88] Petrus Aejmelaeus-Lindström et al., “Jammed Architectural Structures: Towards Large-Scale Reversible Construction,” Granular Matter 18, no. 2 (2016): 28.

[89] Petrus Aejmelaeus-Lindström et al., “Rock Print Pavilion: Robotically Fabricating Architecture from Rock and String,” Construction Robotics, 2020, 1–17.

F.36. Autonomous Stone Stacking attempts to stack pre-scanned irregular components in the form of a tower.



Autonomous Robotic Stone Stacking , which is shown in figures F.36 and F.37, is another study conducted at ETH Zurich which uses random salvaged materials. In this study, a series of stones are robotically stacked on top of one another. The mechanism designed to handle these non-standard components involve algorithmic pose finding, object detection, and an interface for balancing the vertical stack using robotic manipulators. This interface relies upon center of gravity calculations and a gradient descent valid pose search. The authors of this project reported difficulties moving beyond four components in a stack because of lack of planning for future objects. In an ideal scenario, each object in the stack should be not only stable itself, but also provide an appropriate supporting surface for the next object. [90] [91]

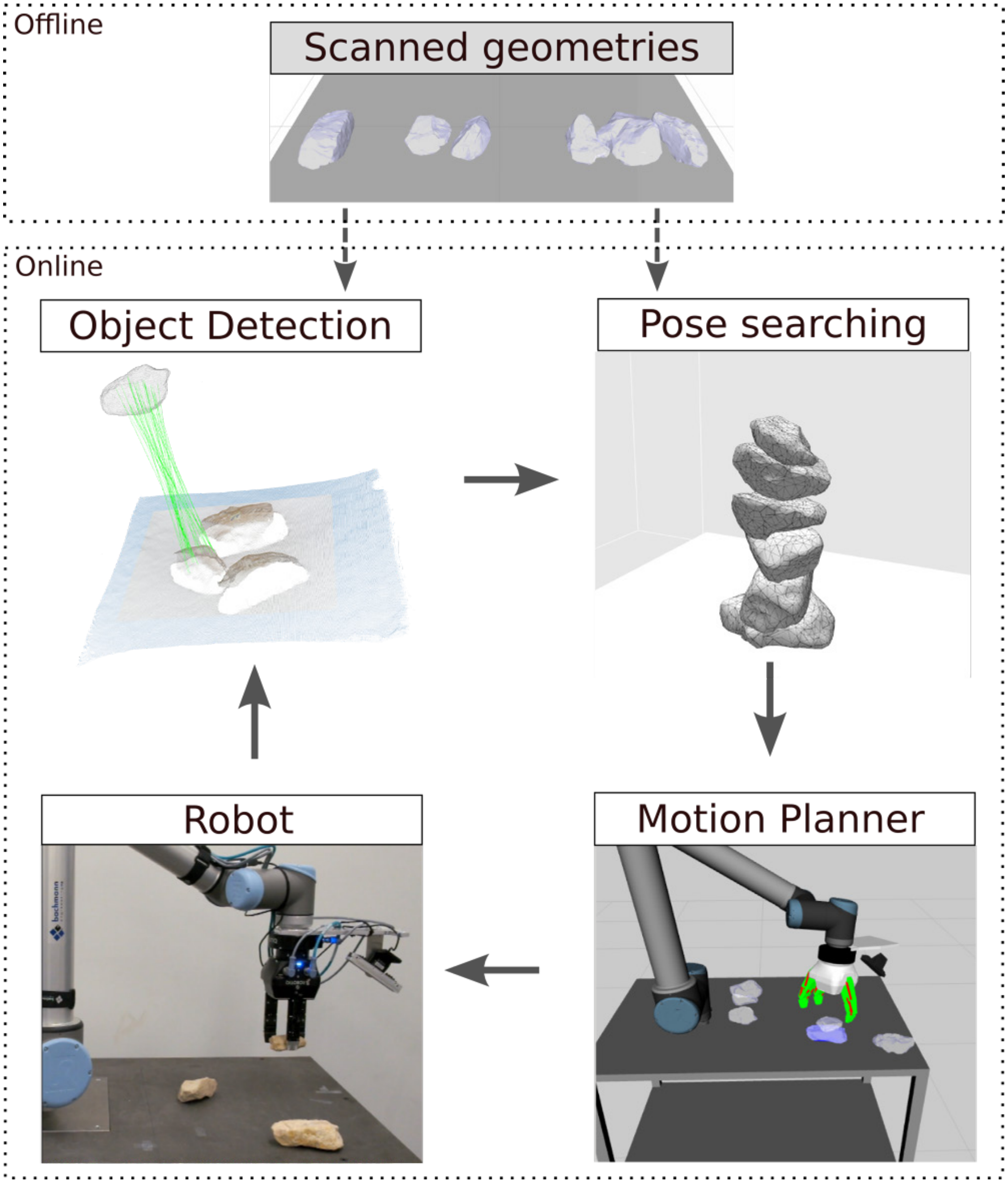
Interfaces for Adaptive Assembly is most likely the closest project to this thesis. *Johns and Anderson* designed a robotic system to reclaim locally-sourced materials in an attempt to build a dry-stacked structure. Refer to figure F.38. This project aimed to contribute to the robotic construction field by increasing the adaptability of these machines; lack of adaptability to errors and material variations is one of the major reasons why robotic fabrication, to date, is not widely implemented in the AEC industry. To recognize and manipulate non-standard components, this project employs Adaptive Assembly Library, which helps detect irregular object and calculate their location. Additionally, a custom-built gripper is developed to grasp and place objects using suction instead of pinching. This project deliberately engages with the challenges surrounding robotic fabrication, avoiding controlled scenarios. [92]

As discussed, *Wood Chip Barn, Rock Print, Autonomous Stone Stacking*, and *Interfaces for Adaptive Assembly* capitalize on the logic of found materials. Nonetheless, there are fundamental differences in how these projects addressed irregular components in the field of robotic fabrication. In the first two projects, *Wood Chip Barn* and *Rock Print*, found objects are scanned prior to design generation. Then, a best fit algorithm finds the ideal location for each component. While this method provides extraordinary results, it is not resilient to change; it does not tackle the issue of adaptability. For instance, if one of the pre-scanned objects gets removed from the set, the whole solution will be obsolete.

90. Gramazio, Kohler, and Willmann, The Robotic Touch.

91. Fadri Furrer et al., "Autonomous Robotic Stone Stacking with Online next Best Object Target Pose Planning," in 2017 IEEE International Conference on Robotics and Automation (ICRA) (2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, Singapore: IEEE, 2017), 2350–56, https://doi.org/10.1109/ICRA.2017.7989272.

92. Johns and Anderson, "Interfaces for Adaptive Assembly."



F.37. The interface used in Autonomous Robotic Stone Stacking with Online next Best Object Target Pose Planning, ETH, Zurich.

F.38. Interfaces for Adaptive Assembly attempts to construct a wall with as-found objects.

In contrast, *Autonomous Stone Stacking* and *Interfaces for Adaptive Assembly* use Online 3D scanning methods to perceive their environments. These projects, while not producing magnificent end-results, have a higher level of resiliency which is significantly important for real-world adaptation of robotic fabrication.

Wood Chip Barn and *Rubble Aggregation* attempted to assemble the materials in the form of a puzzle. In contrast, *Rock Print* relies on a compacting strategy to force the materials into place. While material jamming is effective for small objects, it cannot be applied to large objects without first crushing the objects. Furthermore, crushing certain components such as reclaimed concrete requires excessive amount of force. The "puzzle" approach outperforms the "jamming" method when dealing with large and durable components. Therefore, recognizing the geometry of salvaged objects and assembling them in the form of a structure with no to little machining is the best method for handling reclaimed construction and demolition waste such as concrete, masonry, and rubble.

F.39. Wood Chip Barn project by Design + Make Group.

Computation and Robotics

The field of computation and robotics is advancing rapidly. Many of the questions which are beginning to emerge in digital fabrication have been asked or even already answered in robotics.[93] Thus, robotic construction in architecture can benefit from a brief literature review on Mechanism Design, Perception, and Motion Planning. Mechanism design involves the establishment of the degrees of freedom, kinematics, reach, manipulators, and other characteristics of the robot. Perception manages the environmental data collected with a multitude of sensors in order to generate feedback later. Lastly, motion planning handles the complex algorithms and calculations of the robotic movement including object manipulation, clash detection, and movement mode. *Corell* and his colleagues study these subjects in the *Amazon Picking Challenge*. [94] See figure F.40.

Amazon Picking Challenge 2015 and *Amazon Robotics Challenge 2017* are analyzed to obtain a holistic understanding of different mechanisms and their effectiveness for handling irregular objects. These examinations report an incredible diversity at hardware, software, and scripting levels. Moreover, the results indicate that in many cases “we do not need to reinvent the wheel”; off-the-shelf devices paired with open-source libraries provide reliable results. [95] Refer to figures F.41, F4.2, and F.43. For example, Open-CV enables image-video processing and Point Cloud Library (PCL) enables 3D perception and pose estimation. Furthermore, MoveIt and Open Motion Planning Library (OMPL) can be used for motion planning. Lastly, AGEIA PhysX, Bullet, and Open Dynamics Engine are three of the many free physics engines which could be utilized to accurately run a rigid-body simulation. [96]

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93. Johns and Anderson.

94. Correll et al., “Analysis and Observations From the First Amazon Picking Challenge.”

95. Correll et al.

96. Adrian Boeing and Thomas Bräunl, “Evaluation of Real-Time Physics Simulation Systems,” in Proceedings of the 5th International Conference on Computer Graphics and Interactive Techniques in Australia and Southeast Asia - GRAPHITE ’07 (the 5th international conference, Perth, Australia: ACM Press, 2007), 281, https://doi.org/10.1145/1321261.1321312.

F.40. RBO team's robot participating in the first Amazon Picking Challenge.

Computation and robotics field has made adequate advancement to automate picking and placement of random objects. *Amazon Picking Challenge* has proved that conventional technologies and open source code libraries, if coupled, can create a functional interface for detecting irregular objects, grasping, and placing. Nevertheless, these systems are still beneath the capabilities of a human. On average, a warehouse worker sorts about 400 units per hour while the best robot in this competition only achieved a rate of 30 units per hour. Also, the error rates of these tools were noticeable higher than the mistakes made by a human worker. Reaching the speed and accuracy of an individual requires further optimization of mechanisms and algorithms. [97]

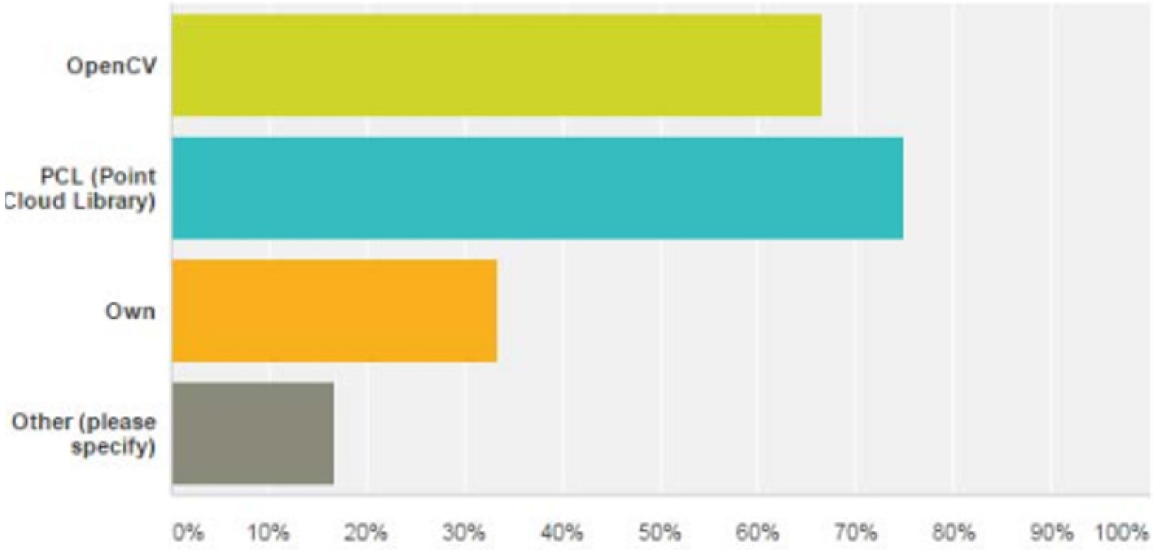
Conclusion

This thesis argues that attention to context is crucial in the advancement of digital fabrication technologies. The significance of these machines stems from their use, cultural, environmental, and economical advantages. [98] The necessity of reusing and recycling construction and demolition waste, heavy and irregular components, and high labor costs, incentivize usage of modern tools which are able to automatically handle these components with minimal modification. Artificially intelligent robots have the capacity to scan irregular objects, devise a plan to meet design goals, and evaluate the outcome. Additionally, these machines can operate under hazardous circumstances, reducing workplace accidents for humans. In regions where architecture is affected by expensive labor, these making devices can play an important role. Finally, the ability to build using found material makes these technologies the perfect choice for construction in remote areas. [99]

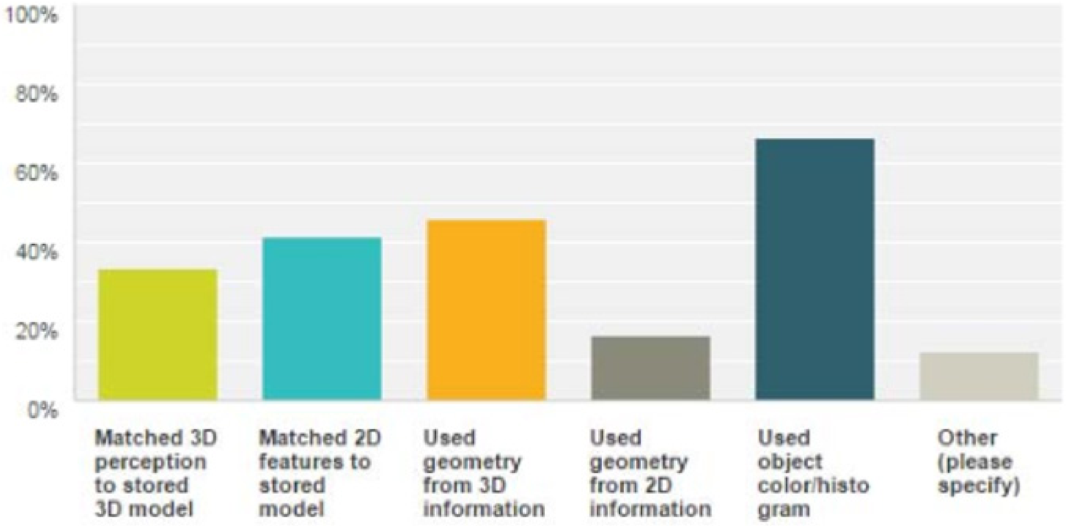
97. Correll et al., “Analysis and Observations From the First Amazon Picking Challenge.”

98. Gramazio, Kohler, and Willmann, The Robotic Touch.

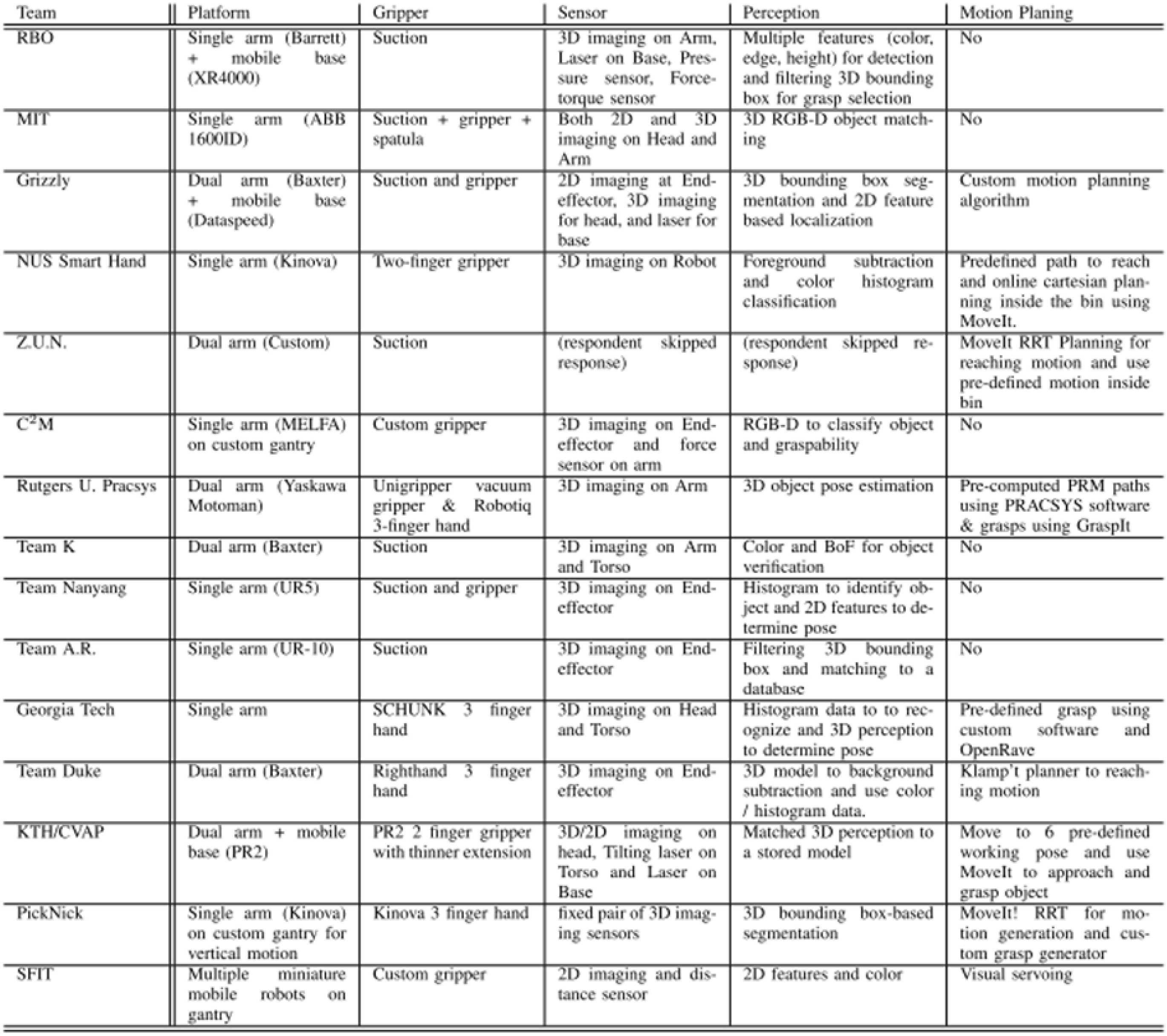
99. Daas and Wit, Towards a Robotic Architecture.



F.41. Software programs used by different teams in the first Amazon Picking Challenge.



F.42. Object recognition methods employed by different teams in the first Amazon Picking Challenge.



F.43. Summary of the employed methods by the participating teams in the first Amazon Picking Challenge.

Team	Platform	Gripper	Sensor	Perception	Motion Planing
RBO	Single arm (Barrett) + mobile base (XR4000)	Suction	3D imaging on Arm, Laser on Base, Pressure sensor, Force-torque sensor	Multiple features (color, edge, height) for detection and filtering 3D bounding box for grasp selection	No
MIT	Single arm (ABB 1600ID)	Suction + gripper + spatula	Both 2D and 3D imaging on Head and Arm	3D RGB-D object matching	No
Grizzly	Dual arm (Baxter) + mobile base (Dataspeed)	Suction and gripper	2D imaging at End-effector, 3D imaging for head, and laser for base	3D bounding box segmentation and 2D feature based localization	Custom motion planning algorithm
NUS Smart Hand	Single arm (Kinova)	Two-finger gripper	3D imaging on Robot	Foreground subtraction and color histogram classification	Predefined path to reach and online cartesian planning inside the bin using MoveIt.
Z.U.N.	Dual arm (Custom)	Suction	(respondent skipped response)	(respondent skipped response)	MoveIt RRT Planning for reaching motion and use pre-defined motion inside bin
C^2M	Single arm (MELFA) on custom gantry	Custom gripper	3D imaging on End-effector and force sensor on arm	RGB-D to classify object and graspability	No
Rutgers U. Pracsys	Dual arm (Yaskawa Motoman)	Unigripper vacuum gripper & Robotiq 3-finger hand	3D imaging on Arm	3D object pose estimation	Pre-computed PRM paths using PRACSYS software & grasps using GraspIt
Team K	Dual arm (Baxter)	Suction	3D imaging on Arm and Torso	Color and BoF for object verification	No
Team Nanyang	Single arm (UR5)	Suction and gripper	3D imaging on End-effector	Histogram to identify object and 2D features to determine pose	No
Team A.R.	Single arm (UR-10)	Suction	3D imaging on End-effector	Filtering 3D bounding box and matching to a database	No
Georgia Tech	Single arm	SCHUNK 3 finger hand	3D imaging on Head and Torso	Histogram data to to recognize and 3D perception to determine pose	Pre-defined grasp using custom software and OpenRave
Team Duke	Dual arm (Baxter)	Righthand 3 finger hand	3D imaging on End-effector	3D model to background subtraction and use color / histogram data.	Klamp't planner to reaching motion
KTH/CVAP	Dual arm + mobile base (PR2)	PR2 2 finger gripper with thinner extension	3D/2D imaging on head, Tilting laser on Torso and Laser on Base	Matched 3D perception to a stored model	Move to 6 pre-defined working pose and use MoveIt to approach and grasp object
PickNick	Single arm (Kinova) on custom gantry for vertical motion	Kinova 3 finger hand	fixed pair of 3D imaging sensors	3D bounding box-based segmentation	MoveIt! RRT for motion generation and custom grasp generator
SFIT	Multiple miniature mobile robots on gantry	Custom gripper	2D imaging and distance sensor	2D features and color	Visual servoing

METHODOLOGY

- Material Study
- Mechanism Design
- Perception
- Computational Design
- Experiment 0: Fetch - Machine Vision
- Experiment 1: The Leaning Tower of Lire - Column
- Experiment 2: 3D-Bin Packing Problem - Wall

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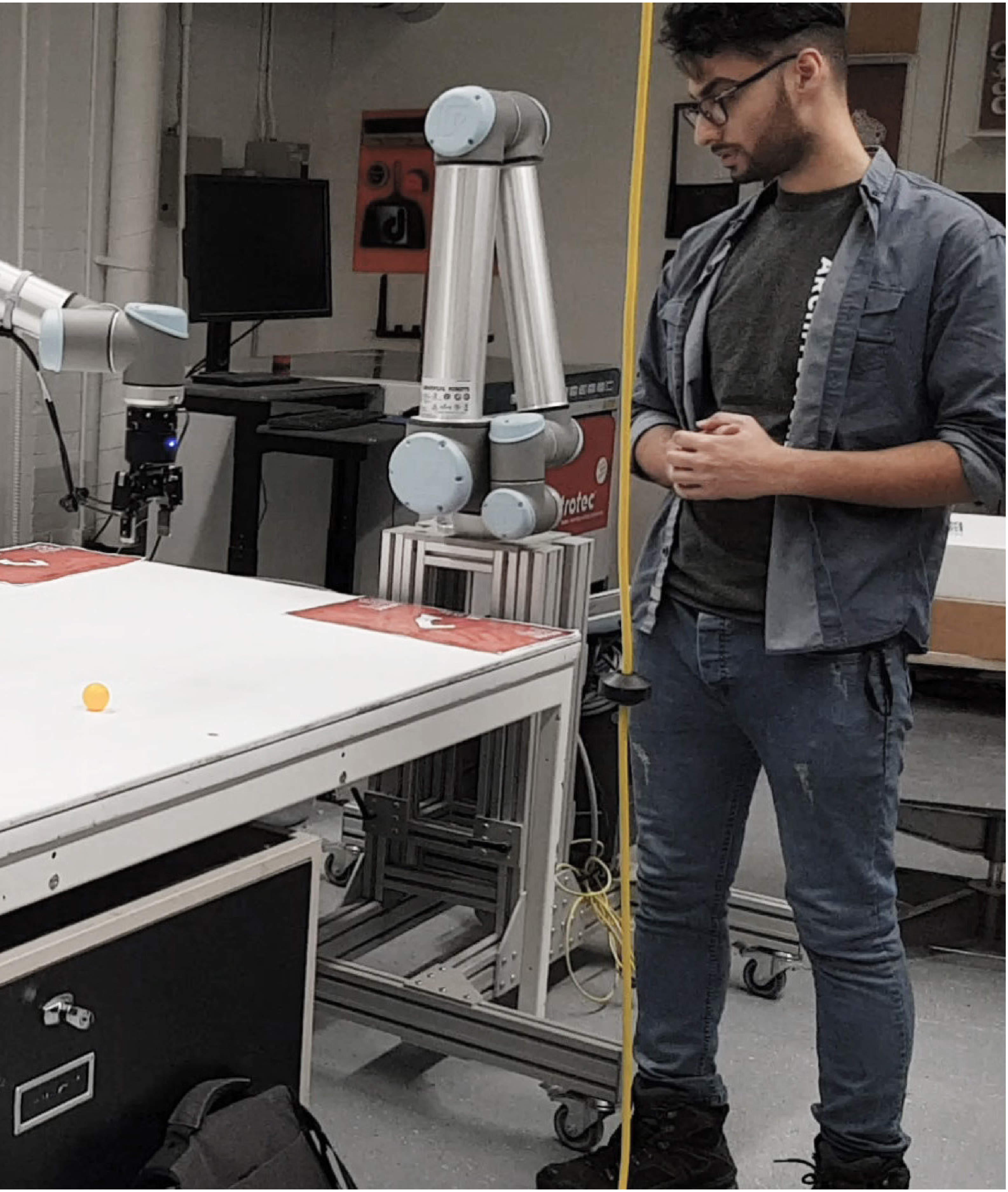
F.44. In Experiment 0: Fetch, a ping pong ball is placed on the table and the robotic arm automatically proceeds to grasp the item.



#Process

#Fabrication

#Prototype

#Simulation

#Rigid-body

#Irregular Objects

#Grasshopper

#Python

#Machine Vision

#Mechanism Design

This thesis aims to create an intelligent system for the robotic stacking of recovered rubble as irregular components. This system repurposes construction, demolition, and disaster waste into the main component for the construction of environmentally-friendly, materially-informed, and compression-only structures. This chapter acts as a bridge between the literature and the outcome of this thesis, including material study, hardware, software, experiments, and algorithm design. Two sets of experiments are conducted to help develop the algorithm; each set includes physical prototyping, study of existing assembly systems, and digital prototyping. First set attempts to recreate an interface similar to Autonomous Stone Stacking, see page 72, in order to stack objects vertically. The second set attempts to take a step further by prototyping a wall. This part can be deemed as an extension to Interfaces for Adaptive Assembly, see page 74.

Material Study

Material study is a crucial part of an architectural fabrication process. This section of the design provides insight about strength, price, warmth, form, function, color, and locality of the materials. [100] As-found waste materials often possess a lower strength than a new component. Although these objects can come in many different shapes, the overall geometric properties are the same provided they are similar in material composition. For instance, pieces of rubble have a roughly round form with fragile bumps on the surface, whereas pieces of broken tiles and mosaics have flat sides with a few sharp corners.

To conduct the experiments in this thesis, one hundred thirty-six pieces of construction and demolition waste were retrieved from a road construction site in Cambridge, Ontario. Some of these materials are portrayed in figures F.45, F.46, and F.47. The majority of this mix was pieces of concrete rubble with a low number of broken tile pieces. The weight of these elements ranged from approximately one hundred grams to four and a half kilograms. The smallest dimension for was about an inch, while the largest dimension was nearly one foot. The color variations were different shades of brown and gray. These reclaimed components were used for physical prototyping and gaining first-hand experience with their respective assembly systems. The following pages include photographs by author portraying the salvaged components.

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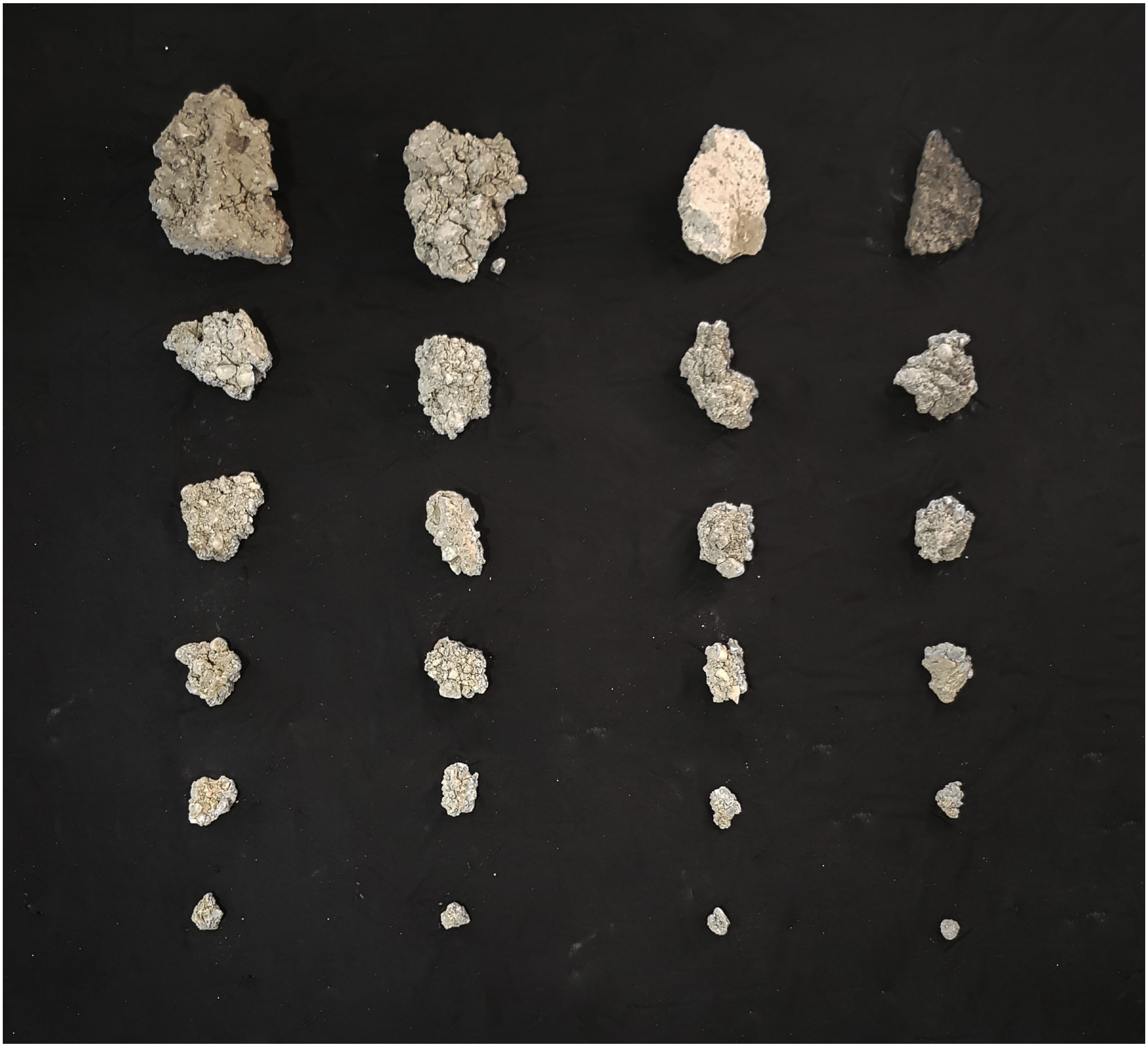
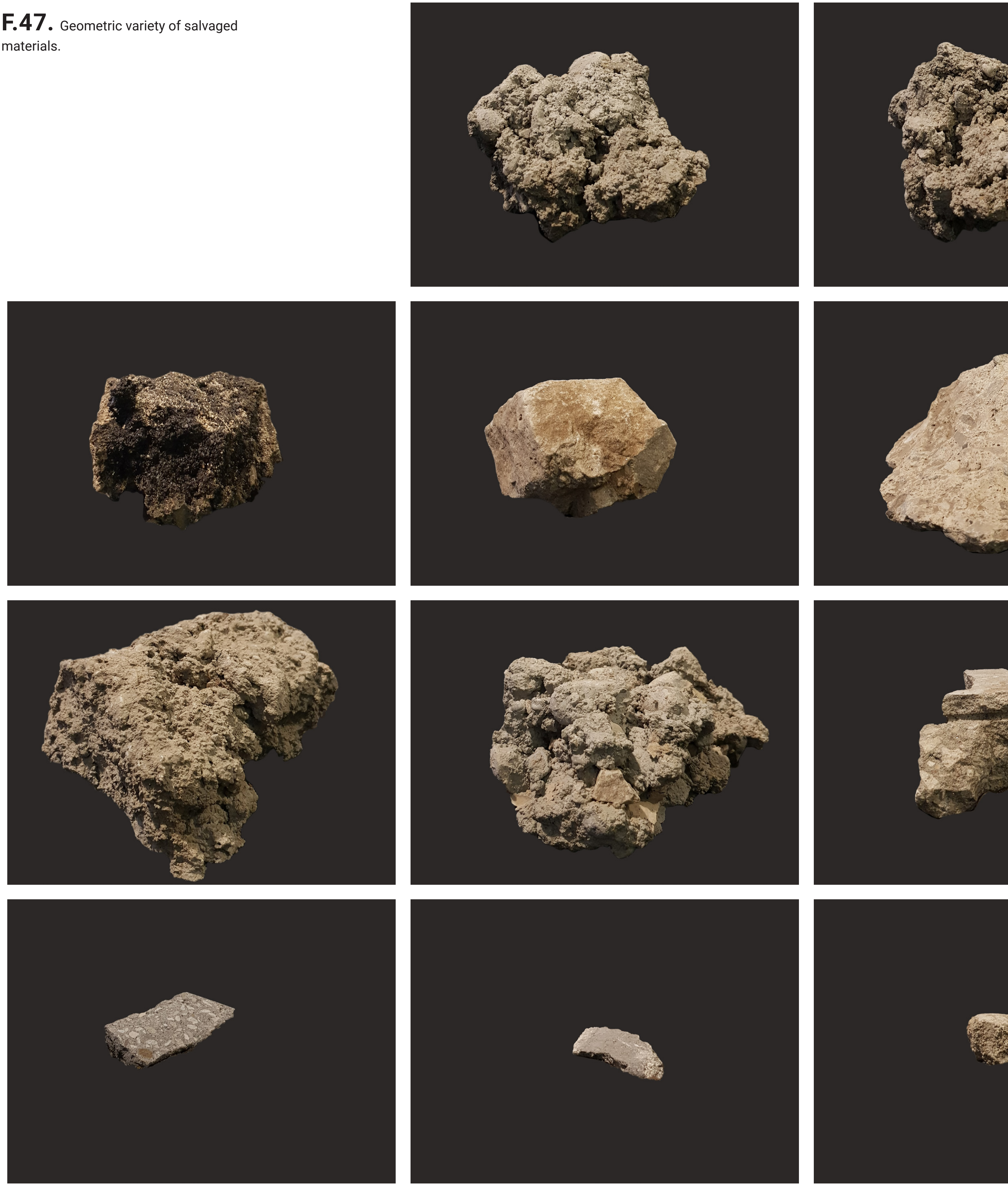
100. Lisa Wastiels and Ine Wouters, "Material Considerations in Architectural Design: A Study of the Aspects Identified by Architects for Selecting Materials" (Undisciplined! Design Research Society Conference 2008, Sheffield Hallam University, Sheffield, UK, 2009), http://shura.shu.ac.uk/511/.

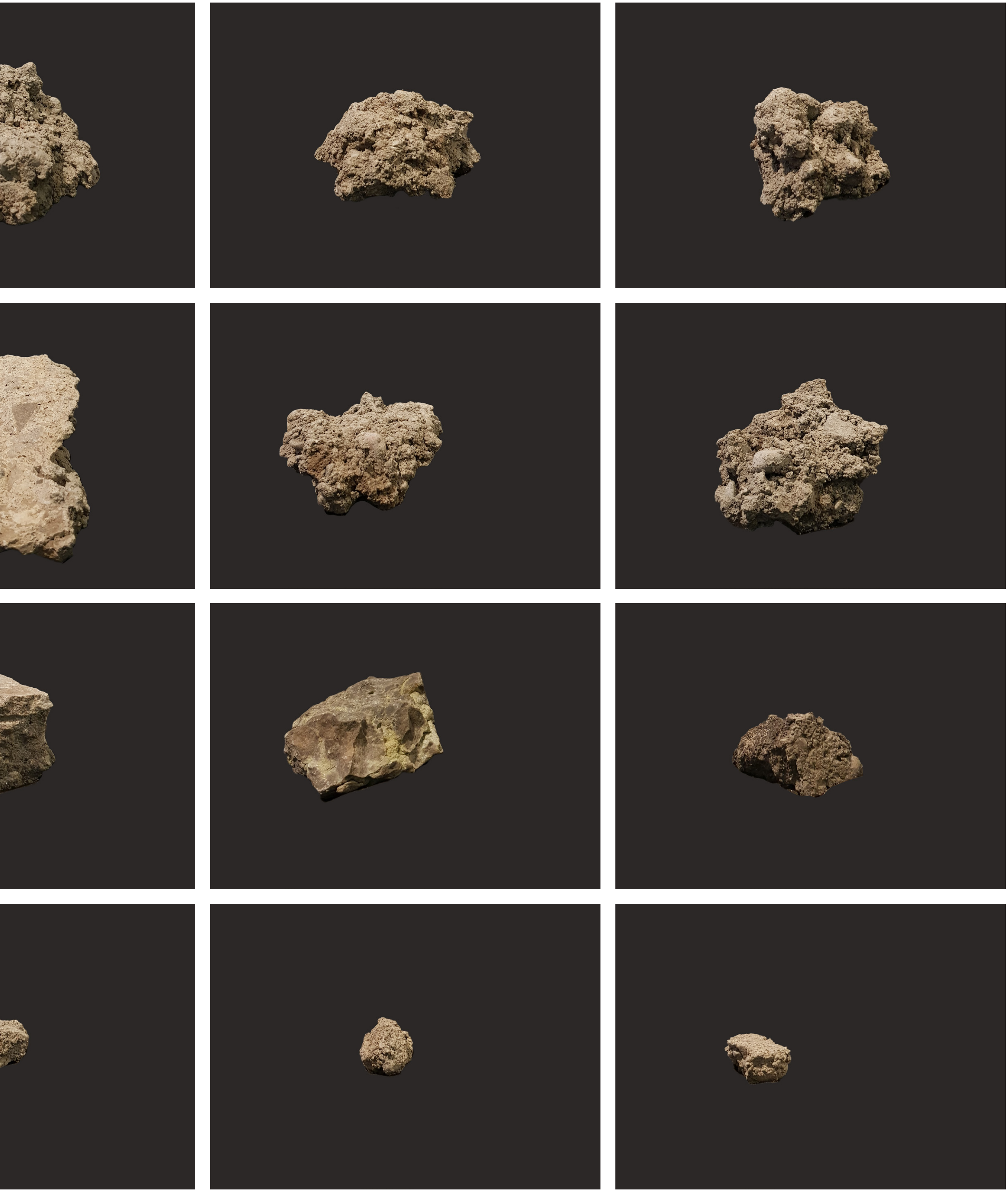


F.45. Studying the size and the geometry of the materials is an important step in designing a robotic fabrication interface.

F.46. Unique textures of reclaimed rubble.

F.47. Geometric variety of salvaged materials.





Mechanism Design

A computationally enabled system was developed that can autonomously manipulate irregular components to assemble compression-only stack structures. This process is illustrated in figure F.49. This system is a network of interconnected devices, shown in figure F.48, that enable perception, computation, and manipulation. Perception, observation and understanding the non-standard components, is achieved through the use of two cameras with depth sensor installed on the 3D scanning platform and the robot. Computation, which is the "brain" of the operation, is done with Python, Rhinoceros 3D, and Grasshopper on a windows computer. Lastly, object manipulation, grasping and placement of components, is accomplished through employing a six-axis industrial robot and a two-finger gripper as end-effector. While, this mechanism is not ideal to handle the irregular objects, it is adequate to provide a working proof of concept.

UR10 is a collaborative industrial robot manufactured by The Universal Robots. This machine, which is used in numerous industrial applications such as packaging, palletizing, assembly, and pick and place, weighs 33.5 kilograms, can carry 10 kilograms, and reaches as far as 1300 millimeters. The popularity and design of UR10 allows many third-party devices to be used, for instance, a variety of grippers, 3D cameras, and force torque sensors can be attached to this device. A user can program the UR10 using three different methods: UR10 interface, offline programming with UR script, and online remote control through TCP/IP protocol. [101]

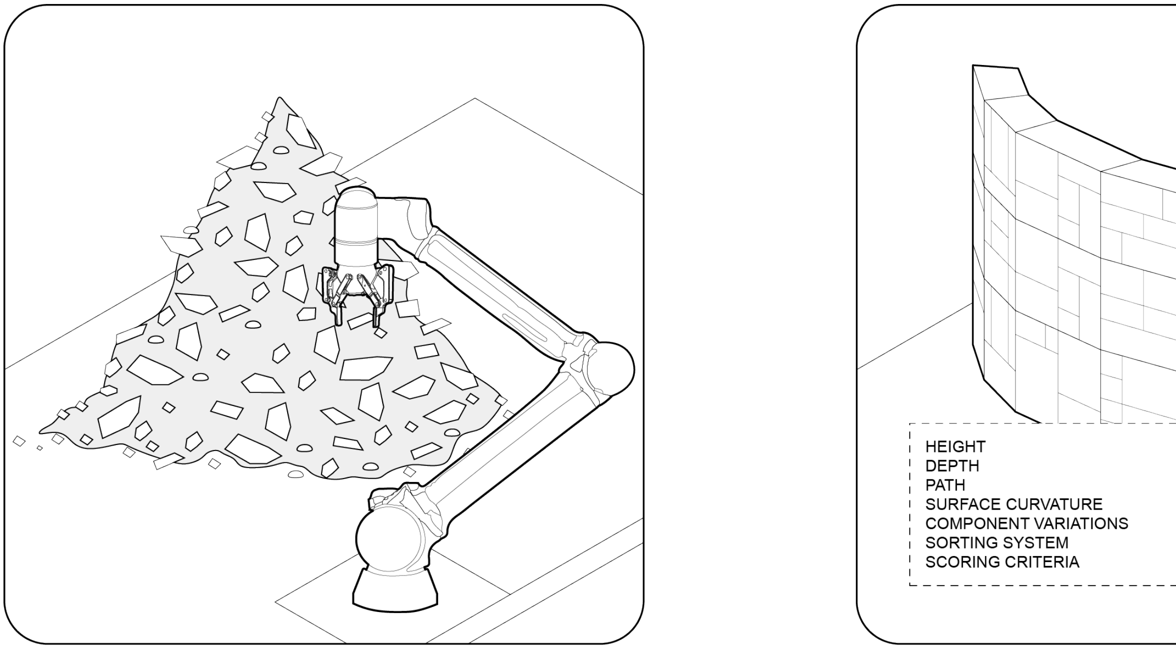
Robotiq 2F-85 gripper is another tool used in this research. This gripper, while not ideal for grasping irregular objects, was chosen due to its immediate availability. This piece of equipment is able to grasp objects as wide as 85 millimeters with a form-fit grip payload of 5 kilograms. The closing speed and the pinching force of the fingers are adjustable. [102] This device is programmable through the UR10 interface, UR10 script, however, can not be controlled remotely through UR10. This gripper has a separate address and should be controlled separately using a python script provided by the manufacturer.

101. "UR10e Collaborative Industrial Robotic Arm - Payload up to 10 Kg," accessed September 7, 2020, https://www.universal-robots.com/products/ur10-robot/.

102. "2F-85 and 2F-140 Grippers," Robotiq, 85, accessed September 7, 2020, https://robotiq.com/products/2f85-140-adaptive-robot-gripper.

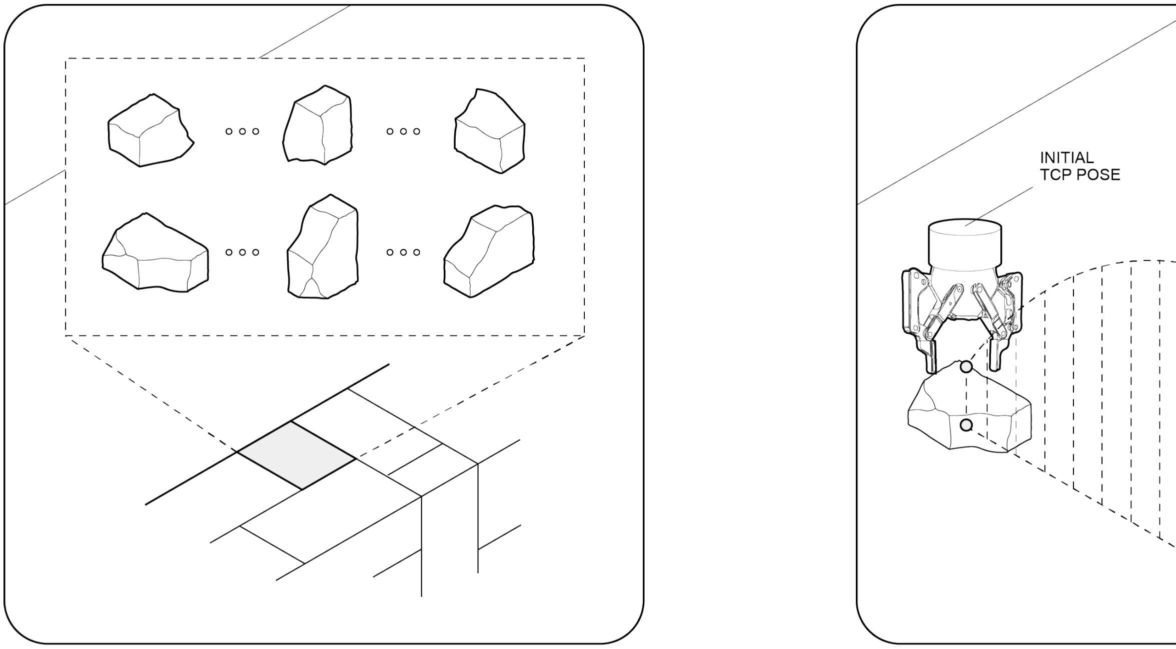
F.48. Hardware used to develop the interface in this thesis. From top left: RGB-D Sensor, Arduino microcontroller, Windows laptop, and UR10 Cobot.

F.49. Process diagram.



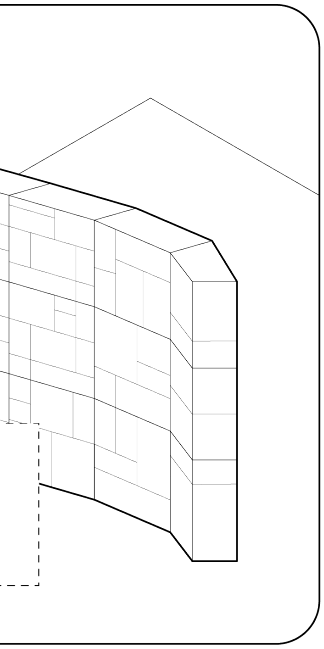
Construction Waste as Building Material

Setting Desi



AI Calculates Best Object & Target Pose

Path Ge



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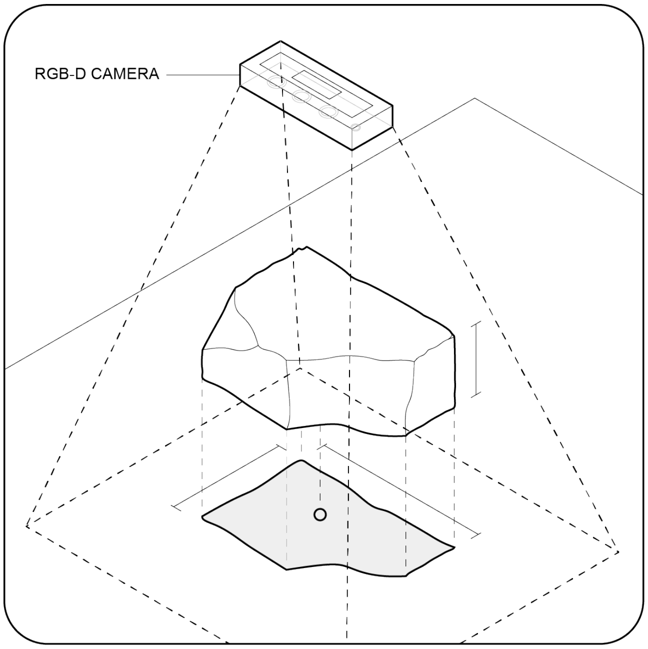
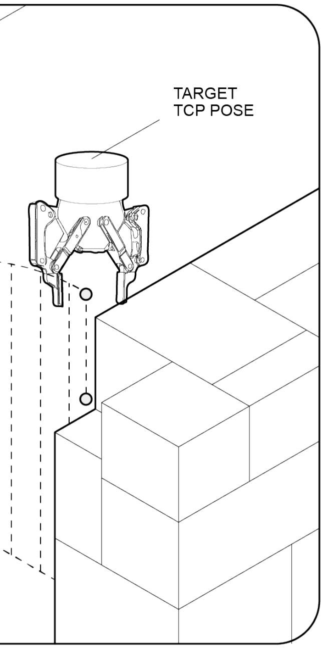


Object is Scanned and Analyzed



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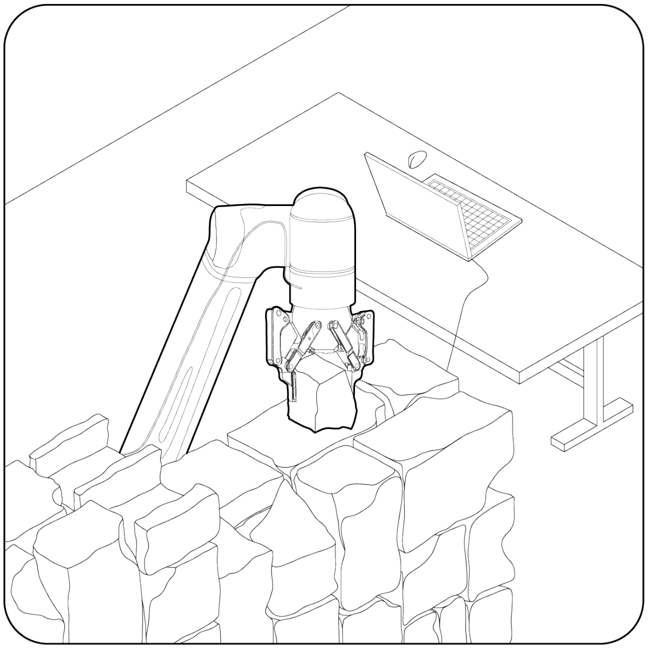

Robot Places Object

Perception

Object recognition is an integral part of the adaptive process. A change should be observed for the system to respond accordingly. This field is heavily researched in robotics as computer-vision or machine-vision which involves automatic analysis of image-based data for process control, guidance, and inspection. As illustrated in *Amazon Picking Challenge*, see page 78, the open-source libraries such as Open-CV and Point Cloud Library (PCL) provide adequate tools to create a digital copy of the physical world. This pipeline can be divided into a number of steps: Shelf Tracking, Feature Extraction, Probability Estimation, Pixel Labelling, Selection, Box Fitting.

While there are industrial options such as PICKIT plug & play 3D camera for robot guidance, this research suggests using two RGB-D camera modules along with open-source libraries to provide more control. [103] One depth sensor is installed on a rotating digital scale which allows comprehensive 3D-scanning and weighing of materials. The second module can be mounted on either the robot or above the working site. This module is responsible for process monitoring and providing the location of the new object, structure, and other physical objects. The former option provides a better object recognition for pick and place scenarios whereas the latter excels in coordination and error detection.

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103. "A Plug and Play 3D Vision Product at a Fixed Price," Pick-it, accessed September 7, 2020, https://www.pickit3d.com/.

Computational Design

To have a working interface, all the hardware must be linked to one another in a computational ecosystem. The robot should be constantly updated about its surroundings to manipulate objects appropriately. To that end, a recursive process is designed using two separate platforms, Python and Grasshopper. Python is a famous and easy-to-use high-level programming language which is employed for using Open-CV and PCL for perception. [104][105][106] Grasshopper is a popular visual programming language on Rhinoceros 3D often utilized by industrial and architectural designers. [107] In this thesis, grasshopper is paired with PhysX, a rigid-body physics simulator, to develop generative algorithms based on a variety of objectives and constraints. Next, Machina is used to establish a real-time communication with the UR10. [108] Figure F.50 depicts a summary of this computational process. For a more detailed diagram, refer to the appendices section.

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104. “Welcome to Python.Org,” Python.org, accessed September 7, 2020, https://www.python.org/.

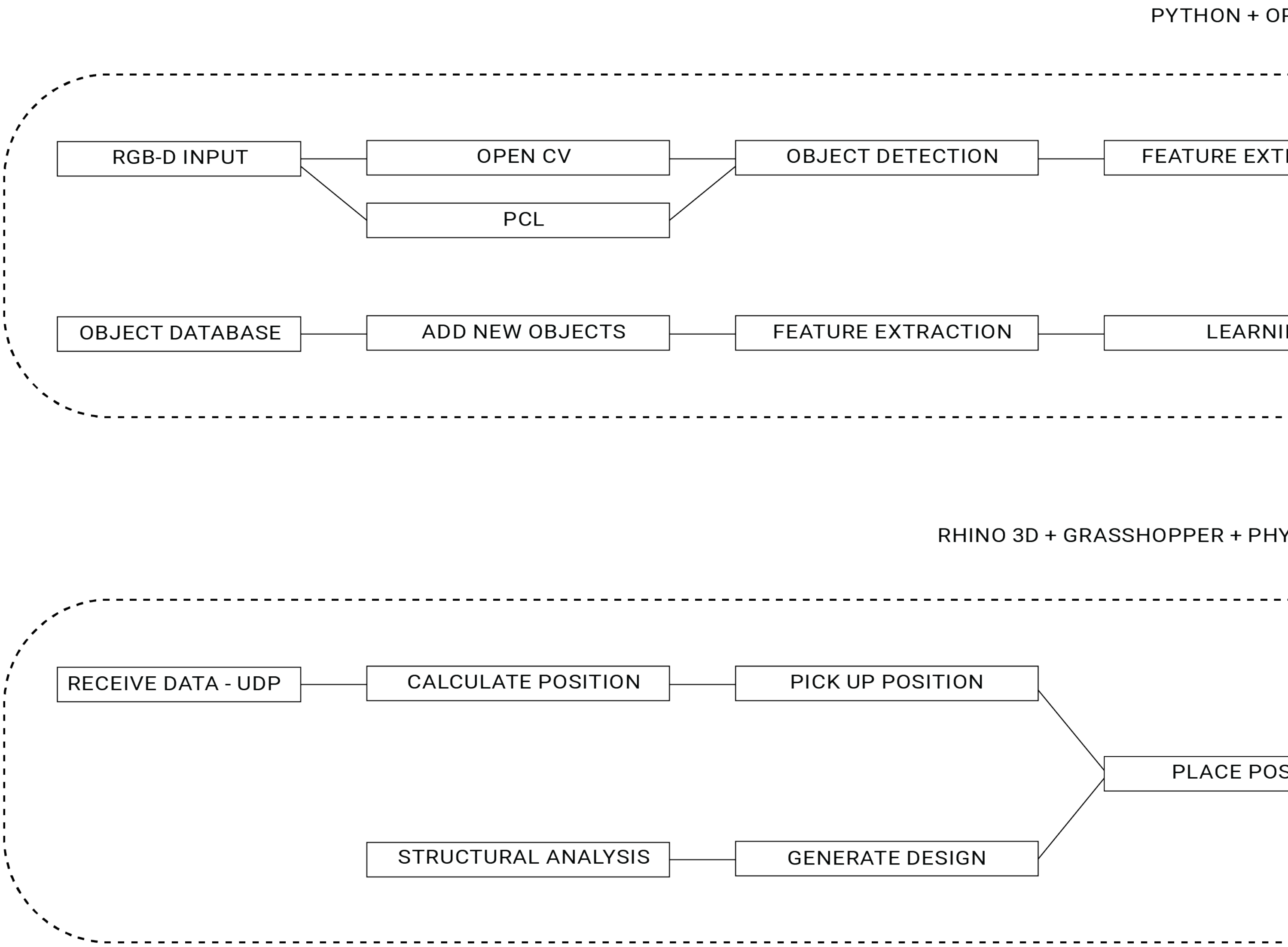
105. “About,” accessed September 7, 2020, https://opencv.org/about/.

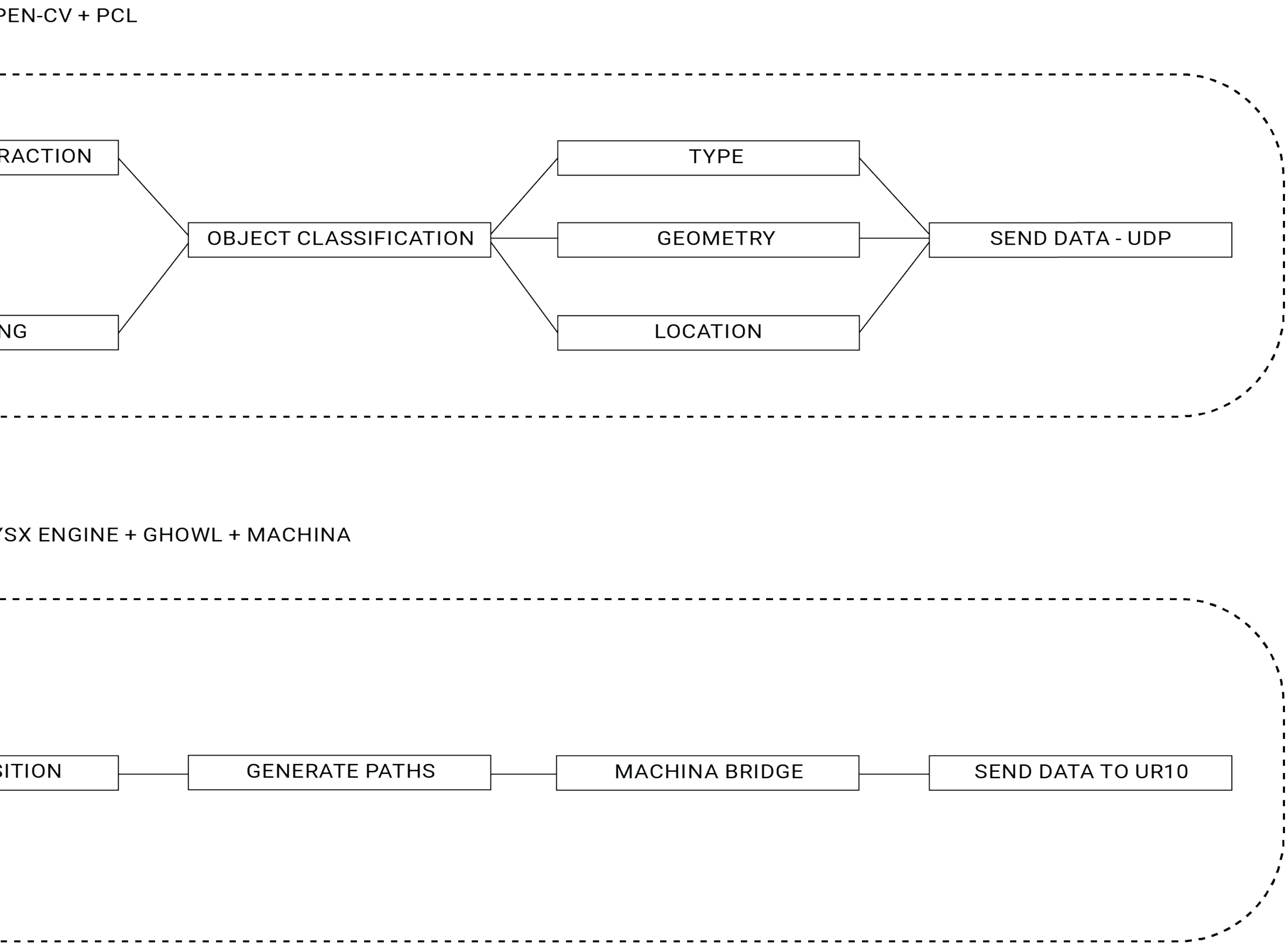
106. “About,” Point Cloud Library, accessed September 7, 2020, https://pointcloudlibrary.github.io/about/.

107. Scott Davidson created this Ning Network, “Grasshopper,” accessed September 7, 2020, https://www.grasshopper3d.com/.

108. “Machina,” Text, Food4Rhino, February 26, 2018, https://www.food4rhino.com/app/machina.

F.50. Summarized computational diagram of how the systems communicate.



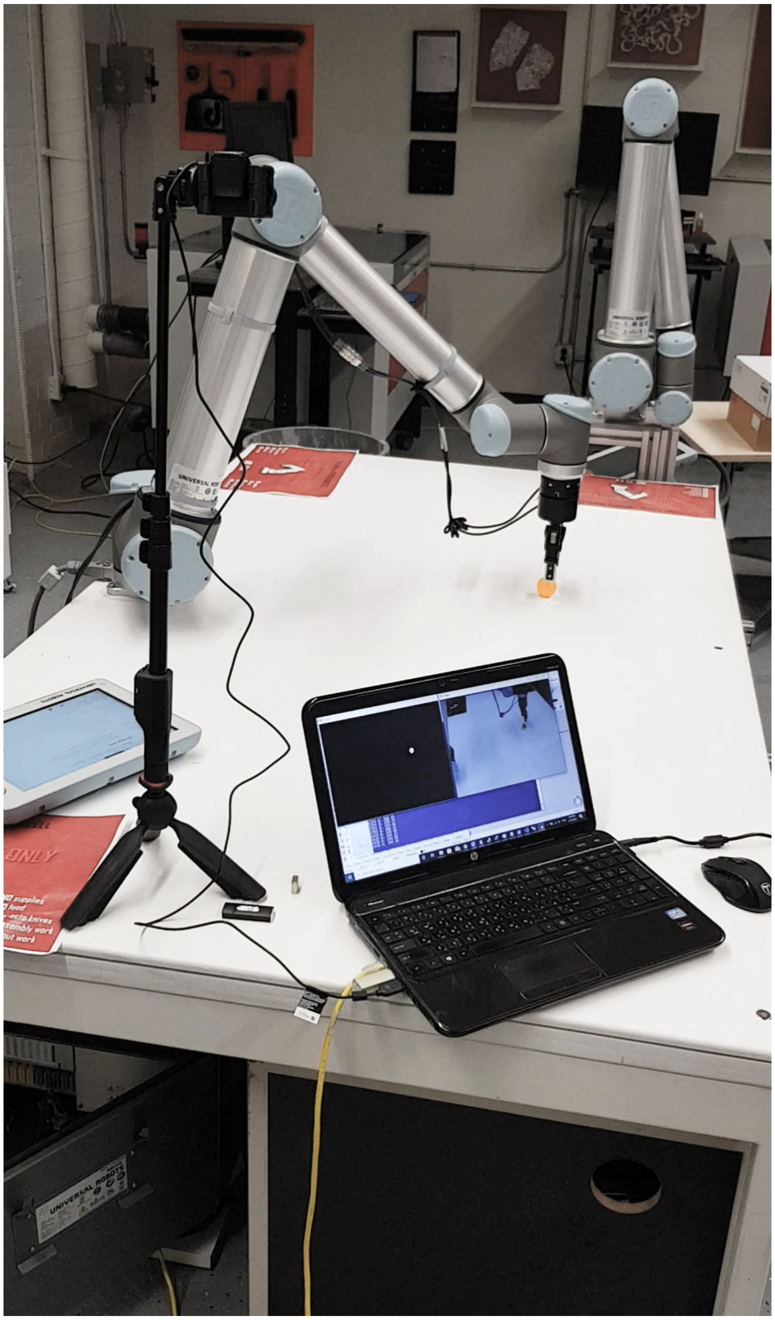

PEN-CV + PCL
RACTION
NG
OBJECT CLASSIFICATION
TYPE
GEOMETRY
LOCATION
SEND DATA - UDP
YSX ENGINE + GHOWL + MACHINA
SITION
GENERATE PATHS
MACHINA BRIDGE
SEND DATA TO UR10

Experiment 0: Fetch – Machine Vision

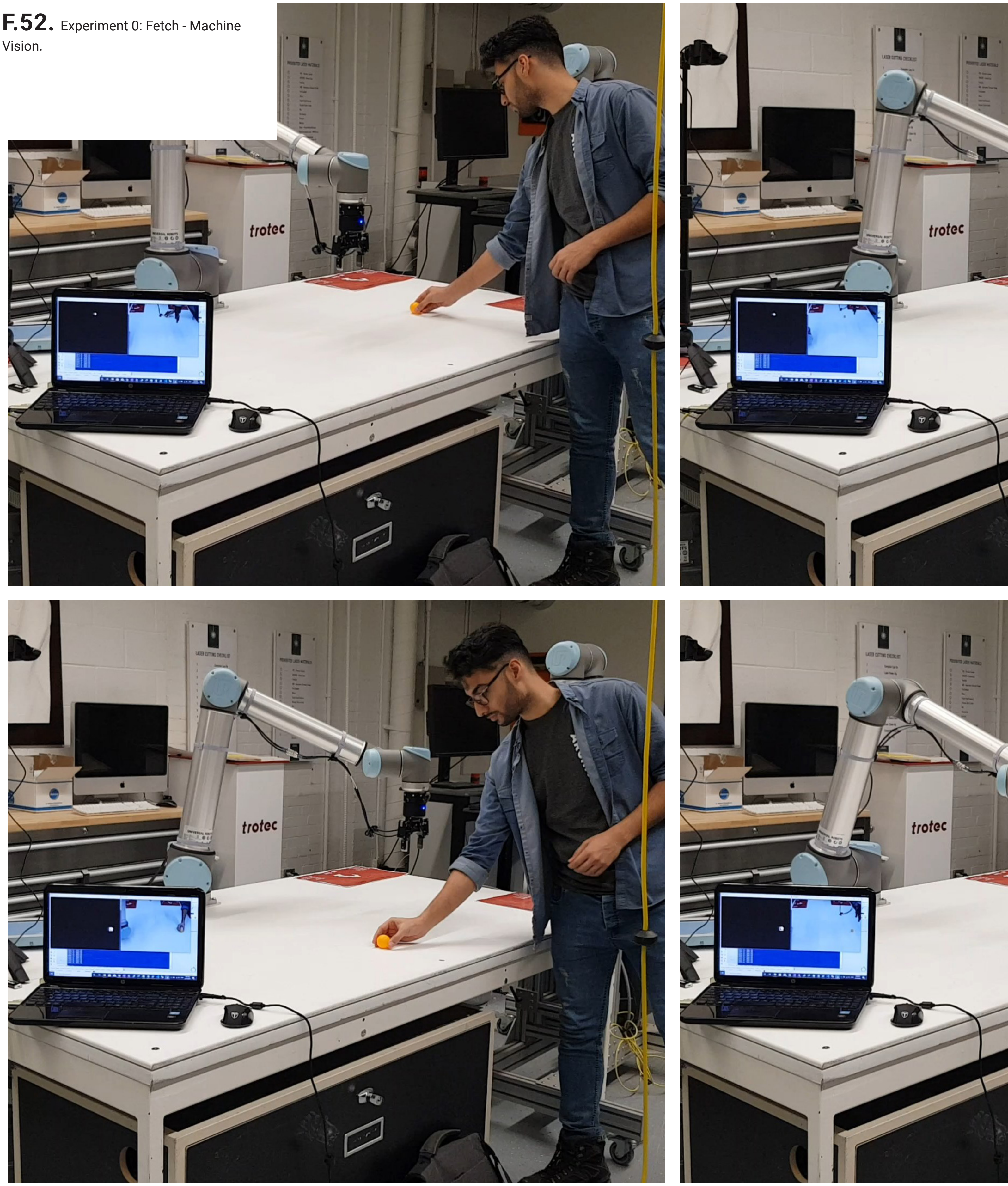
This preliminary experiment, codenamed “Fetch”, depicted in figures F.51 and F.52 investigated machine vision and online UR10 programming application. In this experiment, an off-the-shelf webcam and Open-CV open library were used to track the location of a ping pong ball on the table. Then, the location of the ball was communicated to grasshopper where the UR10 movement path was generated. Next, using Machina, the commands were sent to the robot and the robot proceeded to grasp the object. Unfortunately, this experiment remained at its initial phase due to the closure of digital fabrication facilities due to the COVID-19 pandemic. Nevertheless, this brief test helped me learn operating the UR10 and provided proof that an adaptive interface is achievable.

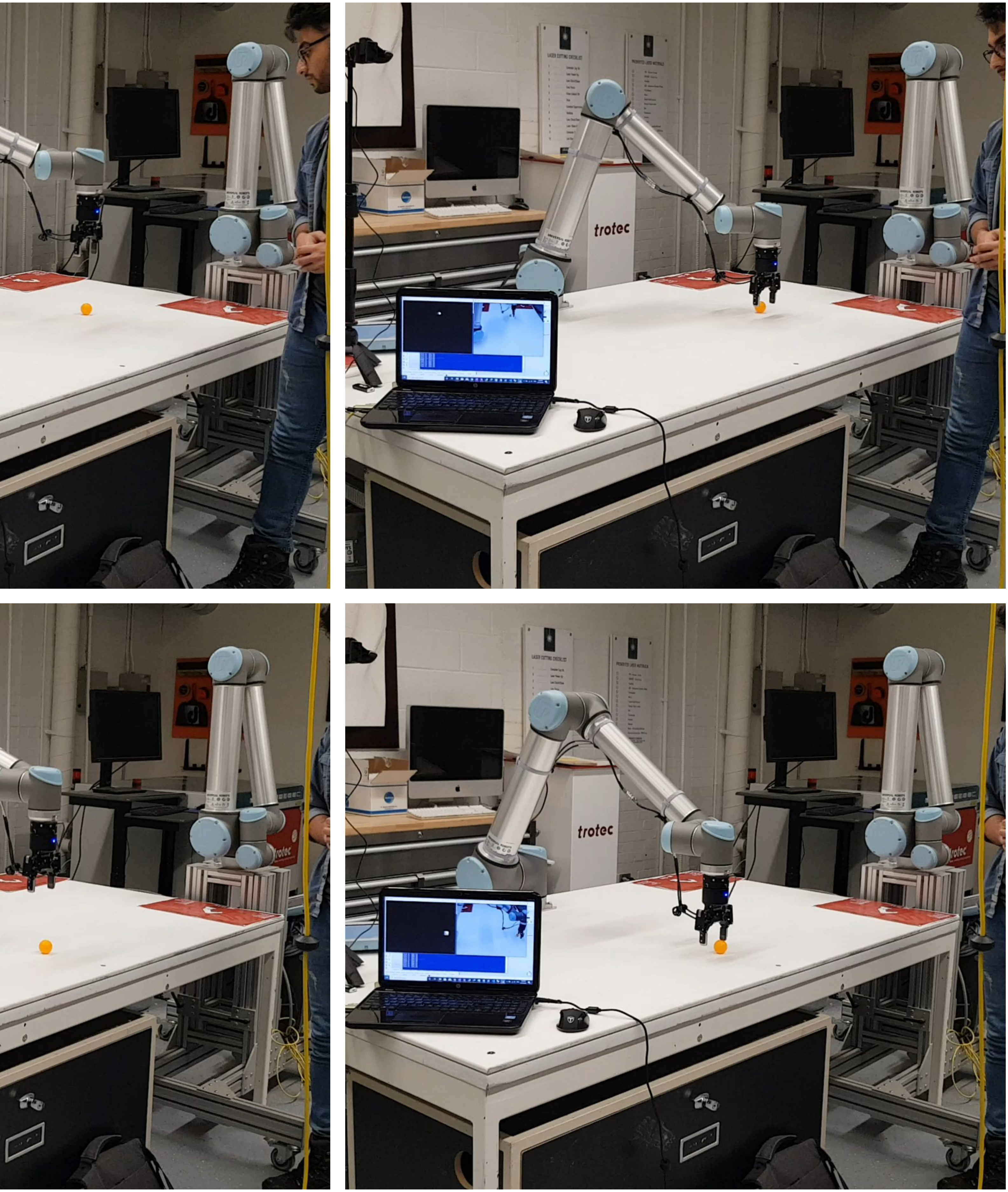
Even though experimenting with reclaimed materials and robots in a physical manner was not possible due to the closure of fabrication labs, this research attempted to consider the challenges of physical prototyping. As a first step, objects should go through a filtering to eliminate inappropriate objects which do not fit certain criteria. This filtering is informed by the design goals as well as the robotic restrictions. The weight of the object should not exceed the payload capability of the robot or the gripper. In addition, the minimum dimension of the component should not be larger than the 85-millimeter stroke limit of the Robotiq 2F-85 gripper. Other factors include having a relatively flat base for stability and a relatively flat top for stackability. See figure F.53.

F.51. Open-CV and Grasshopper 3D communicate to enable the real-time detection and grasping of a ping pong ball.

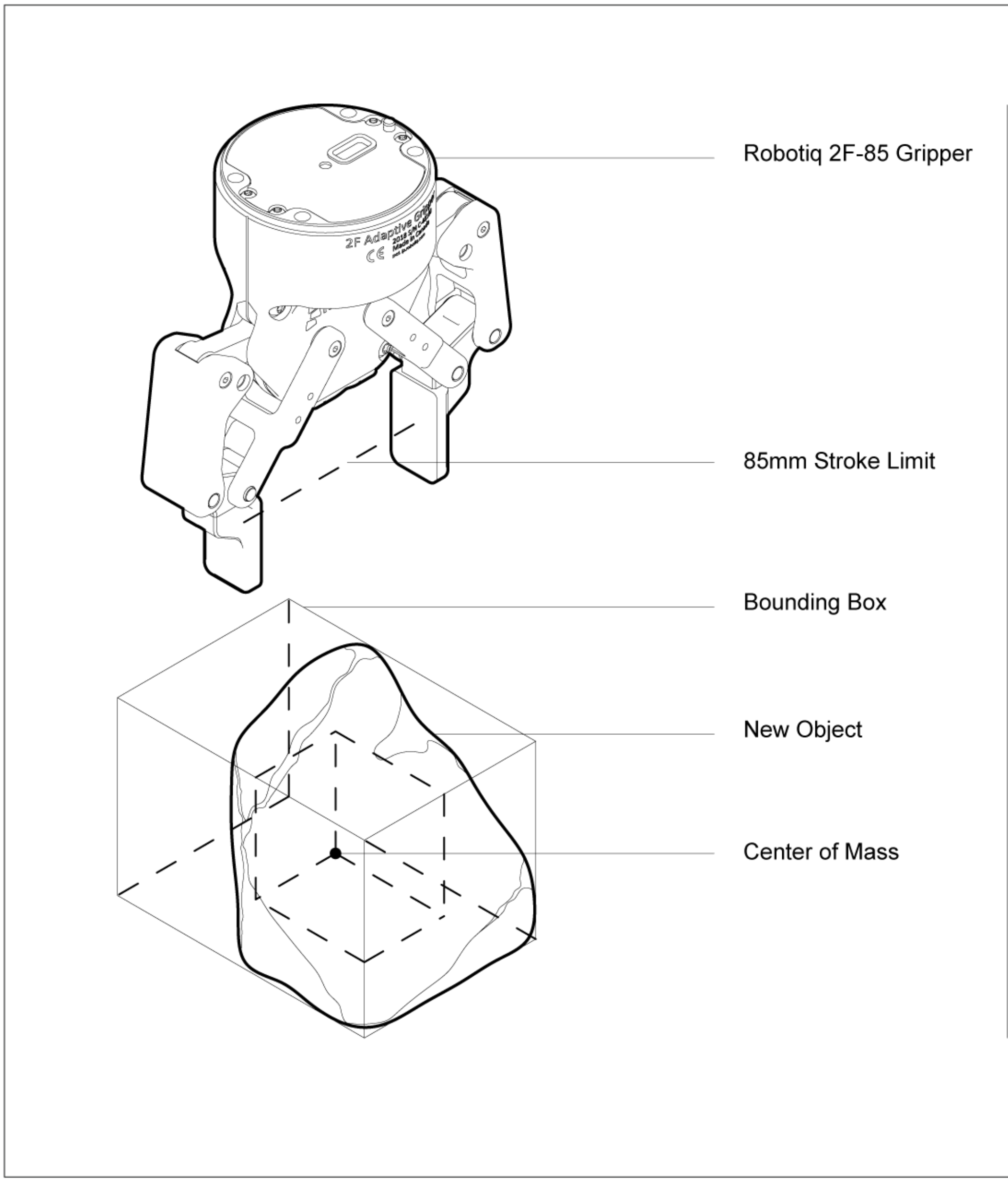


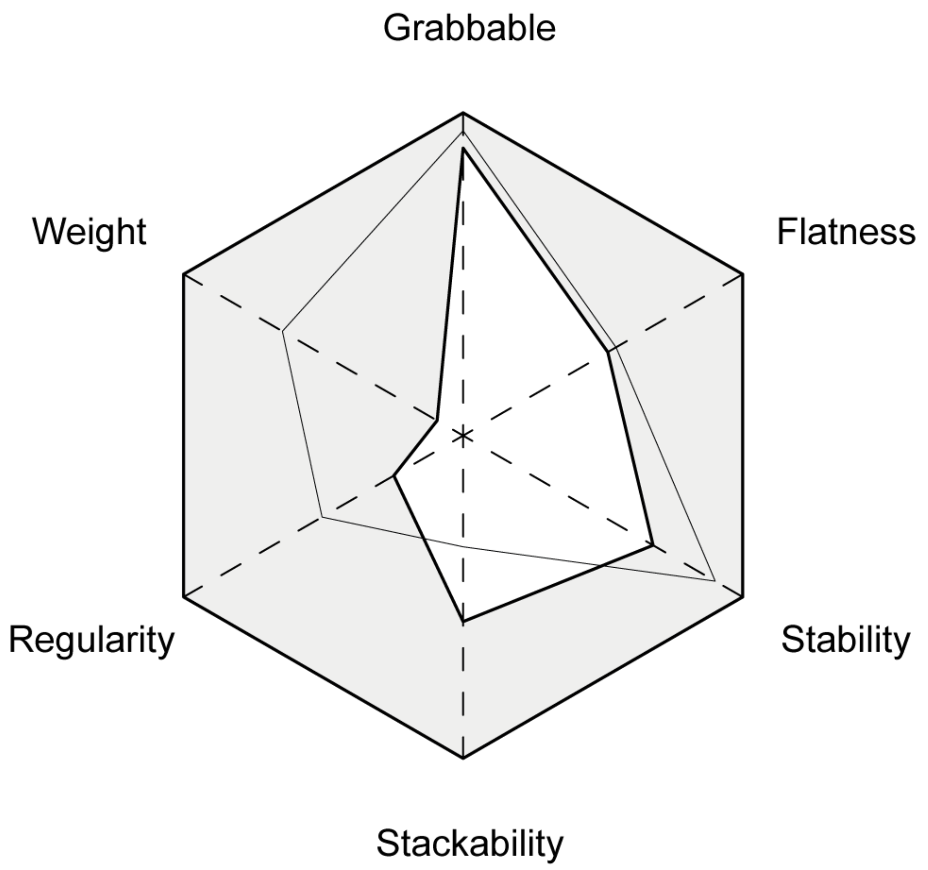
F.52. Experiment 0: Fetch - Machine Vision.





F.53. Objectives and constraints for each new object.




Grabbable
Weight
Flatness
Regularity
Stability
Stackability

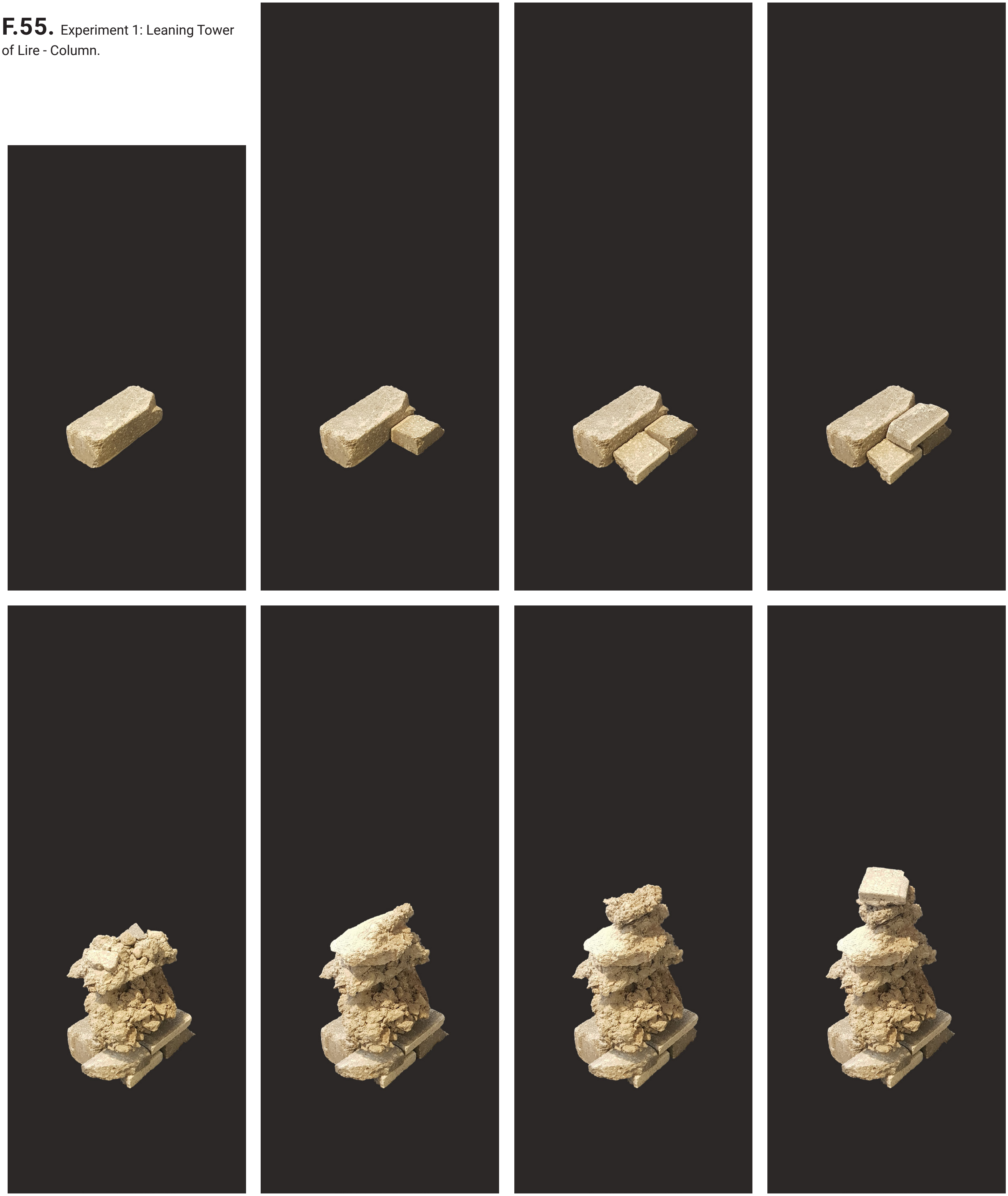
Experiment 1: Leaning Tower of Lire – Column

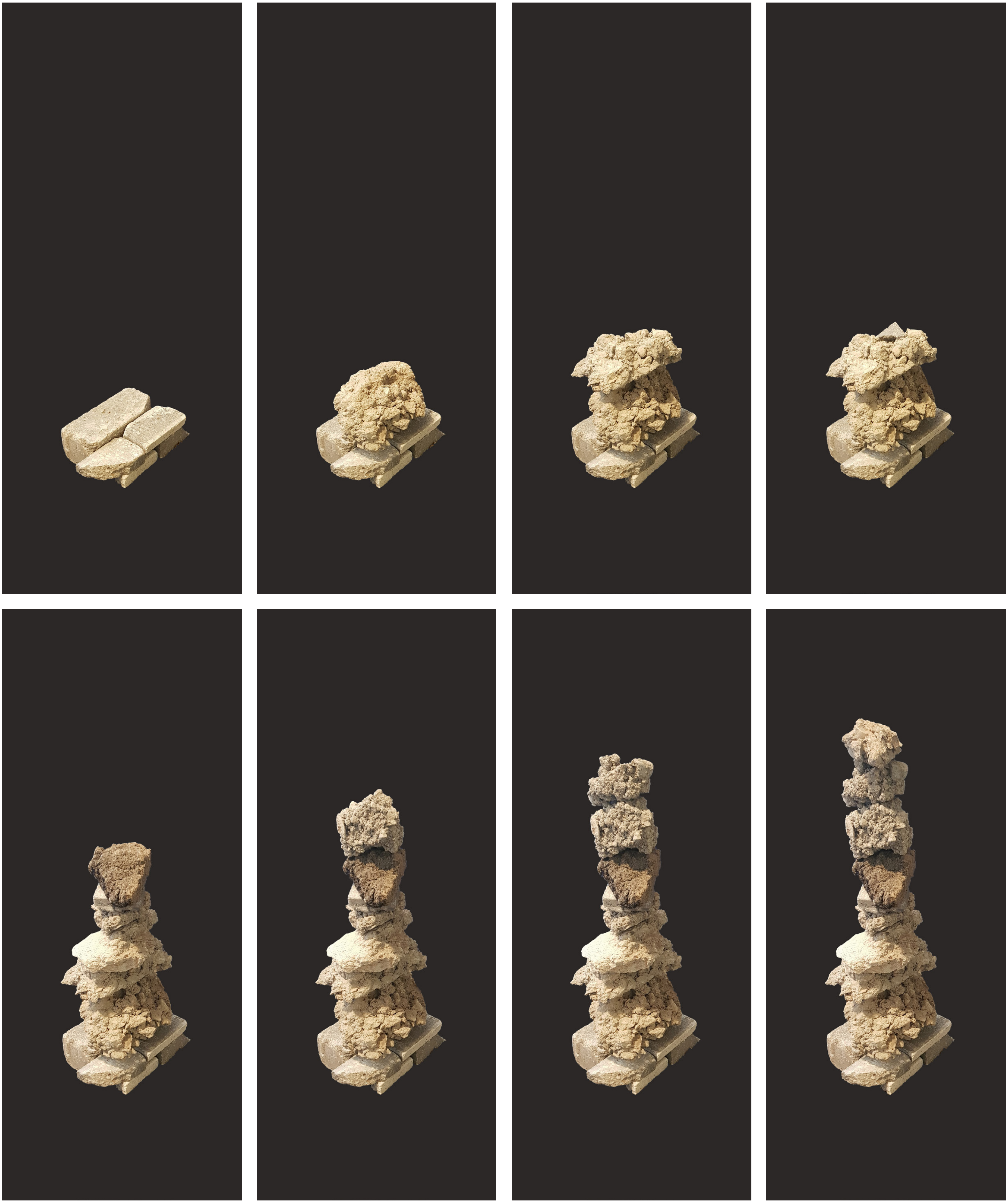
Leaning Tower of Lire is the first experiment in this thesis that attempted to create a stack from randomly selected objects. Single objects are assembled on top of one another to reach a preset height. To create an algorithm capable of tacking this problem, which is similar to autonomous stone stacking, first, a physical prototype was made as depicted in figures F.54, F.55, and F.56. The structural stability of this assembly system mainly revolves around the center of mass (CoM) of each object. To better understand how CoM affects the stability of a dry-stacked tower of stones viewed in figrues F.57 and F.58, the Block Stacking Problem, also reffered to as the Leaning Tower of Lire, is studied. This mathematical problem investigates the maximum possible overhang with a certain number of identical blocks. See figures F.59 and F.60. [109]

[109] John F. Hall, "Fun with Stacking Blocks," American Journal of Physics 73, no. 12 (2005): 1107–1116.

F.54. Physical prototype of a stacked tower.

F.55. Experiment 1: Leaning Tower of Lire - Column.

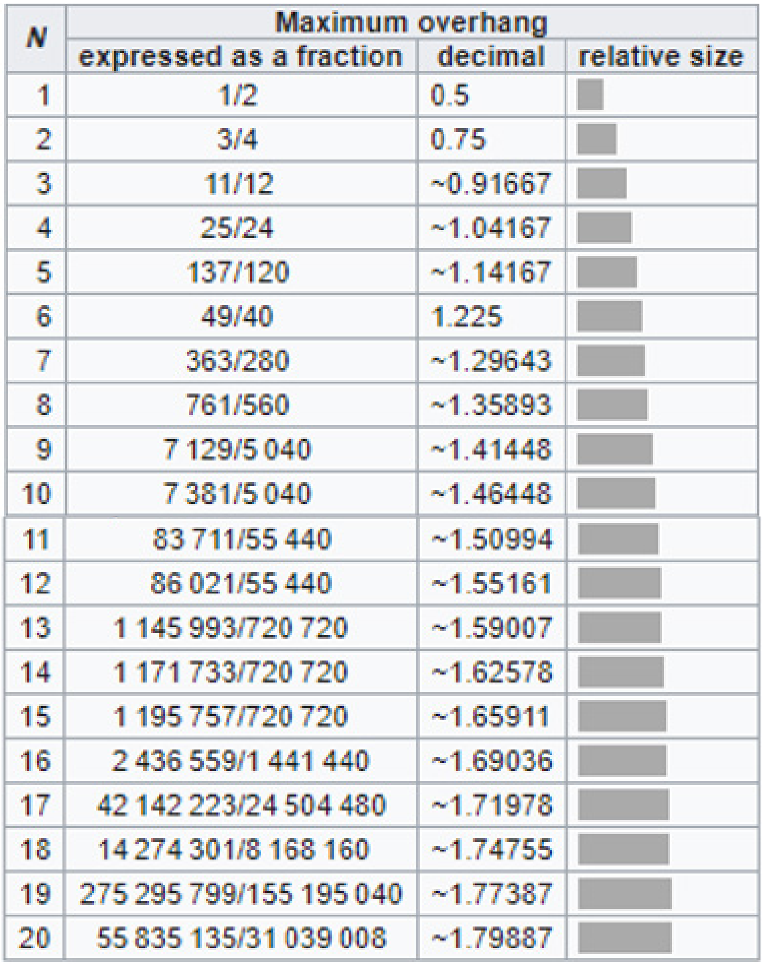




F.56. Center of Mass is the most important factor in a stacked tower.

F.57. Stacked tower can be found in many places.

F.58. Stacked tower can be found in many places.

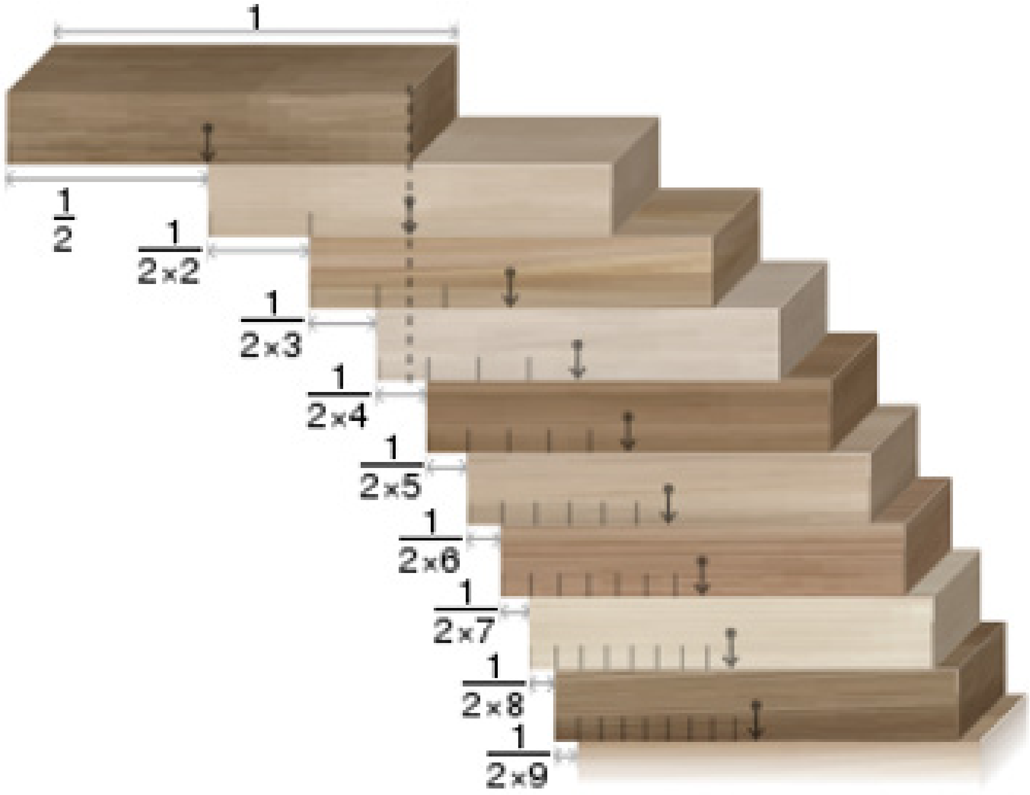


N	Maximum overhang		
	expressed as a fraction	decimal	relative size
1	1/2	0.5	▬
2	3/4	0.75	▬
3	11/12	~0.91667	▬
4	25/24	~1.04167	▬
5	137/120	~1.14167	▬
6	49/40	1.225	▬
7	363/280	~1.29643	▬
8	761/560	~1.35893	▬
9	7 129/5 040	~1.41448	▬
10	7 381/5 040	~1.46448	▬
11	83 711/55 440	~1.50994	▬
12	86 021/55 440	~1.55161	▬
13	1 145 993/720 720	~1.59007	▬
14	1 171 733/720 720	~1.62578	▬
15	1 195 757/720 720	~1.65911	▬
16	2 436 559/1 441 440	~1.69036	▬
17	42 142 223/24 504 480	~1.71978	▬
18	14 274 301/8 168 160	~1.74755	▬
19	275 295 799/155 195 040	~1.77387	▬
20	55 835 135/31 039 008	~1.79887	▬

F.59. Block Stacking Problem maximum overhang table.

$$\mathbf{R} = \frac{1}{M}\sum_{i=1}^{n} m_i \mathbf{r}_i ,$$

where M is the sum of the masses of all of the particles.



F.60. Block Stacking Poblem diagram.

As depicted in figure F.61, a series of digital prototypes are developed to refine the algorithm by testing the results through PhysX rigid-body simulation. First, standard objects are used to add component dislocation and fall detection features to the algorithm. Upon running the simulation, a component either stays at the target location or moves away from that location. Object dislocation is determined by measuring the distance between the target location and the final center point of the simulated component. Fall detection is achieved by checking if there is any intersection between the simulated component and the base surface upon which the structure is built. This surface is referred to as working site in this research.

The second set of experiments in figure F.61 investigates how inclined base surfaces impact the stability of the structure. This part is closely related to the stability and stackability properties displayed in figure F.53. To create a tower successfully, every object should be stable on the lower components and provide an appropriate base surface for the upper components. Next set of images shows a more developed version of the algorithm; unlike the first two experiments which are conducted through manually selecting new objects and setting their orientation, the third experiment is fully automated. In this experiment, an irregular object is arbitrarily selected. Then, this object is moved to the top of the stack and rotated along the x, y, and z axis by a number of angles. Next, this collection of rotated components is run through the rigid-body simulation and the outcome is evaluated based on fall detection and proximity to the column path.

The method employed in this third attempt is an application of the random-walk process. Random-walk, also referred to as stochastic process or random process, is an object that haphazardly deviates from its origin. [110] Likewise, the irregular object is rotated randomly and the result is evaluated to find the best result. While this method provides acceptable results for this experiment, it takes a considerable amount of time to iterate through all the possibilities to find the best solution. To tackle this problem, many of the options have to be eliminated before the simulation phase. This is achieved through introducing an initial scoring system preceding the rigid-body simulation step.

---

110. "Random Walks," accessed September 23, 2020, https://www.mit.edu/~kardar/teaching/projects/chemotaxis(AndreaSchmidt)/random.htm.

This initial scoring system constitutes of five objectives illustrated in figure F.62. These goals are related to either the CoM of each object, the shared surface between stacked items, or the user-set design path. Stacking irregular objects is directly affected by the components' geometry and center of mass. If the center of mass for each block is within its shared surface with the block beneath it, that block will be stable. However, for higher numbers of blocks the average of all the centers of masses is equally important. The average CoM should be within the boundaries of the base of the column. Meeting the former objective ensures the stackability of two objects while the latter focuses on the stability of the stack as a whole.

The amount of shared surface and its orientation are the other primary goals in this algorithm. It is preferable if the supporting surfaces are horizontal, meaning that stackability is less dependent on frictional forces at steep angles. The next goal is to get as close as possible to the design objective which is the column path set by the user. These goals are accumulated as the total score. Each individual score is used to eliminate undesirable iterations and the total score is employed to sort the iterations. Next, these solutions are simulated to ensure structural stability. After finalizing the ideal pose, a path is generated connecting the initial pose of the new component to the final pose. This process is followed by an Inverse Kinematic Solver to calculate robotic actuations required to travel the generated path. [111] Figure F.63 displays six process photos of how this algorithm successfully stacks irregular components to form a tower, while figure F.64 depicts the final result.

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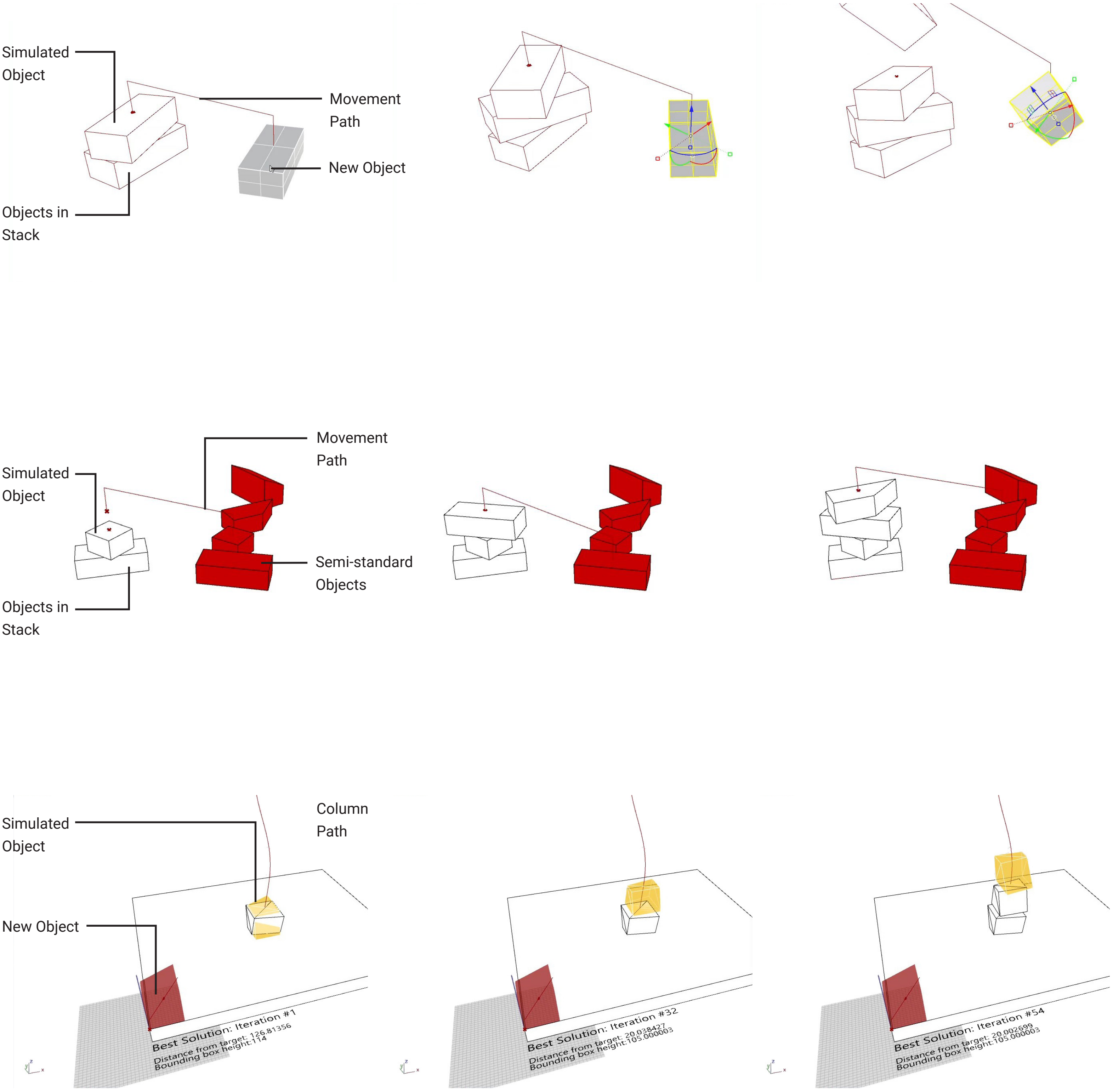
111. "What Is Inverse Kinematics?," accessed September 24, 2020, https://www.mathworks.com/discovery/inverse-kinematics.html.

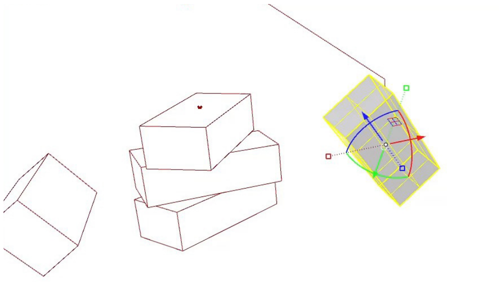
F.61. Preliminary digital prototypes testing the limitations of PhysX rigid-body simulation for standard, semi-standard, and irregular objects.

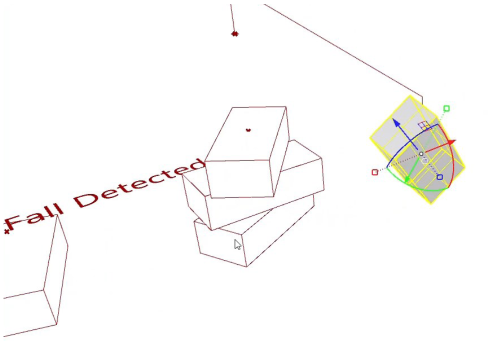


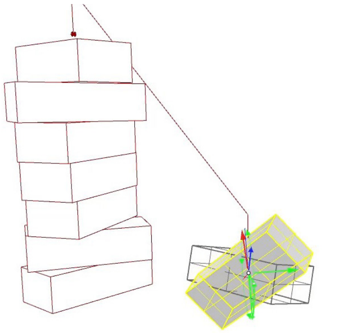
```
Best Solution: Iteration #1
Distance from target: 126.81356
Bounding box height:114
```

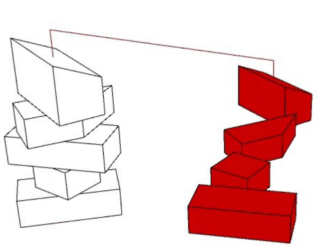
```
Best Solution: Iteration #32
Distance from target: 20.038427
Bounding box height:105.000003
```

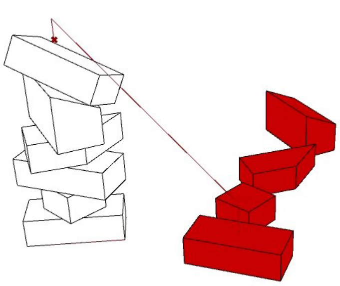
```
Best Solution: Iteration #54
Distance from target: 20.002699
Bounding box height:105.000003
```

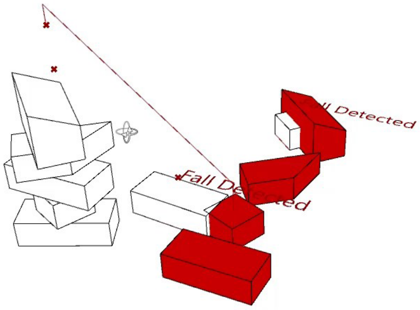


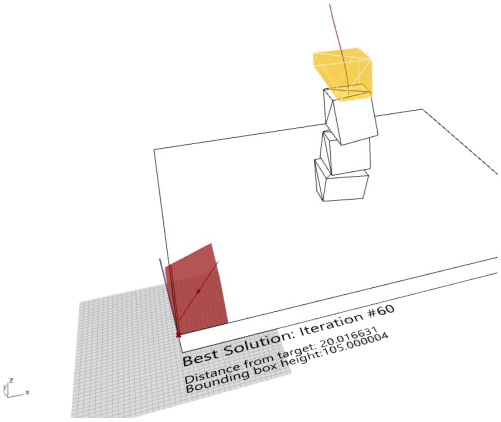

Fall Detected

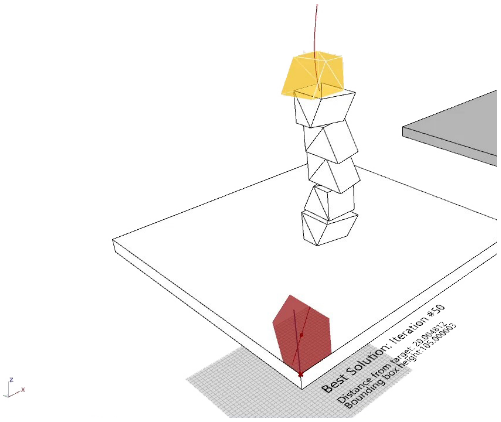


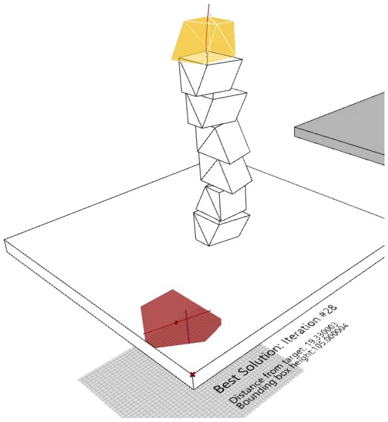




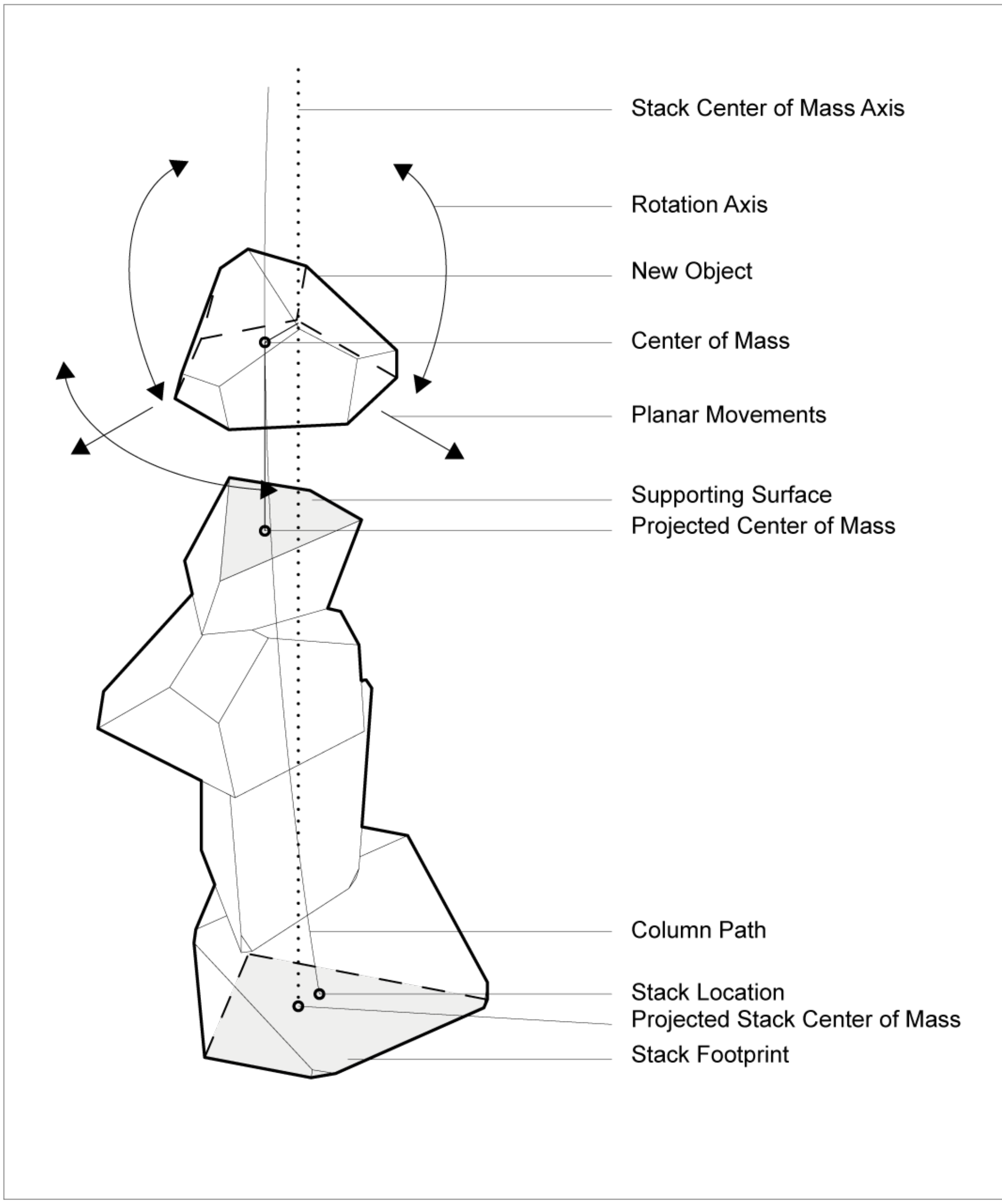

ll Detected
Fall De
ted

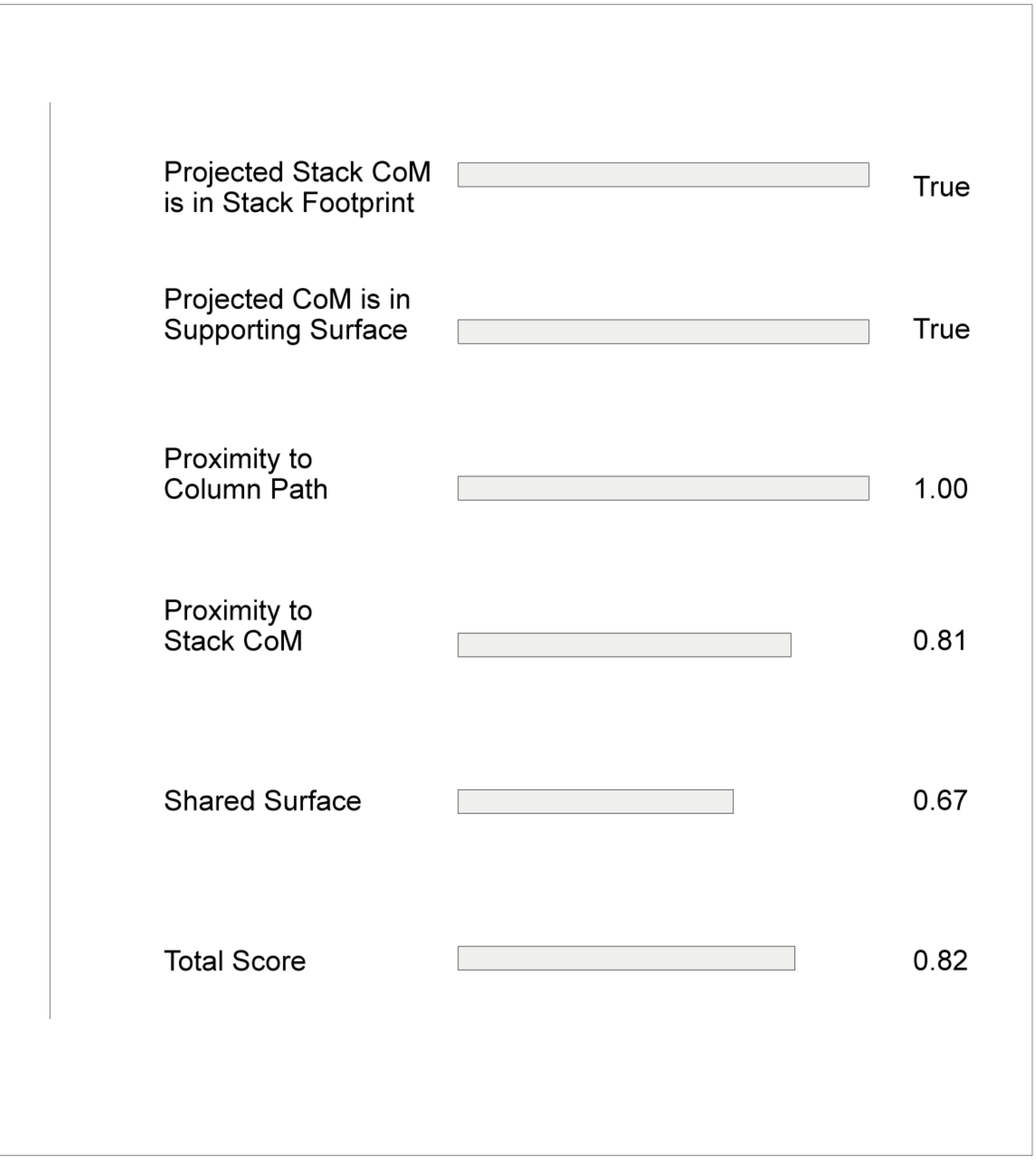

Best Solution: Iteration #60
Distance from target: 20.016631
Bounding box height:105.000004


Best Solution: Iteration #50
Distance from target: 20.004812
Bounding box height:105.000003

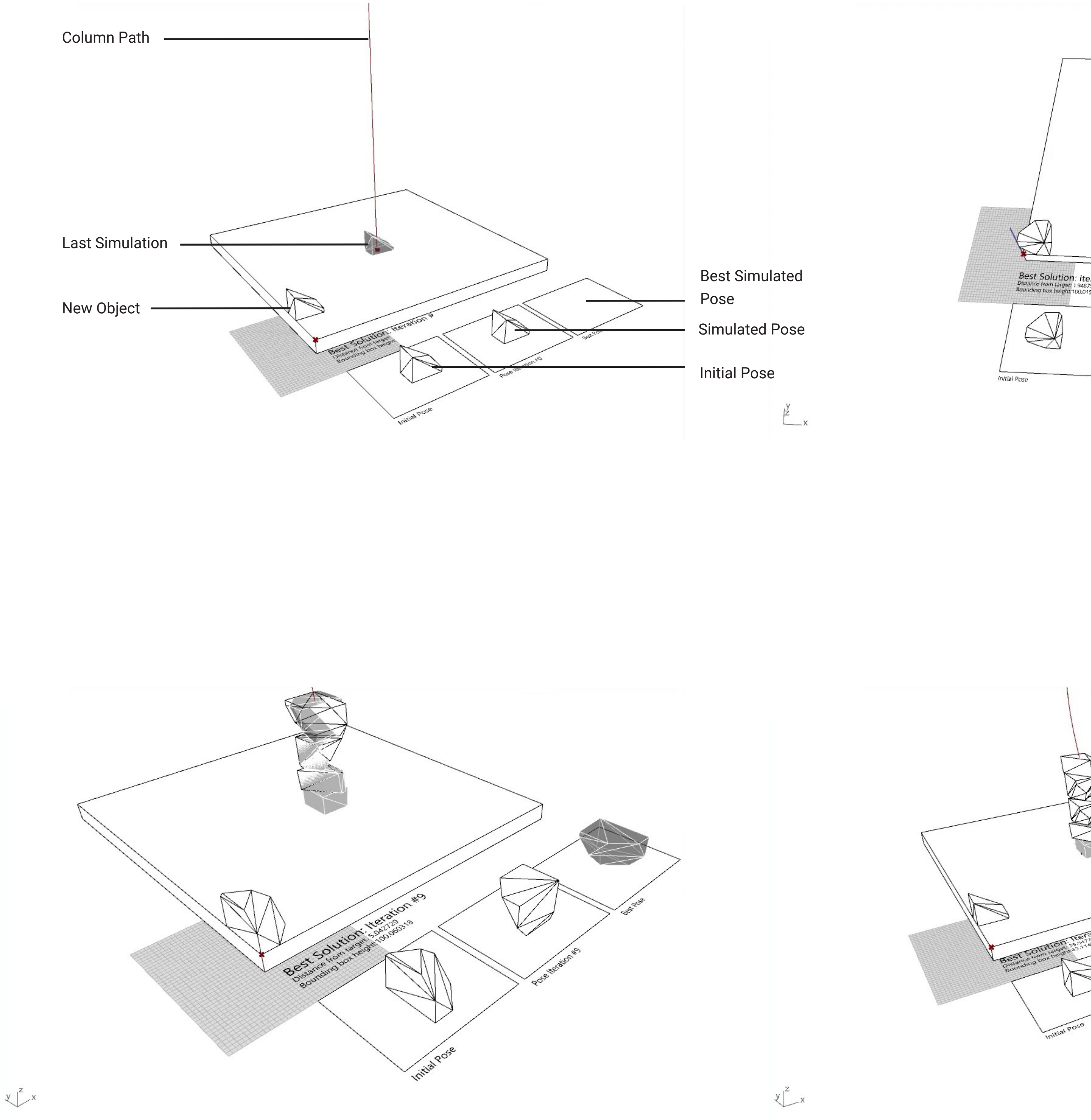

Best Solution: Iteration #28
Distance from target: 19.330003
Bounding box height:105.000004

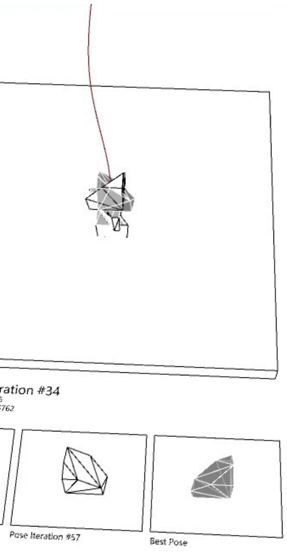
F.62. Objectives and constraints for the column stacking algorithm.

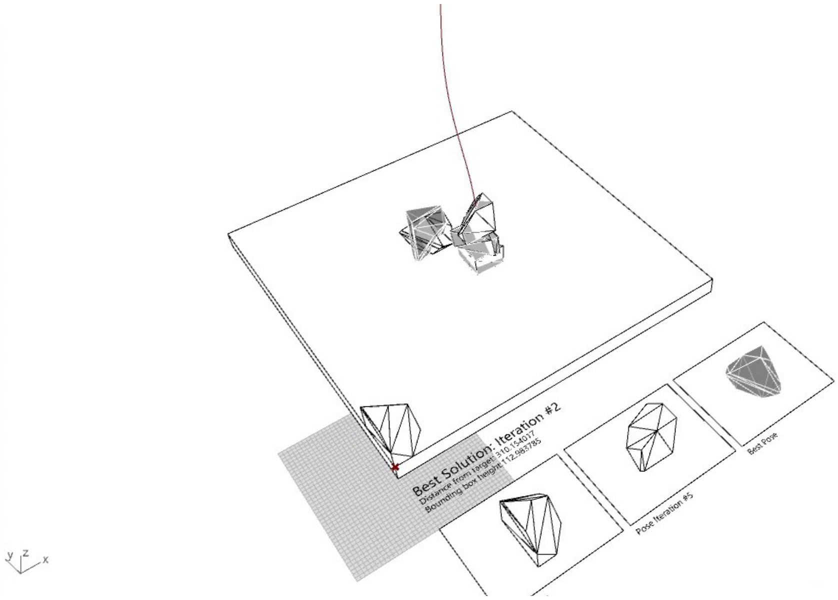


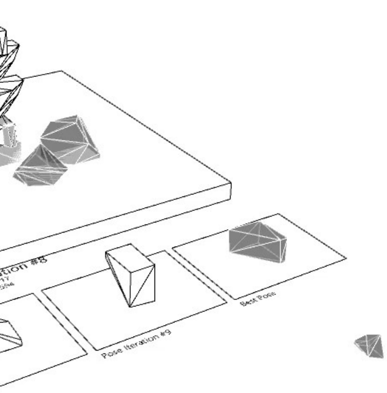

Projected Stack CoM is in Stack Footprint
True
Projected CoM is in Supporting Surface
True
Proximity to Column Path
1.00
Proximity to Stack CoM
0.81
Shared Surface
0.67
Total Score
0.82

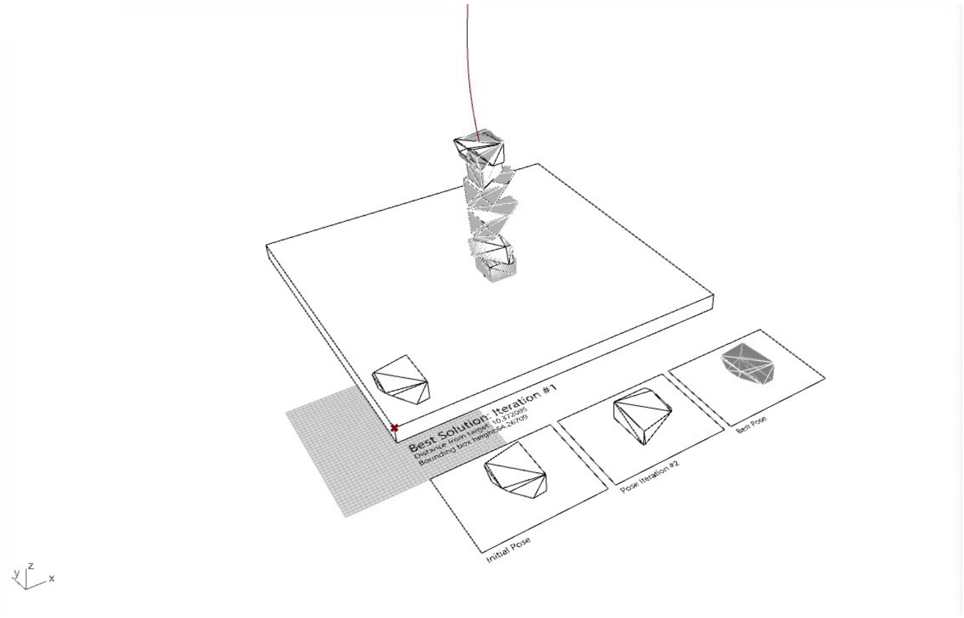
F.63. Final algorithm generating a stacked column with irregular objects through a stochastic process.



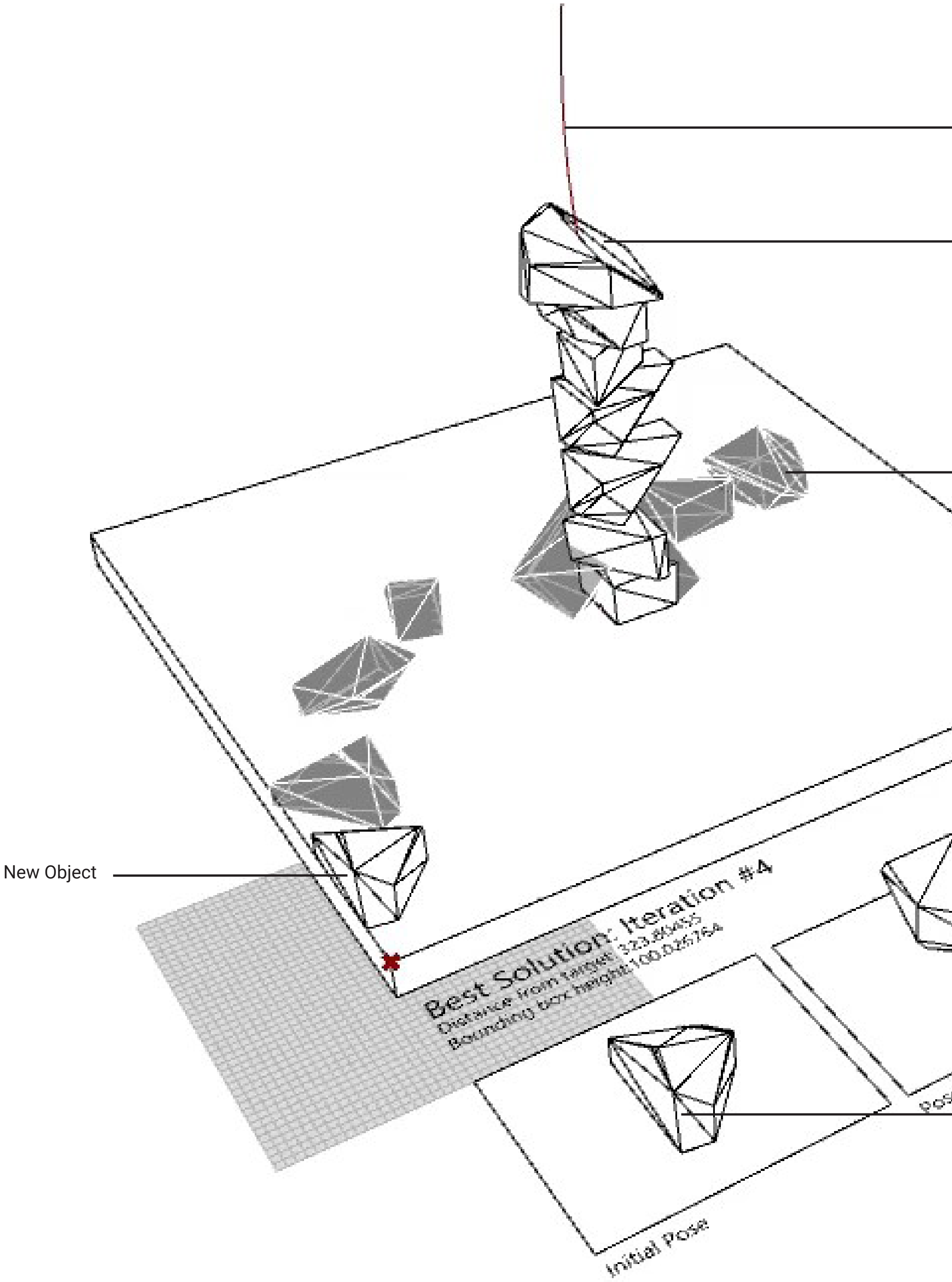

ration #34
5
5762
Pose Iteration #57
Best Pose

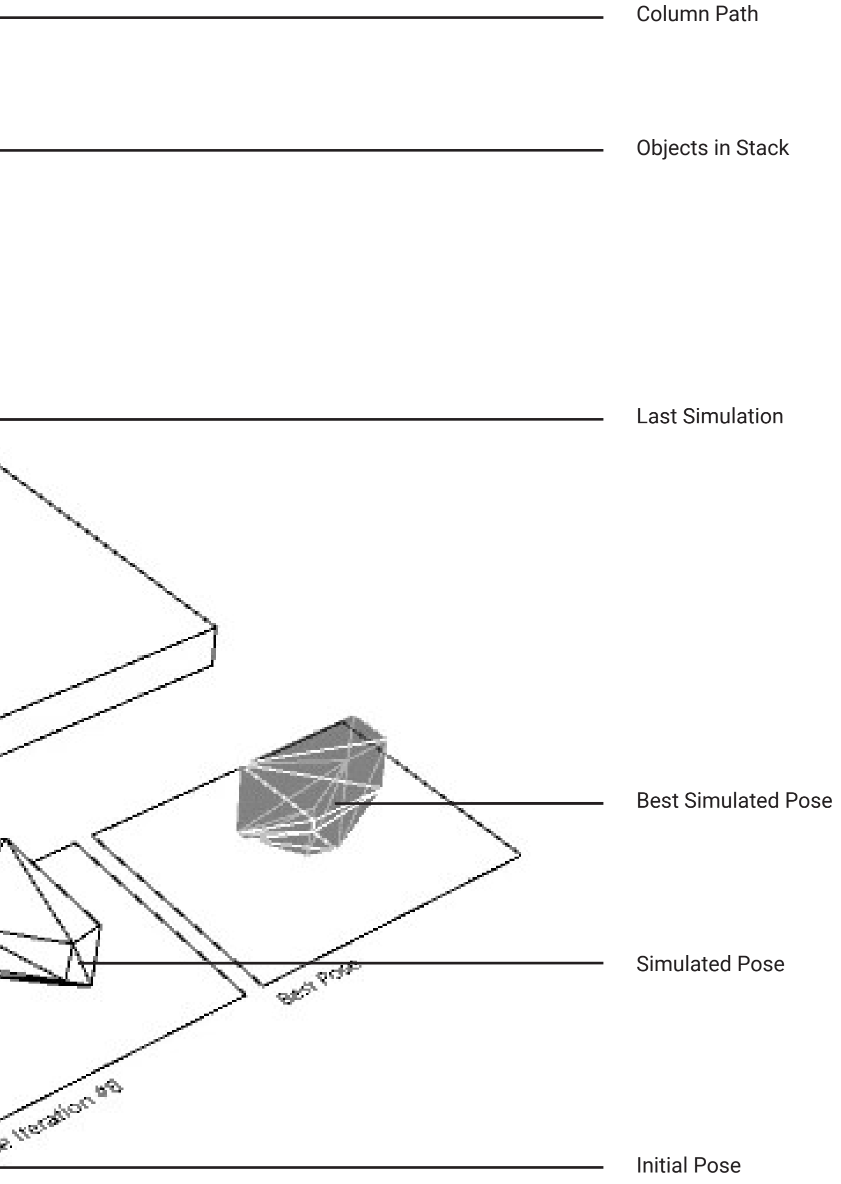

Best Solution: Iteration #2
Distance from target: 310.154017
Bounding box height: 112.983785
Pose Iteration #5
Best Pose
y z x


ation #8
Pose Iteration #9
Best Pose


Best Solution: Iteration #1
Distance from target: 10.372095
Bounding box height: 64.26709
Initial Pose
Pose Iteration #2
Best Pose
y z x

F.64. Each object has to be stable itself and provide a suitable supporting surface for the next object.




Column Path
Objects in Stack
Last Simulation
Best Simulated Pose
Simulated Pose
Best Pose
Iteration #9
Initial Pose

Experiment 2: 3D Bin Packing Problem – Wall

Autonomous construction of a wall is much more complex than stacking a column. Similar to the previous experiment, developing a physical prototype is the first step, see figures F.65 to F.70. Then, assembly systems for other irregular objects such as stones are studied to understand the logic behind these structures. As depicted in figures F.71, F.72, and F.73, in dry-stacked stone walls, which can be used as retaining walls, the size and geometry of each stone has an impact on its location and role in the overall structure; larger stones tend to be placed towards the perimeter of the structure while the smaller stones are used as fillers.

On the one hand, stacking these various components to achieve the densest structure can be compared with Tetris, a puzzle game created in 1984 that involves assembling various two-dimensional shapes to complete a horizontal line without a break. [112] On the other hand, stacking non-standard elements can be compared to the Bin Packing problem depicted in figure F.74. Bin Packing is a mathematical problem in which a number of objects with varying volumes are fit in a limited number of containers. [113] Similar to 3D Bin Packing, dry-stacking stones is an optimization problem; an attempt to fit the highest number of irregular objects in the lowest space. The difference, however, is that all objects are known in a Bin Packing algorithm, whereas objects are not predefined in this thesis.

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112. “About Tetris®,” Tetris, accessed September 28, 2020, https://tetris.com/about-us.

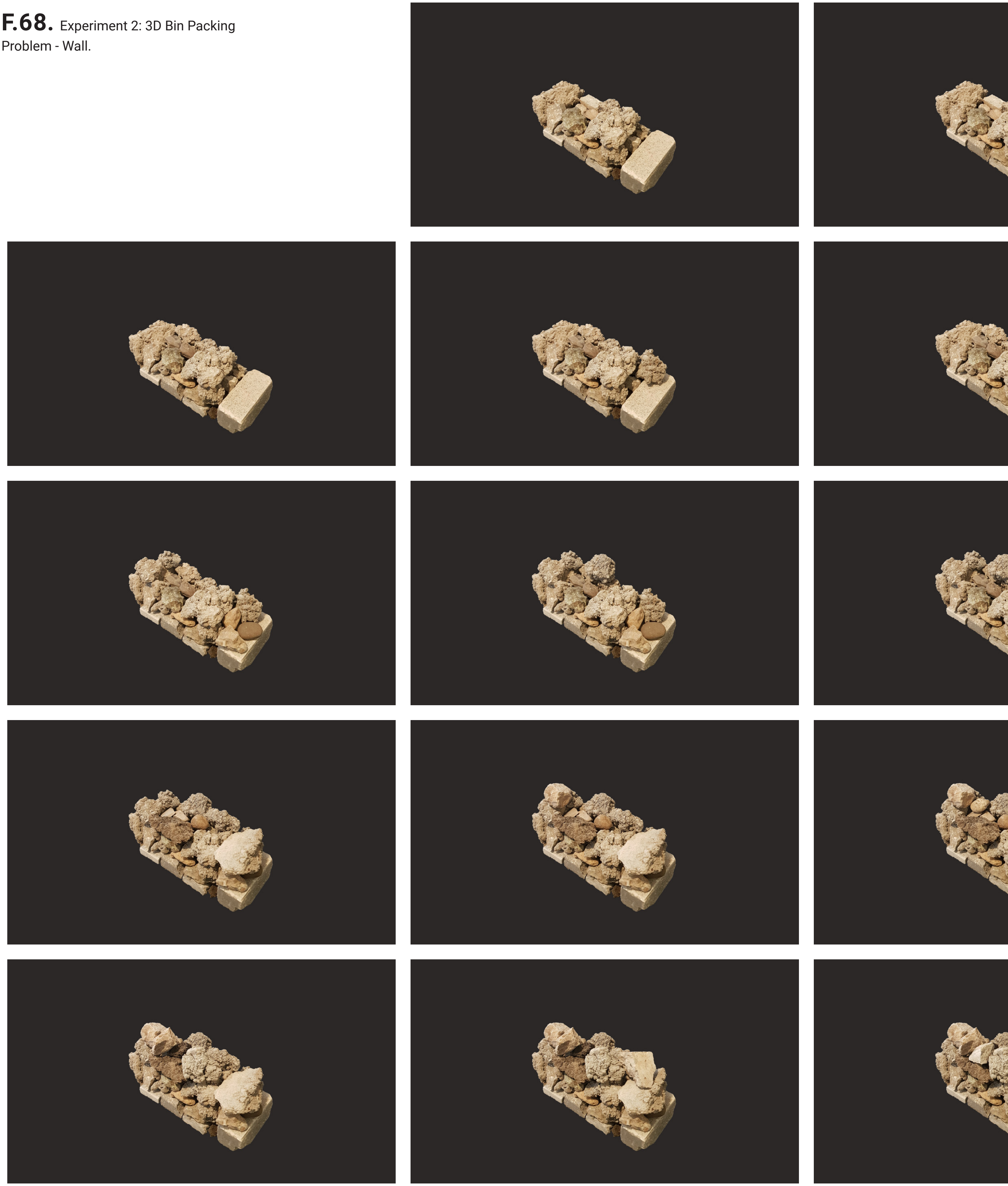
113. Yong Wu et al., “Three-Dimensional Bin Packing Problem with Variable Bin Height,” European Journal of Operational Research 202, no. 2 (April 16, 2010): 347–55, https://doi.org/10.1016/j.ejor.2009.05.040.

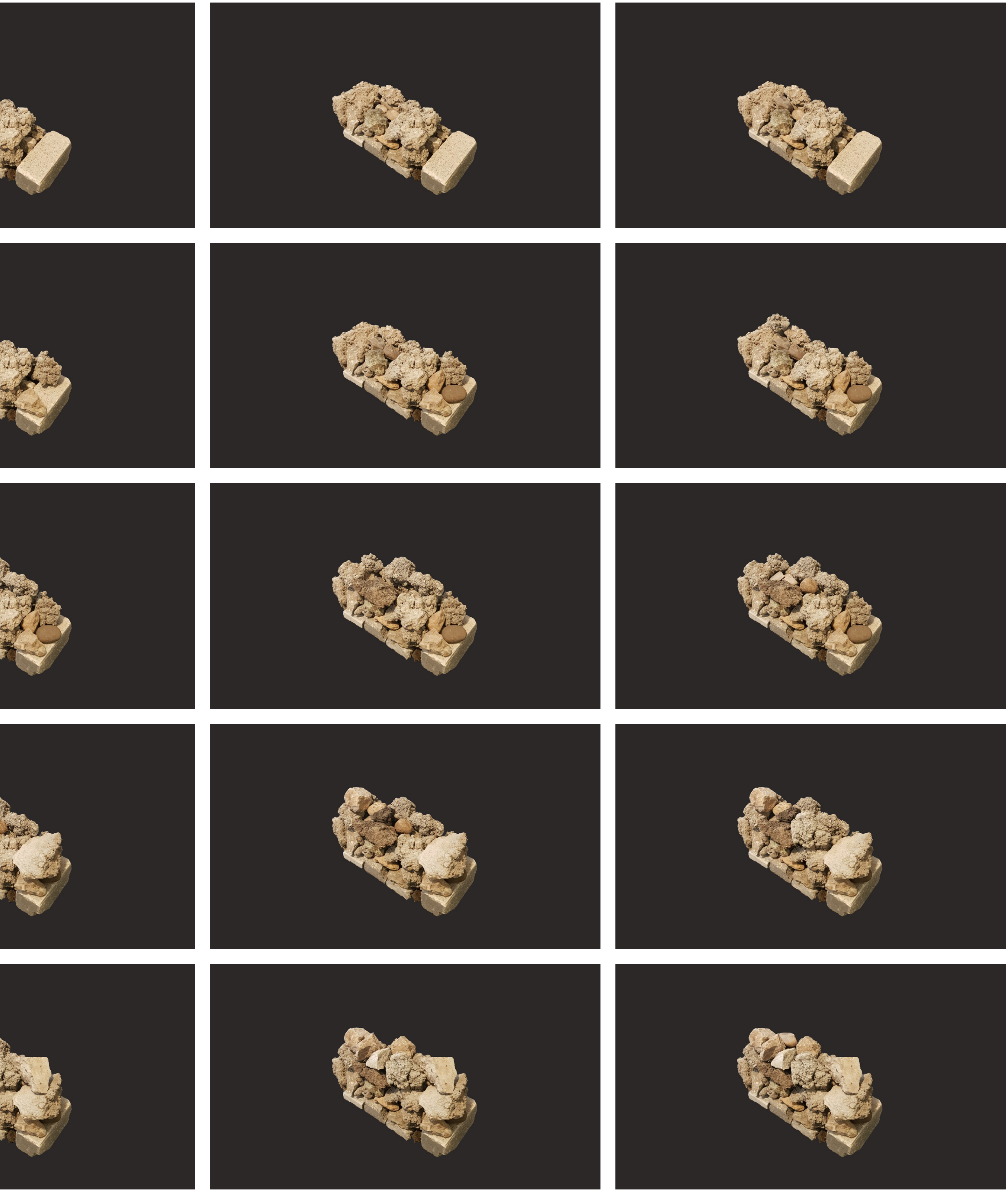
F.65. Physical prototype of a stacked wall.

F.66. Experiment 2: 3D Bin Packing Problem - Wall.

F.67. Experiment 2: 3D Bin Packing Problem - Wall.

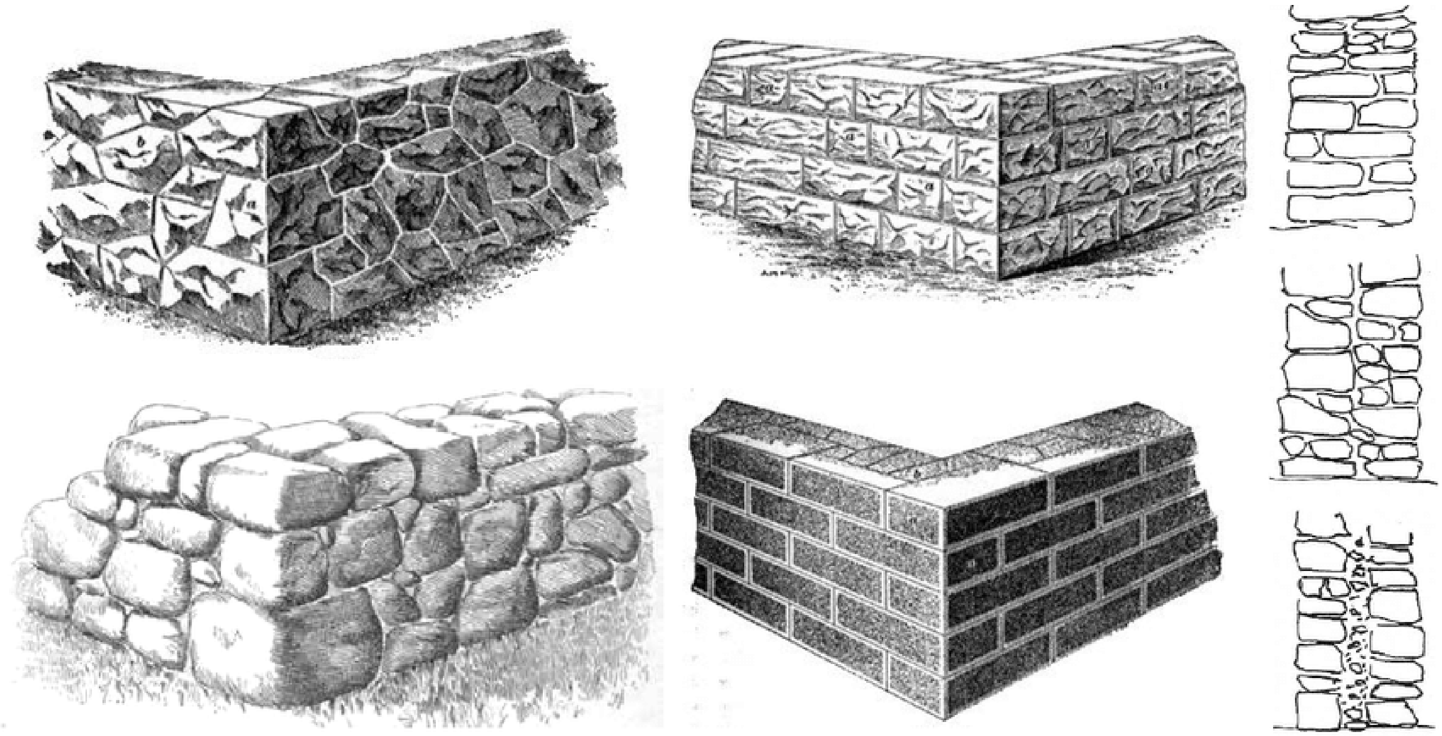
F.68. Experiment 2: 3D Bin Packing Problem - Wall.





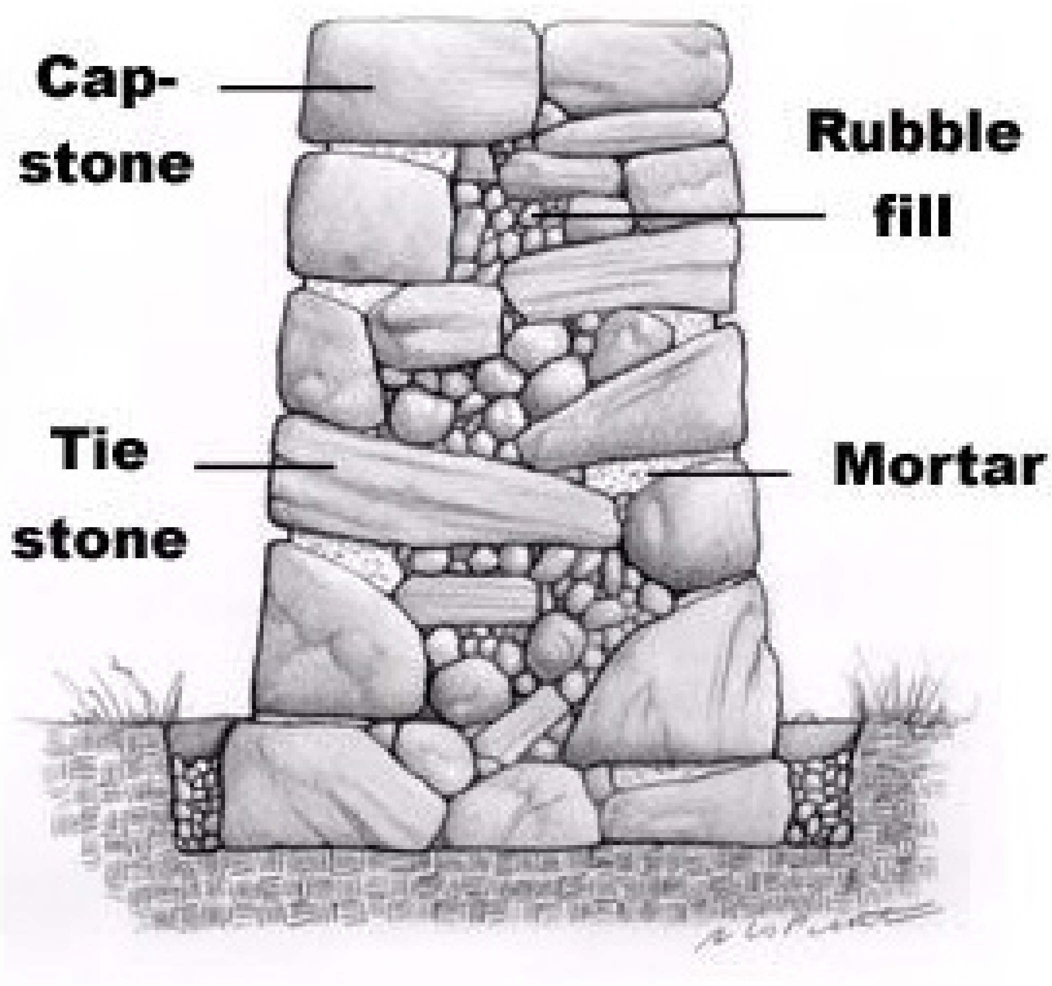
F.69. Interlocking geometries are crucial in a dry-stacked wall.

F.70. Small filler components are as essential as large regular components.

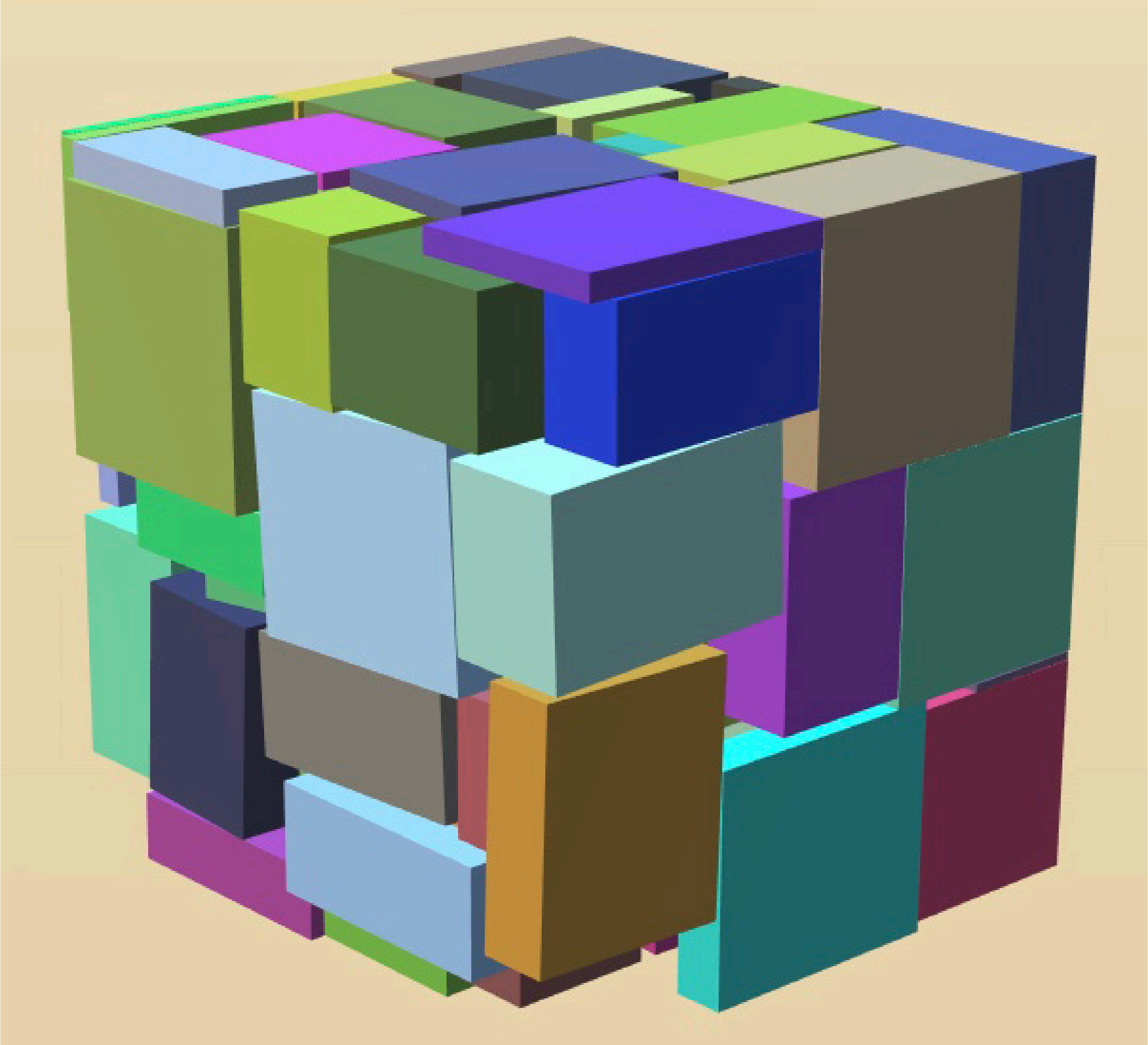


F.71. Dry-stacked stone wall assembly systems.

F.72. The assembly system of a dry-stacked stone wall can be used for stacking reclaimed rubble.



F.73. Section of a dry-stacked stone wall.



F.74. 3D Bin Packing Problem.

To develop an algorithm capable of automated construction of a self-supporting wall, first, the overall design of the wall is determined. This design is informed by technical constraints, structural properties, and user-set design objectives. Figure F.76 illustrates that an overall of ten steps are required to achieve the final results. A path is set by the user to reach from point A to point B, then based on the dimensional range of the irregular components, the wall depth is set. The height of the wall is set to match design requirements. Then, the wall is formed into a shape of half-circles to increase its stability. This approach is derived from Crinkle Crankle walls, also referred to as Serpentine Walls, which unlike a straight-line wall do not require buttresses. The waved geometry of these walls creates arches providing lateral stability for the structure. See figure F.75. [114]

The fifth step depicted in figure F.76 describes how the radii of the half-circles are influenced by the reach of the industrial robot, UR10. Additionally, the overall geometry is tapered inside to create a trapezoid-shaped section with a larger base than top; this modification improves the overall stability of the structure. As the seventh step, the number of anchor objects along the length and the height of the wall are set. At last, the generated geometry is used as a guide for the stacking algorithm. How closely this guide is followed is based on tolerance settings defined by the user.

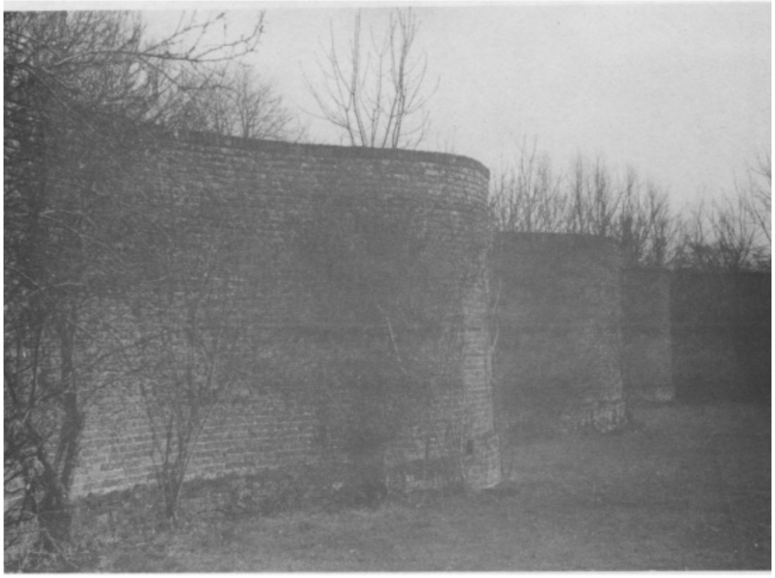
The automated wall assembly algorithm is developed during a series of digital prototypes. Initially, regular brick-sized components are used in order to determine objectives and constraints. See figure F.77. This experiment illustrates that each new object should be positioned at the lowest level to create the most stable base for the next components. Moreover, the amount of shared surface between a new object and the already placed objects, referred to as objects stack in this thesis, is crucial to provide the best support. The shared surface among multiple elements is prioritized over the shared surface between two components. This strategy incentivizes an assembly pattern similar to a running bond rather than a stack, which leads to a higher number of interlocking objects. [115]

---

[114] Jean O’Neill, “Walls in Half-Circles and Serpentine Walls,” Garden History 8, no. 3 (1980): 69–76, https://doi.org/10.2307/1586736.

[115] “Figure 8-33.-Types of Masonry Bonds.,” accessed September 30, 2020, http://constructionmanuals.tpub.com/14043/css/Figure-8-33-Types-of-masonry-bonds-234.htm.

F.75. Walls in half-circles and serpentine walls, O'Neill - 1980.

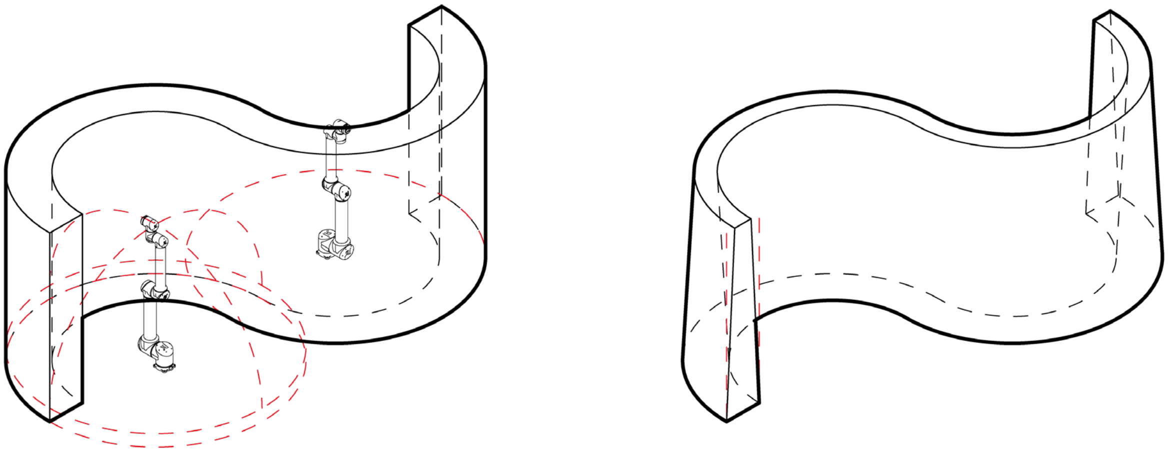


The second digital prototype uses three differently sized components. In this experiment which is shown in figure F.78, a link is established between the size of an object and its possible location. Large objects are preferred in anchor positions to hold the structure, medium objects are located at the perimeter of the structure, and small components are used as fillers. Figures F.79 and F.80 illustrate object placement probabilities based on size of object and the location of target planes. In these diagrams, a white plane is a more ideal location for the specified object. Theoretically, in an ideal scenario where every object needed by the algorithm is available, the object distribution in a wall constructed with this algorithm resembles these diagrams.

F.76. Design process of the wall structure.

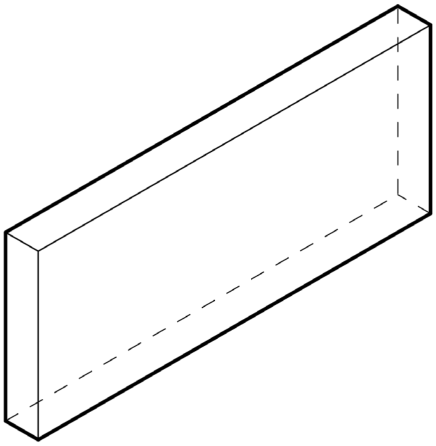
Path
(Design)

Wall Depth Based on Object Size
(Structural)

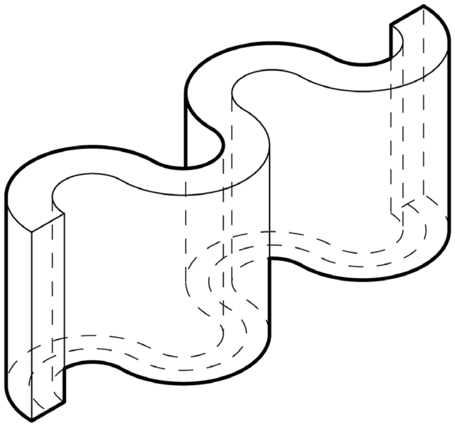


Matching UR10 Reach
(Technical)

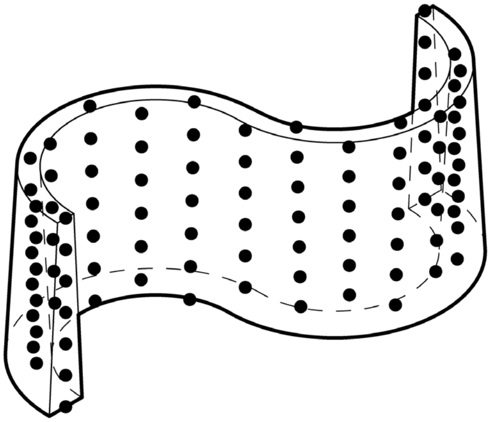
Tapering for Further Stability
(Structural)



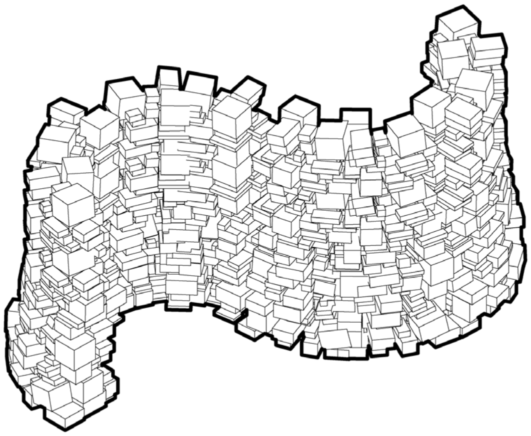
Extrude
(Design)



Wave for Stability
(Structural)

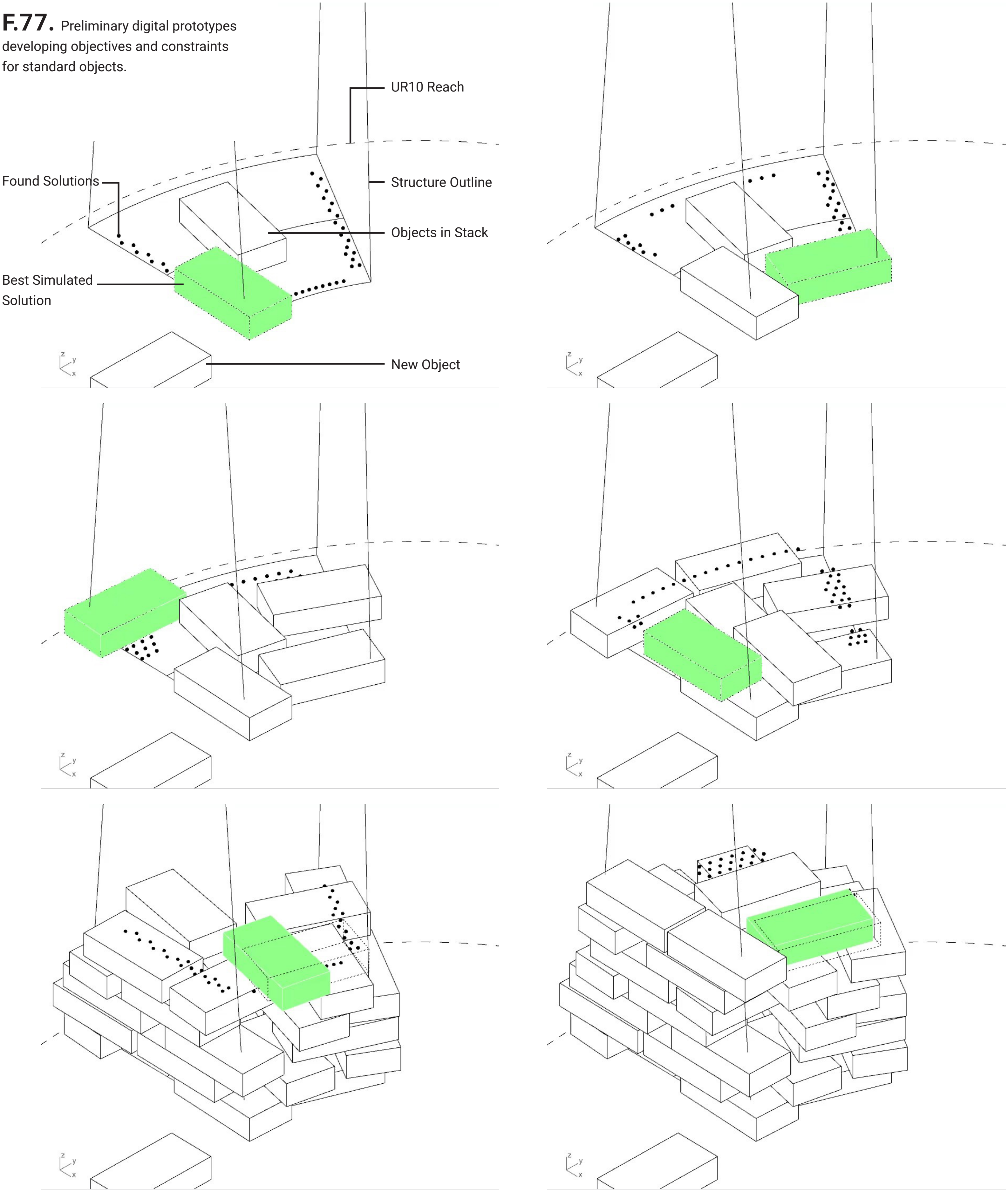


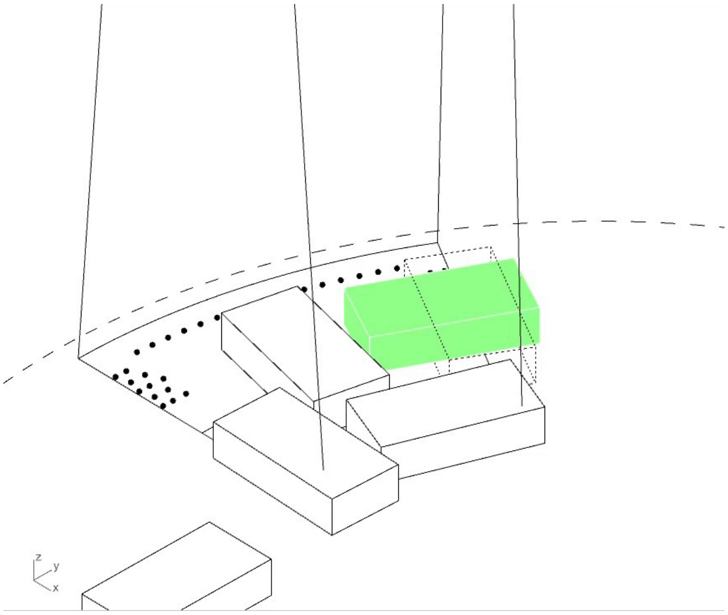
Location of Anchor Objects
(Structural)

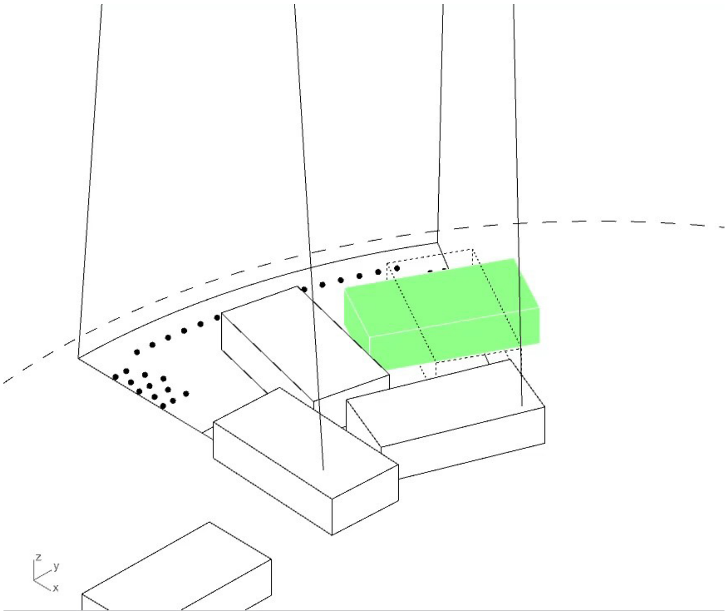


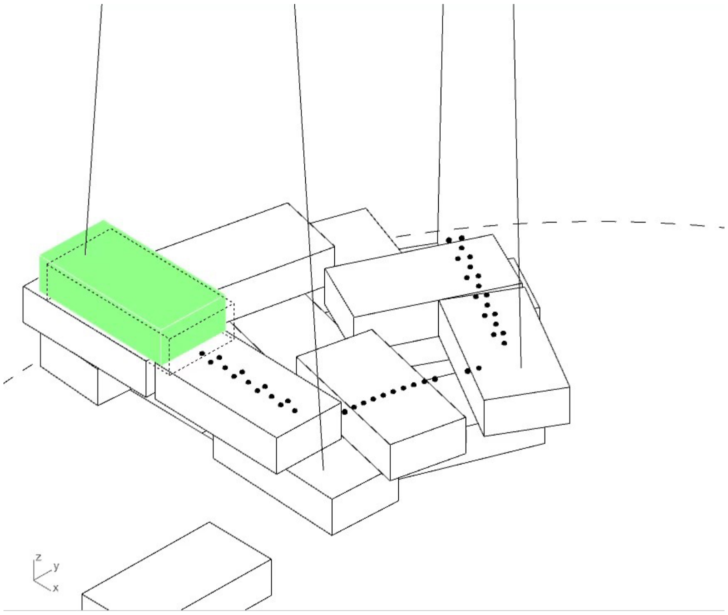
Results

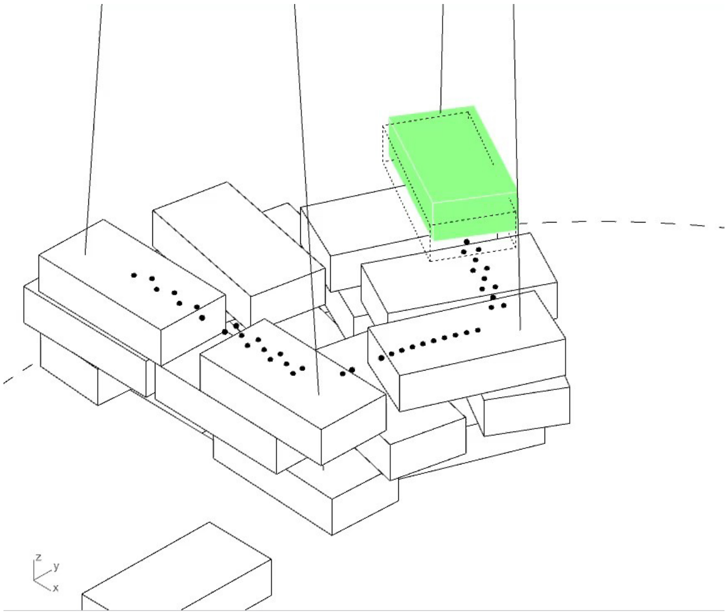
F.77. Preliminary digital prototypes developing objectives and constraints for standard objects.

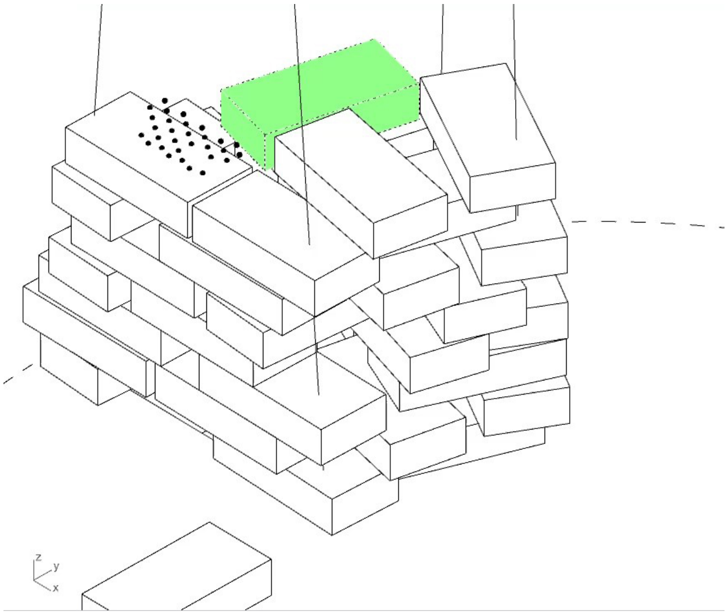


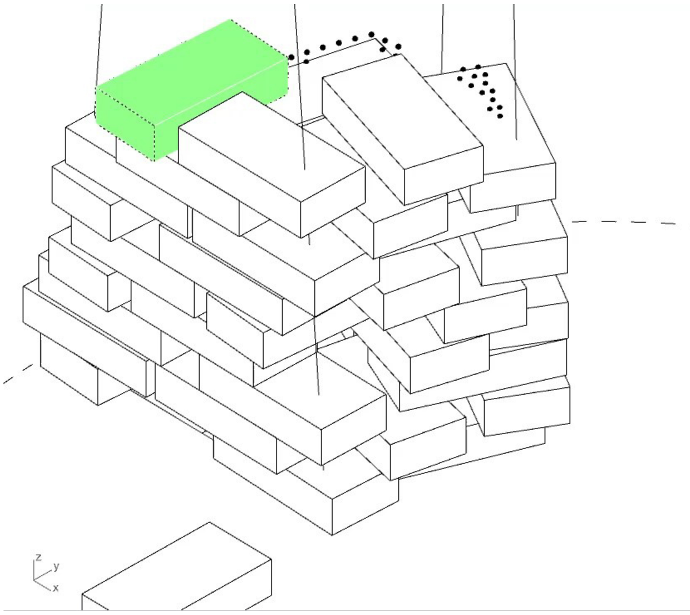

z
y
x

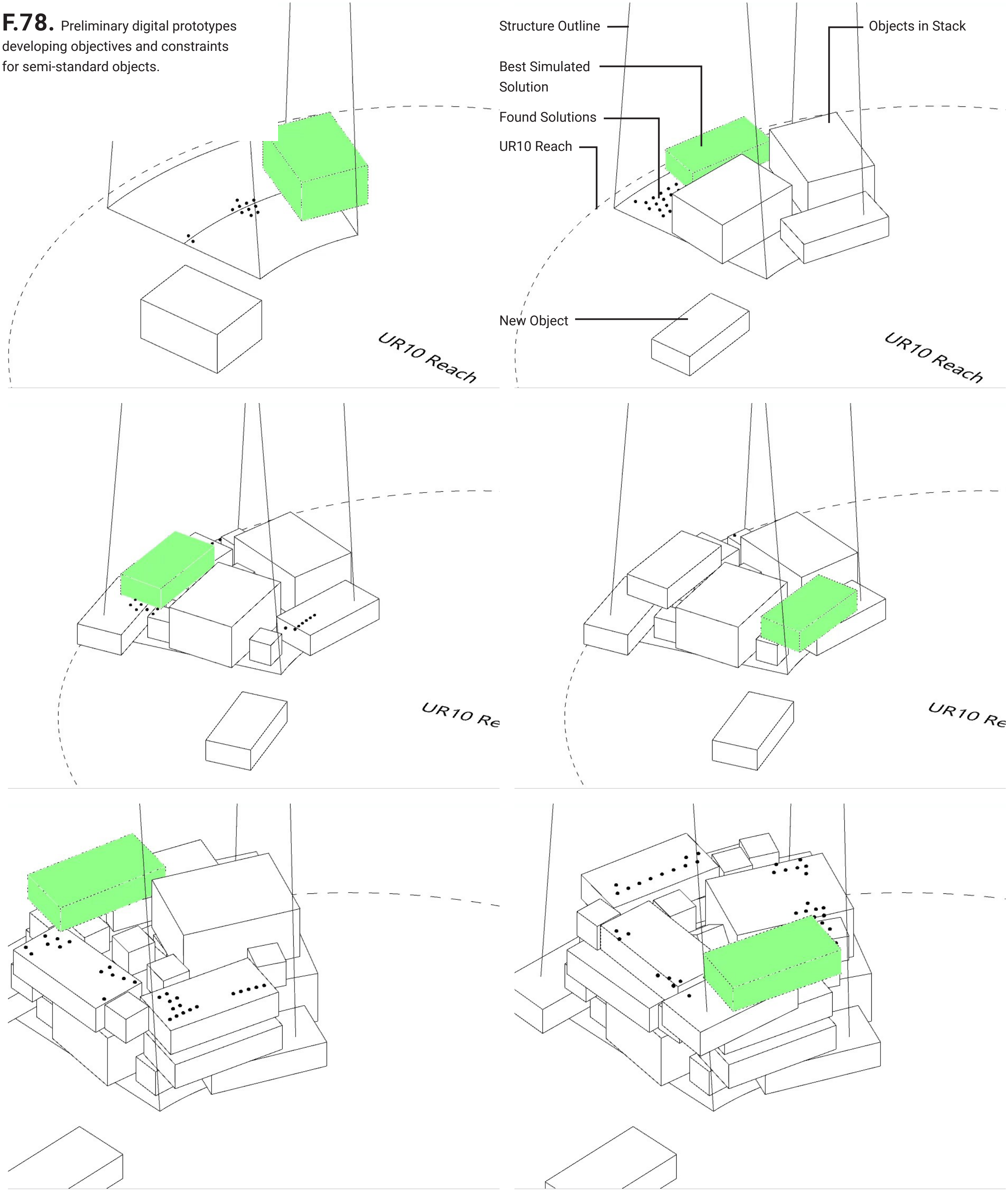

z
y
x


z
y
x

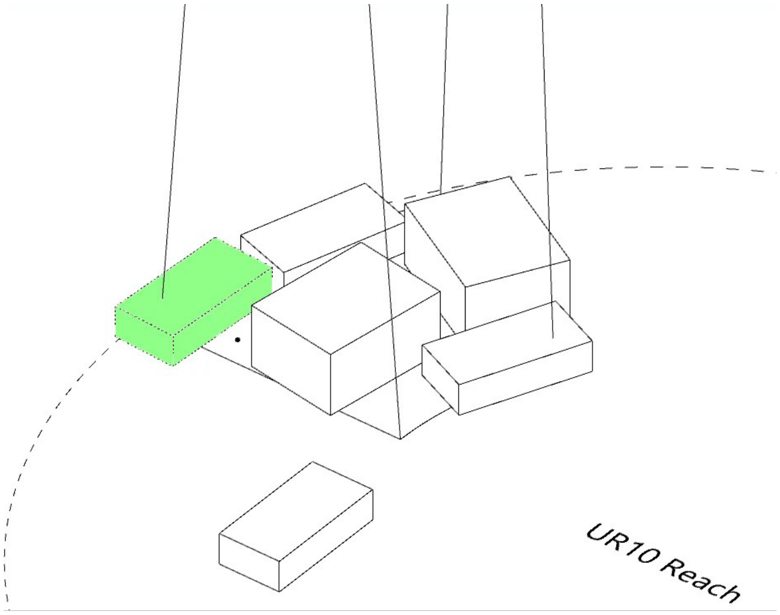

z
y
x

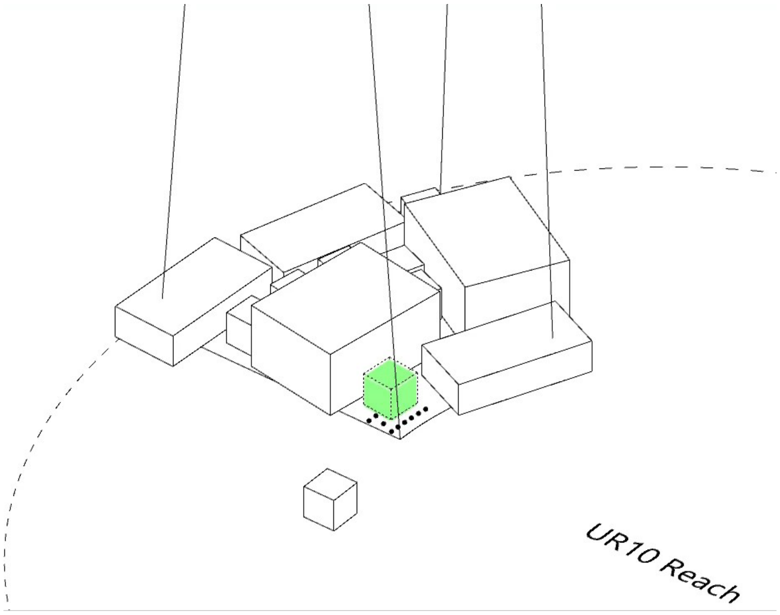

z
y
x

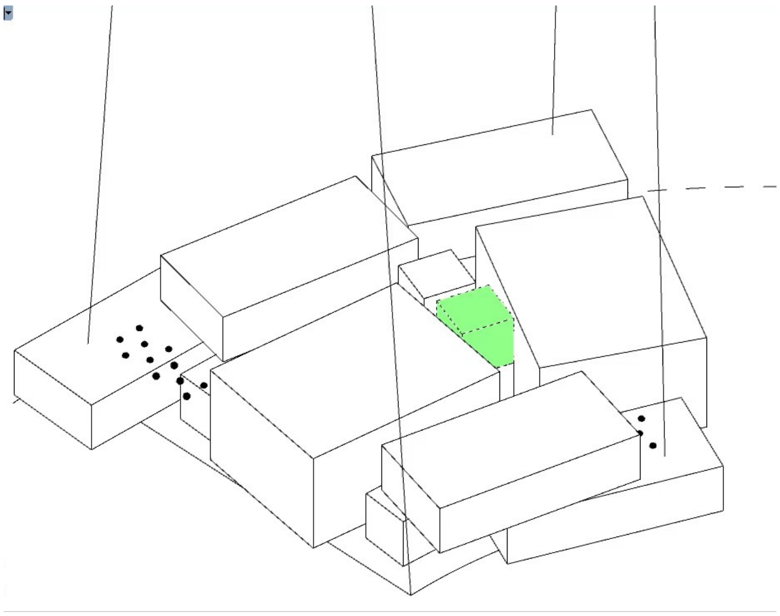

z
y
x

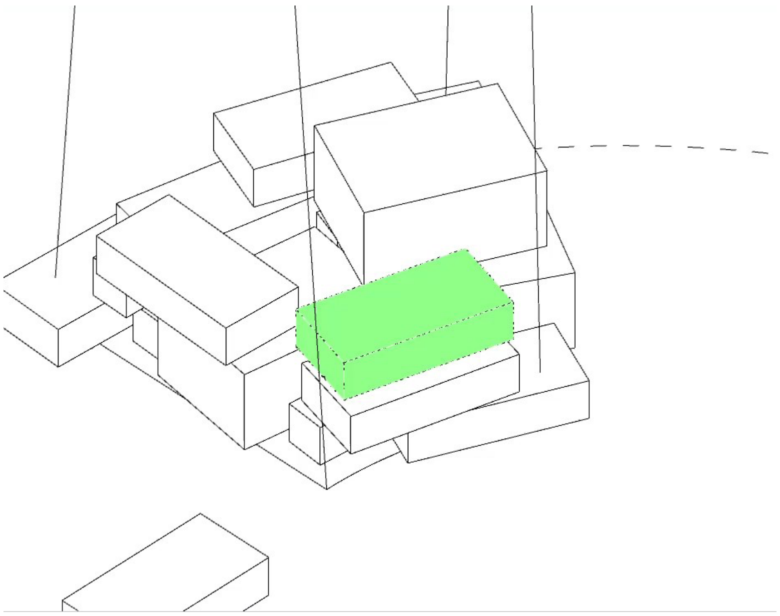


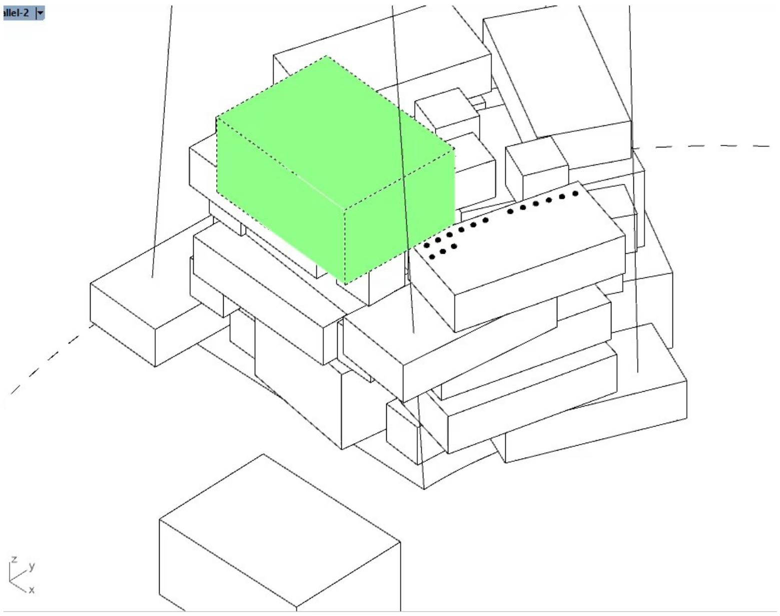
F.78. Preliminary digital prototypes developing objectives and constraints for semi-standard objects.

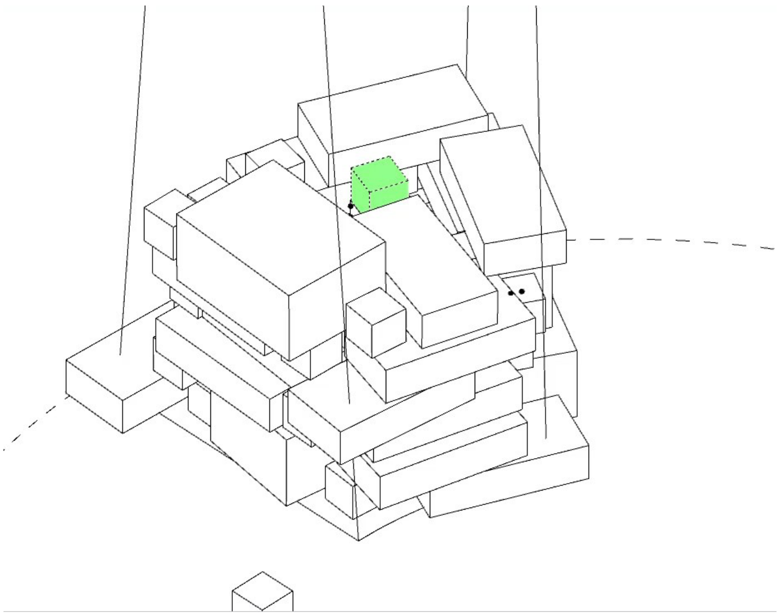

UR10 Reach

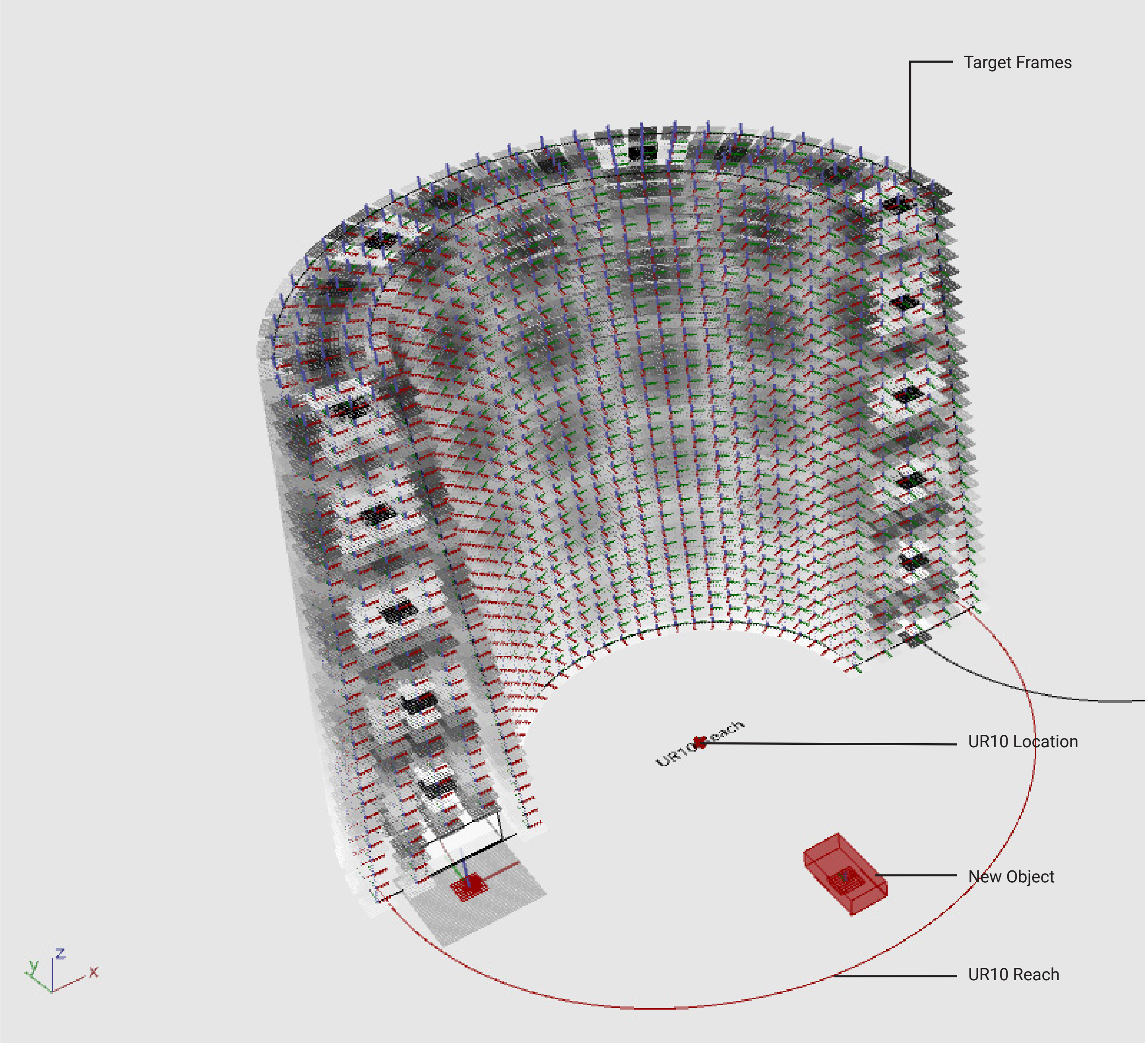

UR10 Reach



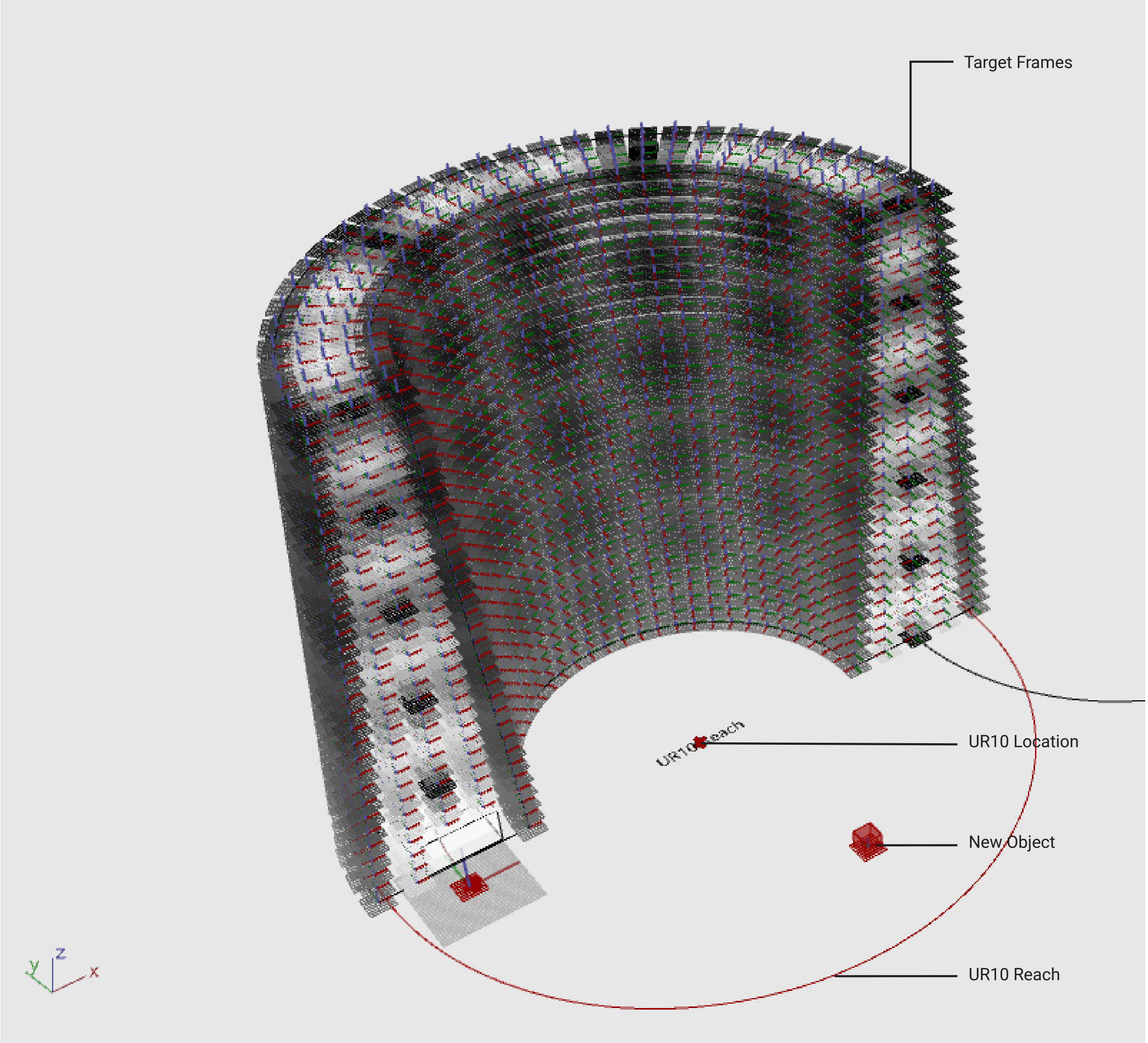



allel-2
z
y
x





F.79. Diagram of location scoring based on the object size; white indicates high score. Medium objects move towards the facade of the structure.



F.80. Diagram of location scoring based on the object size; white indicates high score. Small objects move towards the facade of the structure.

As a result of the previous experiments, the final algorithm designed to automatically stack irregular objects has three sets of goals: design, structural, and operability objectives. The first set attempts to follow the guidelines for the overall design as closely as set by the user. The second set of objectives determines how and where an object should be placed to make a stable overall structure. The last collection of goals is set to accommodate the robotic and construction restrictions and workflows. It should be noted that many of the robotic constraints are only hypothesized, not experienced first-hand, due to the closure of digital fabrication facilities during the COVID-19 lock-down.

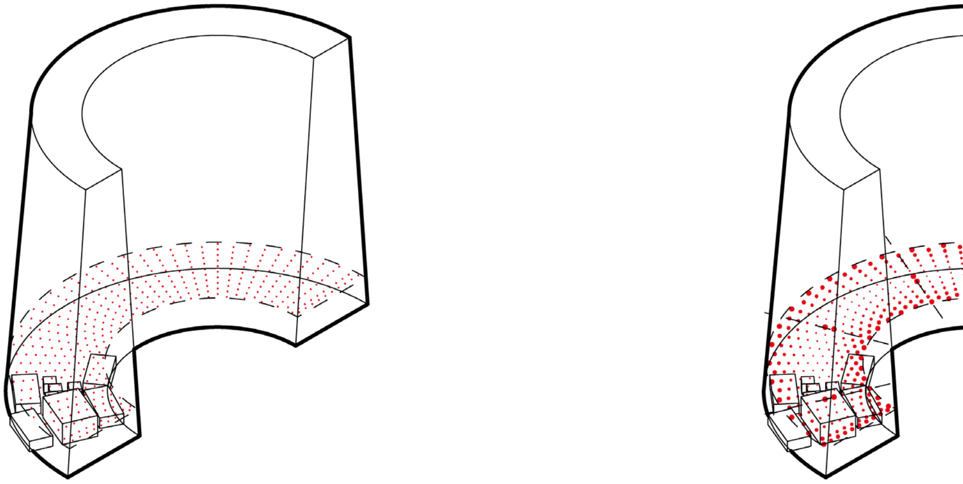
Figures F.81 and F.82 portray all the sections in the stacking algorithm. This process starts by slicing the geometry of the wall near the top of the objects stack or near the base of the wall if there are no objects in the objects stack. Next, a grid is generated, the resolution of which is controlled by the user. This grid is a collection of every possible target location which is rated based on the correlation of location and object size; large objects are used as anchors and create overlaying patterns, medium objects move towards the perimeter, and small objects are moved towards the center of the structure as fillers.

Later, the grid is projected downwards on top of the current stack and the lowest set of locations or planes are selected. This part is done to achieve a layer by layer generation, avoiding a movement along the vertical axis when there is empty space along the horizontal axis. Next, Object-Plane adaptability is calculated, a score that determines the best location for the new object solely based on its size. Afterwards, an orientation search takes place where collision with other objects in the stack and the wall perimeter is analyzed. As the seventh step, the proximity to the stack is analyzed; the new object should be placed next to the stack to create better support.

The next step is a technical constraint which evaluates the distance from the UR10 in order to prioritize further locations over closer locations; this objective helps prevent the robot blocking its own reach by placing a large object close to its center. Measuring the amount of shared surface between the new object and the stack or the ground is the next important step. Additionally, if the new object shares an amount of surface with two or more objects the score is higher than sharing the same amount of surface with only one object; this method creates a running bond pattern which increases component interlocking.

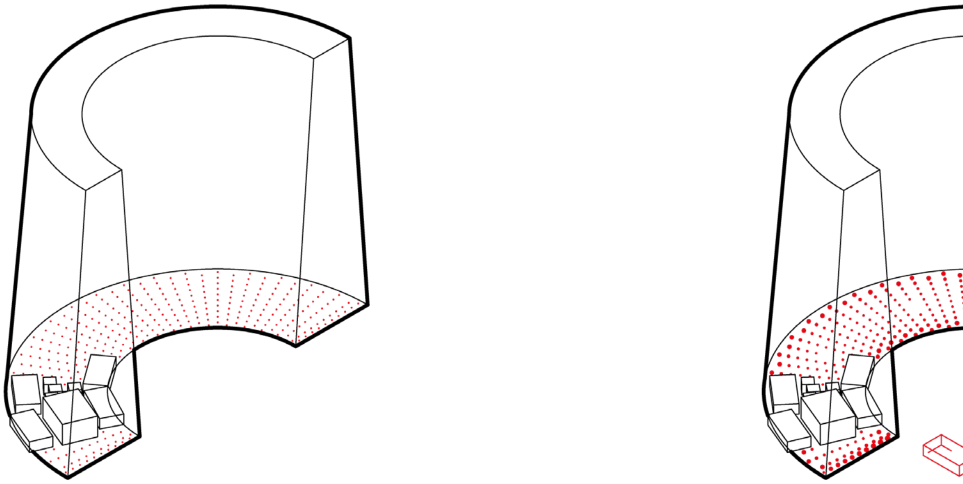
The tenth step assigns different weights to the previous evaluations and averages them into a comprehensive score. In this step, a cut-off point is defined for each individual score as well as the total score to limit the number of solutions and decrease complexity. Next, the solutions are tested in a PhysX rigid-body simulation to find the final pose for the new object. After the final pose is calculated, a path is generated from the initial pose of the object to its final pose, then this path is translated into UR10 script through an Inverse Kinematic Solver. The result is then communicated to the robot using the Machina pipeline.

F.81. Objectives and constraints for the wall stacking algorithm.



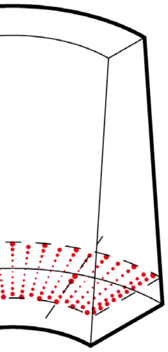
Generate Grid
(Technical)

Scoring Based
(Struc

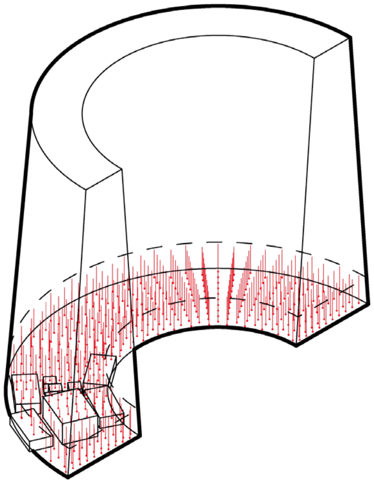


Select Lowest Planes
(Technical)

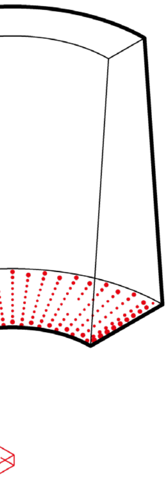
Object-Plane
(Struc



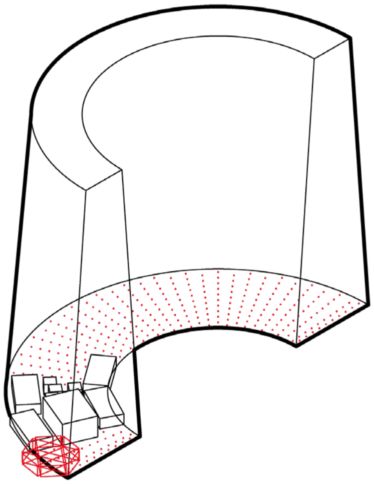
on Object Size
ctural)



Project Grid
(Technical)

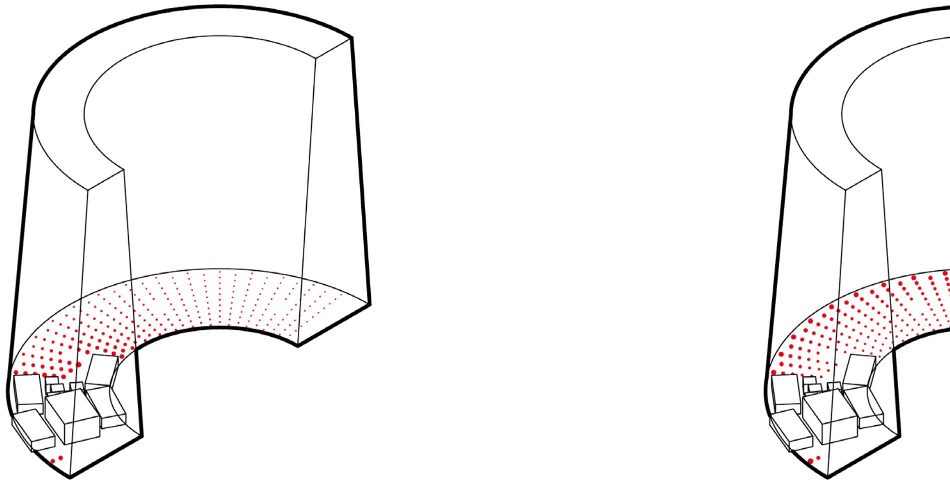


e Adaptability
ctural)



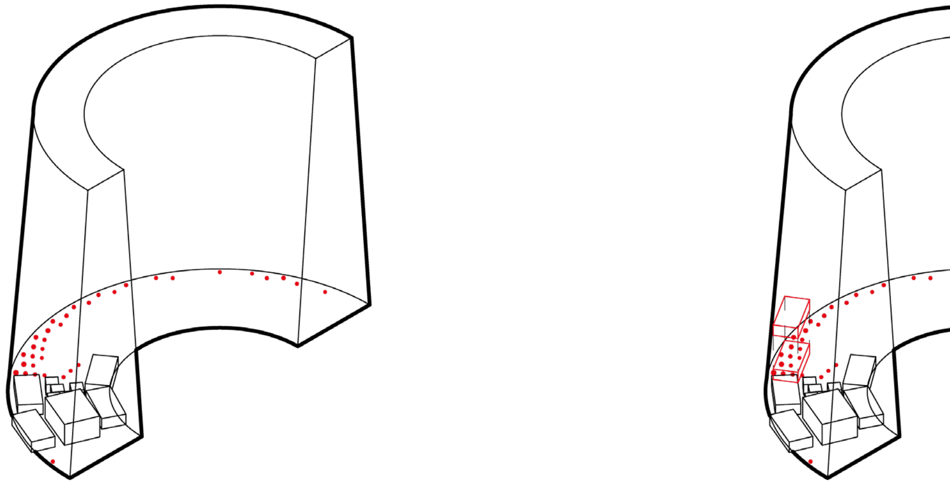
Orientation Search
(Structural)

F.82. Objectives and constraints for the wall stacking algorithm.



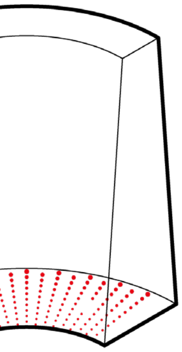
Proximity to the Stack
(Technical)

Distance f
(Tech

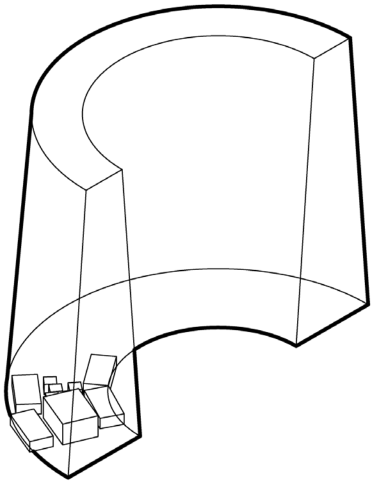


Total Score
(Technical & Structural)

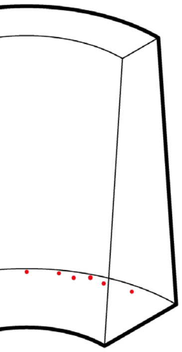
Rigid Body
(Struc



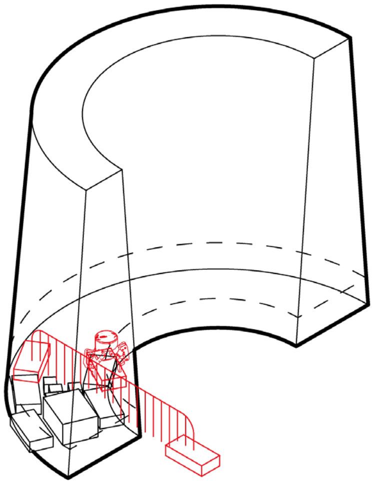
rom UR10
nical)



Shared Surface
(Structural)



Simulation
ctural)



Place Object
(Technical)

Ultimately, figures F.84 to F.87 depict a structure generated by the latest iteration of the algorithm. This algorithm reports the number of used objects, dismissed objects, relative size of the currently selected object, as well as the relative sizes for the next median and largest objects. The ratio of used and dismissed objects is a metric to measure the efficiency of this system in reusing construction waste. Relative size is a variable between zero and one that measures the volume of an object against the smallest and the largest component in the objects set. This metric informs the user about the preferred size for the next component introduced to the system. Moreover, the total number of found solutions and simulated solutions are reported. Additionally, this script reports important settings which are defined by the user including required object-plane match rate, required layer fill rate, and the required surface overlapping rate. The total progress of the structure is monitored and calculated by measuring the achieved height of the structure at the predefined density.

In this example, the algorithm uses a set of objects with randomized edge dimensions. While this method creates a completely random series of objects, the volume distribution is unbalanced. In other words, there might be as many small objects as there are large objects, nevertheless, the total volume of the generated small objects is lower than the total volume of the generated large objects. This leads to a lack of filler objects and therefore a less dense structure as shown in figure F.87. This phenomenon confirms the role of each and every object in this algorithm to stack a self-supporting structure.

F.83. Final algorithm generating a stacked wall with irregular objects through a set of objectives and constraints.

Used Objects 2 | Dismissed Objects 0

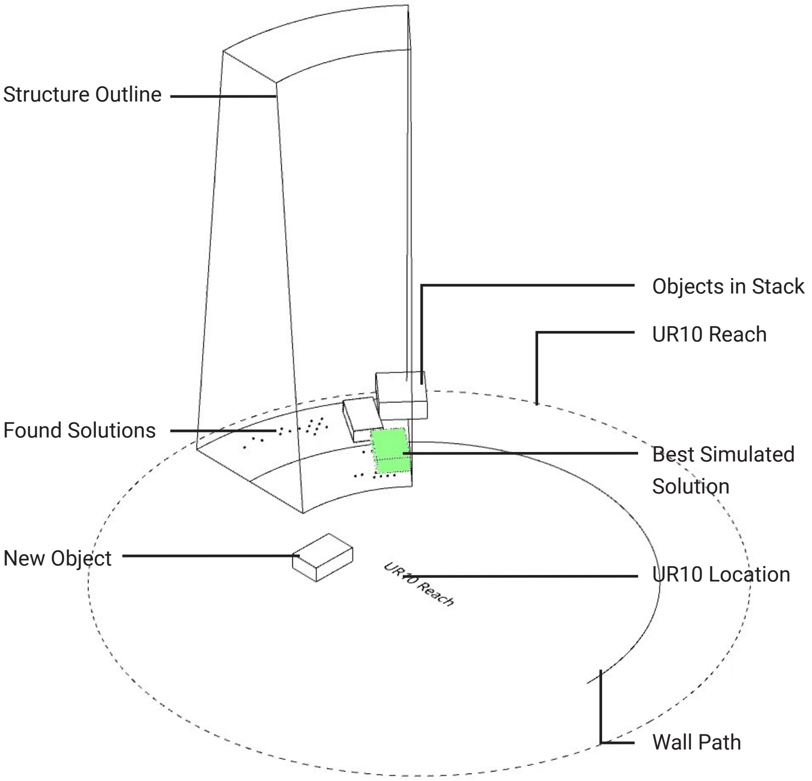
Size of Current Object: 0.12
Next Smallest Object: 0
Next Median Object: 0.23
Next Largest Object: 1

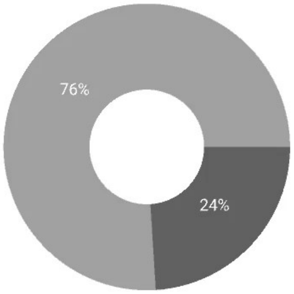
Number of Solutions: 100
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 0.73 %

Message: Simulating Solution #1...





Used Objects 19 | Dismissed Objects 6

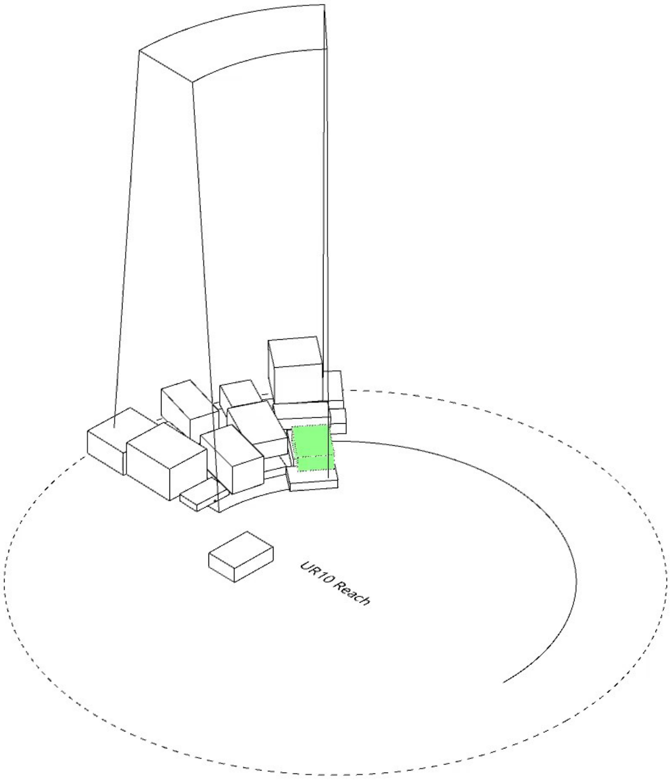
Size of Current Object: 0.14
Next Smallest Object: 0
Next Median Object: 0.15
Next Largest Object: 1

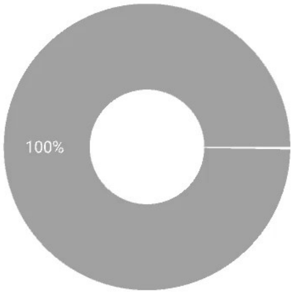
Number of Solutions: 36
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 7.3 %

Message: Adding Object to the Stack...





Used Objects	Dismissed Objects
7	0

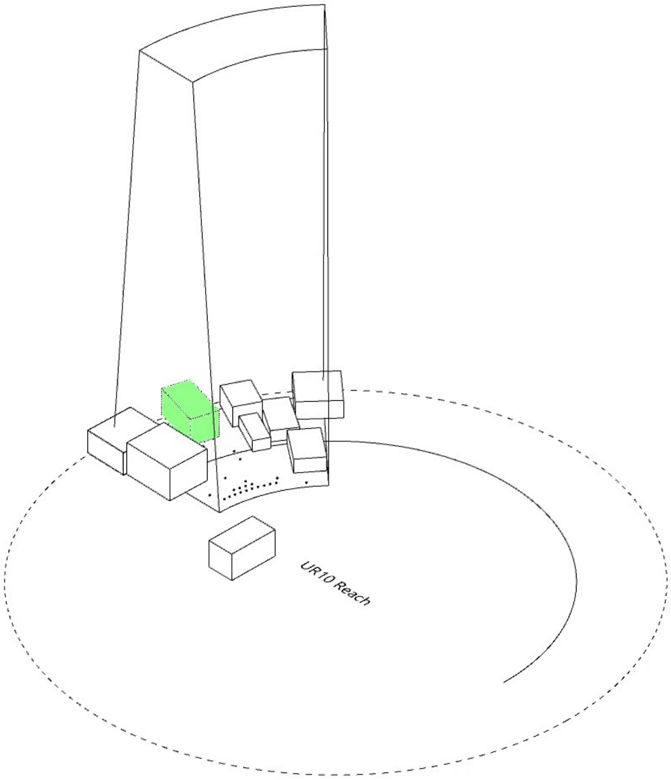
Size of Current Object: 0.27
Next Smallest Object: 0
Next Median Object: 0.17
Next Largest Object: 0.99

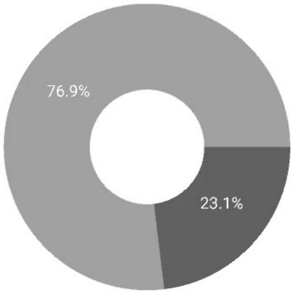
Number of Solutions: 100
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 3.43 %

Message: Adding Object to the Stack...





Used Objects	Dismissed Objects
20	6

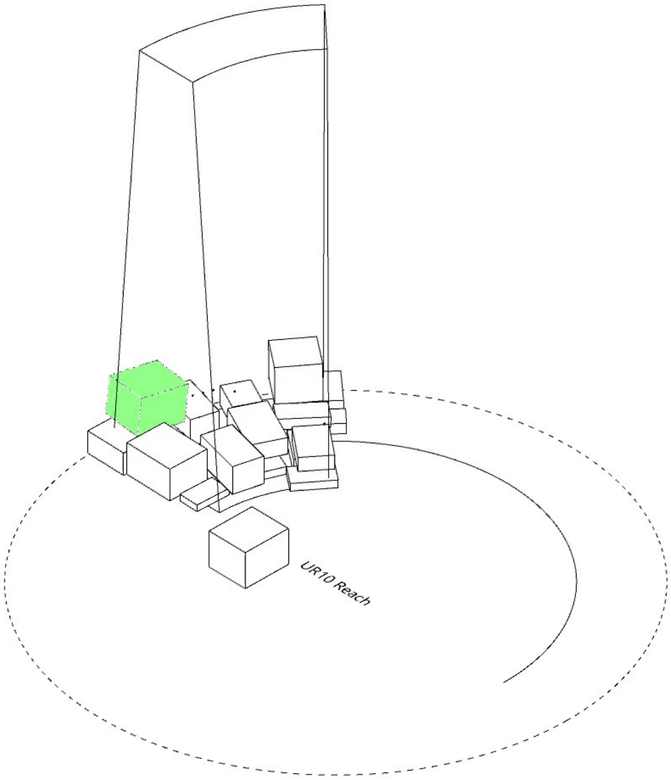
Size of Current Object: 0.59
Next Smallest Object: 0
Next Median Object: 0.12
Next Largest Object: 1

Number of Solutions: 22
Number of Simulated Solutions: 1

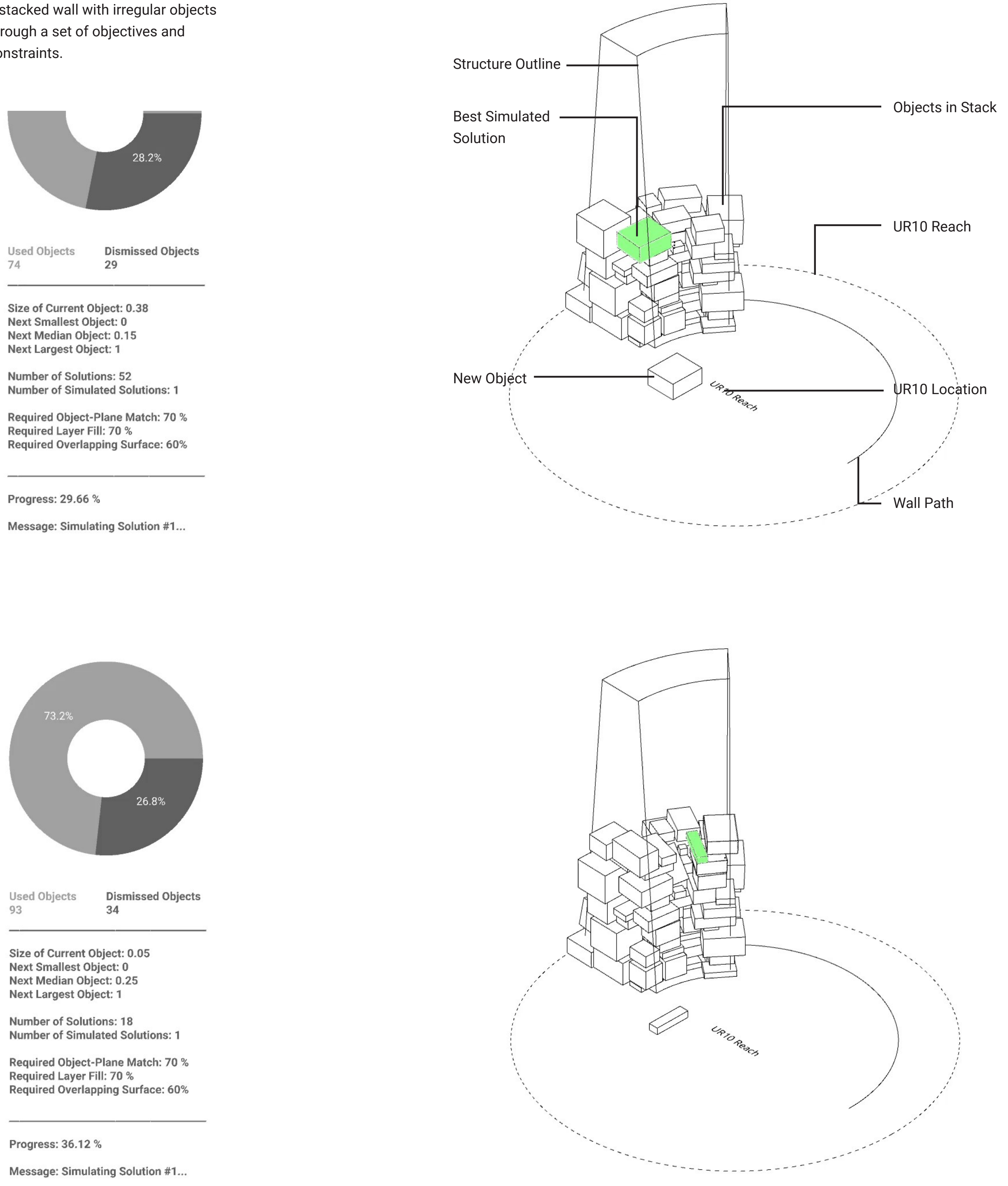
Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 7.62 %

Message: Simulating Solution #0...



F.84. Final algorithm generating a stacked wall with irregular objects through a set of objectives and constraints.



Used Objects
74

Dismissed Objects
29

Size of Current Object: 0.38
Next Smallest Object: 0
Next Median Object: 0.15
Next Largest Object: 1

Number of Solutions: 52
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 29.66 %

Message: Simulating Solution #1...

Used Objects
93

Dismissed Objects
34

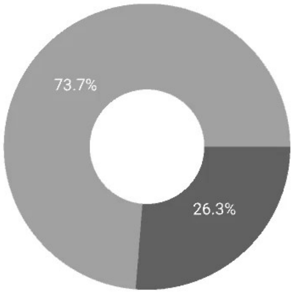
Size of Current Object: 0.05
Next Smallest Object: 0
Next Median Object: 0.25
Next Largest Object: 1

Number of Solutions: 18
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 36.12 %

Message: Simulating Solution #1...



Used Objects	Dismissed Objects
87	31

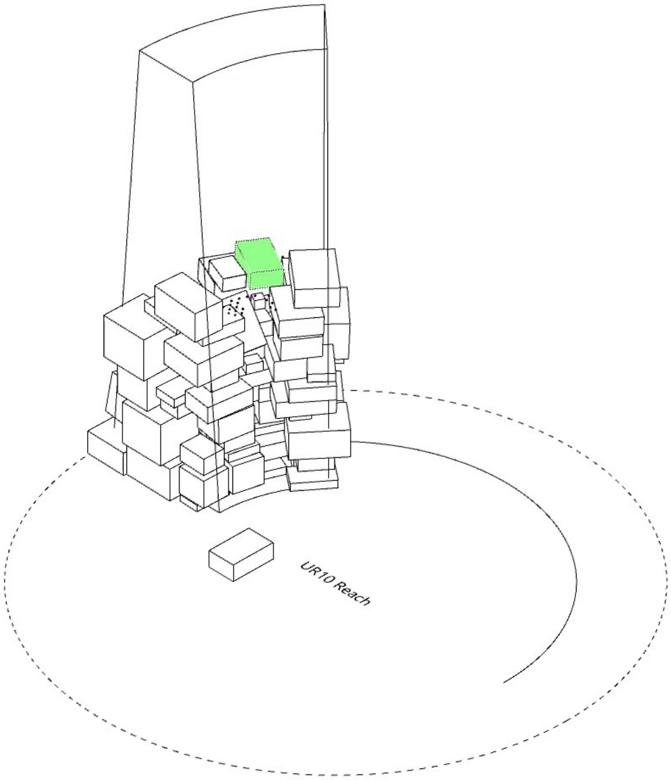
Size of Current Object: 0.16
Next Smallest Object: 0
Next Median Object: 0.22
Next Largest Object: 1

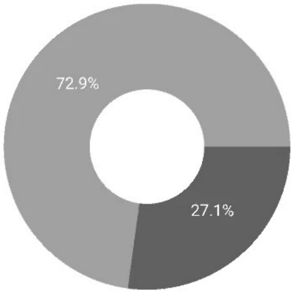
Number of Solutions: 60
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 34.78 %

Message: Simulating Solution #0...





Used Objects	Dismissed Objects
102	38

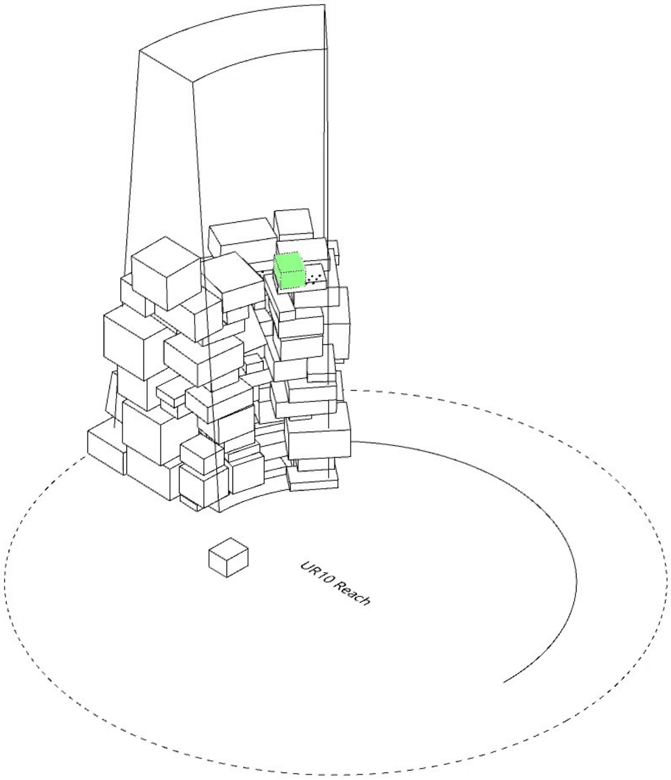
Size of Current Object: 0.06
Next Smallest Object: 0
Next Median Object: 0.34
Next Largest Object: 1

Number of Solutions: 30
Number of Simulated Solutions: 1

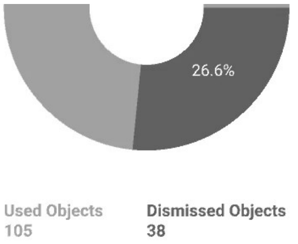
Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 39.49 %

Message: Simulating Solution #0...



F.85. Final algorithm generating a stacked wall with irregular objects through a set of objectives and constraints.



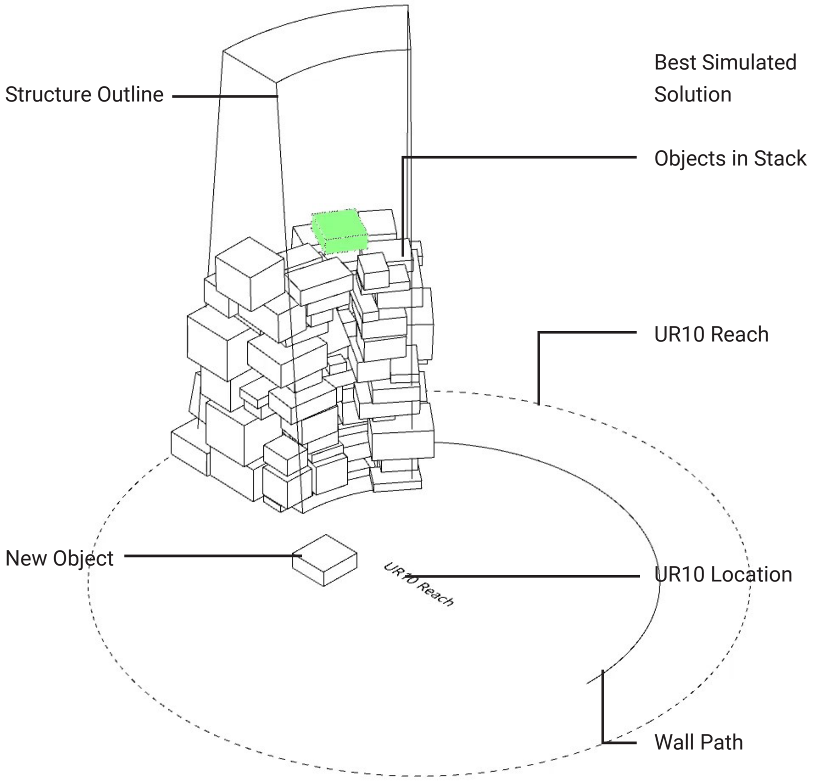
Size of Current Object: 0.15
Next Smallest Object: 0
Next Median Object: 0.27
Next Largest Object: 1

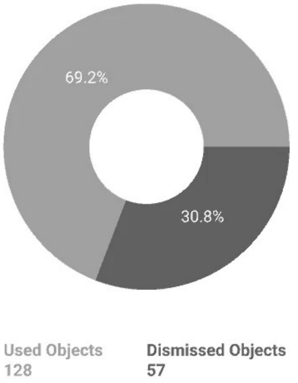
Number of Solutions: 14
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 40.22 %

Message: Adding Object to the Stack...





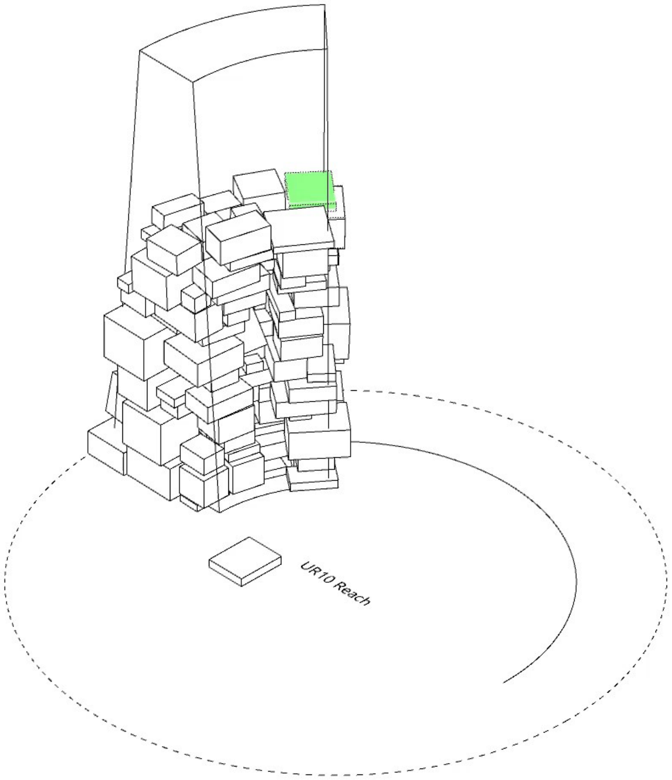
Size of Current Object: 0.1
Next Smallest Object: 0
Next Median Object: 0.26
Next Largest Object: 1

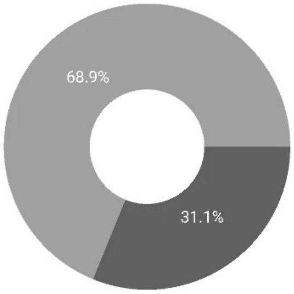
Number of Solutions: 16
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 47.01 %

Message: Simulating Solution #1...





Used Objects	Dismissed Objects
126	57

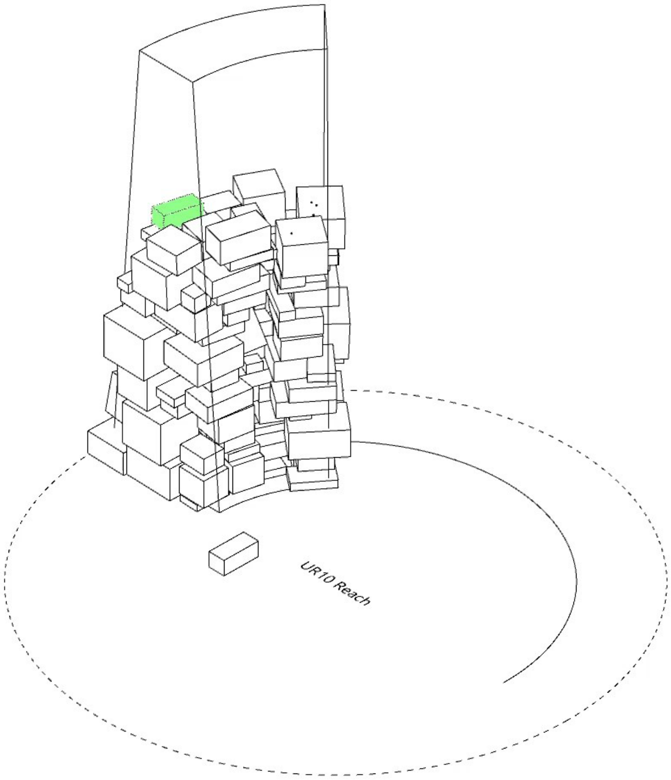
Size of Current Object: 0.08
Next Smallest Object: 0
Next Median Object: 0.33
Next Largest Object: 1

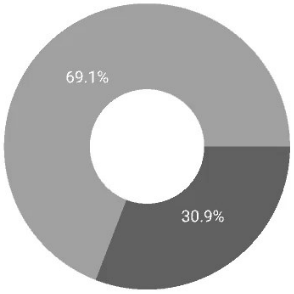
Number of Solutions: 18
Number of Simulated Solutions: 1

Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 46.54 %

Message: Simulating Solution #0...





Used Objects	Dismissed Objects
130	58

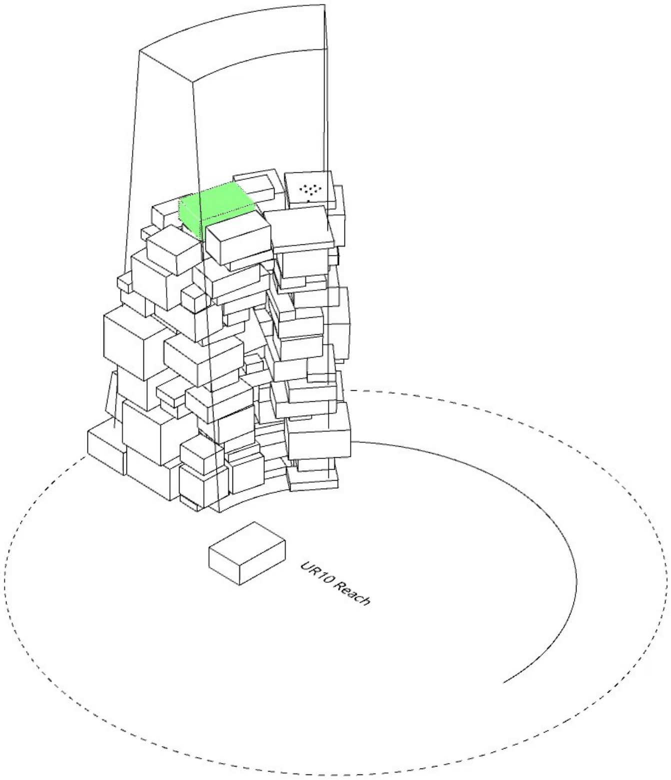
Size of Current Object: 0.28
Next Smallest Object: 0
Next Median Object: 0.25
Next Largest Object: 1

Number of Solutions: 24
Number of Simulated Solutions: 1

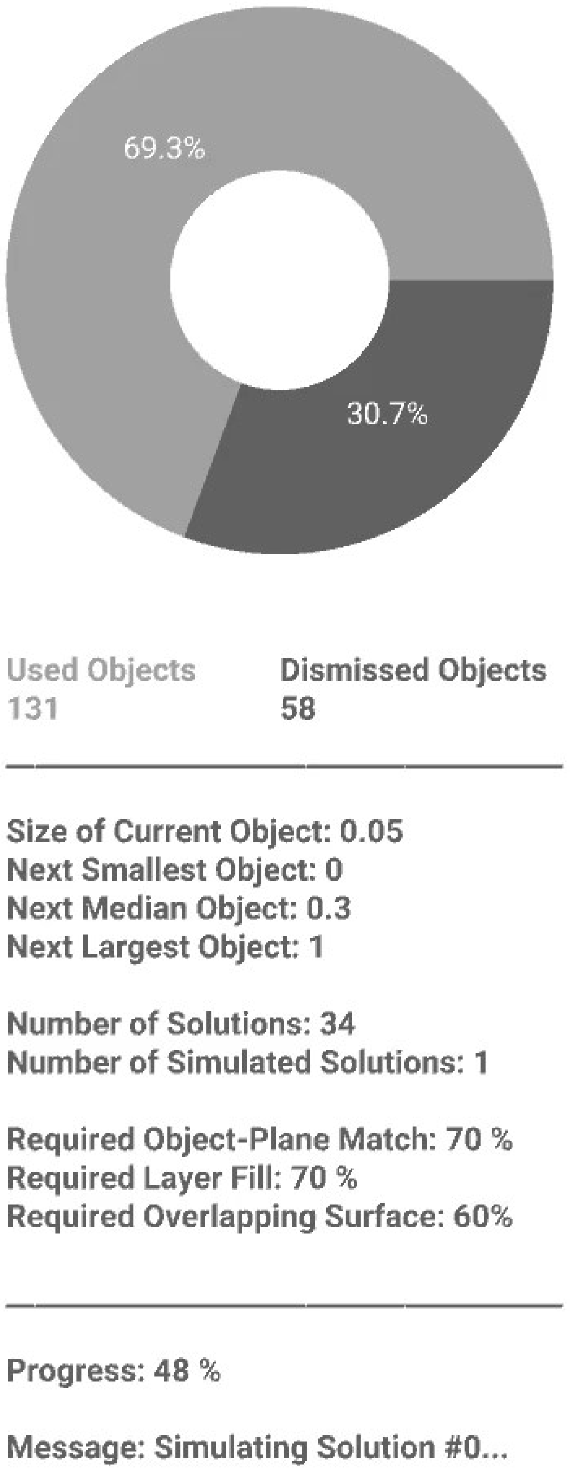
Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

Progress: 47.36 %

Message: Simulating Solution #0...



F.86. The object usage/dismissal rate, completion rate, and height reached are tracked to measure the efficiency of this interface.



Used Objects	Dismissed Objects
131	58

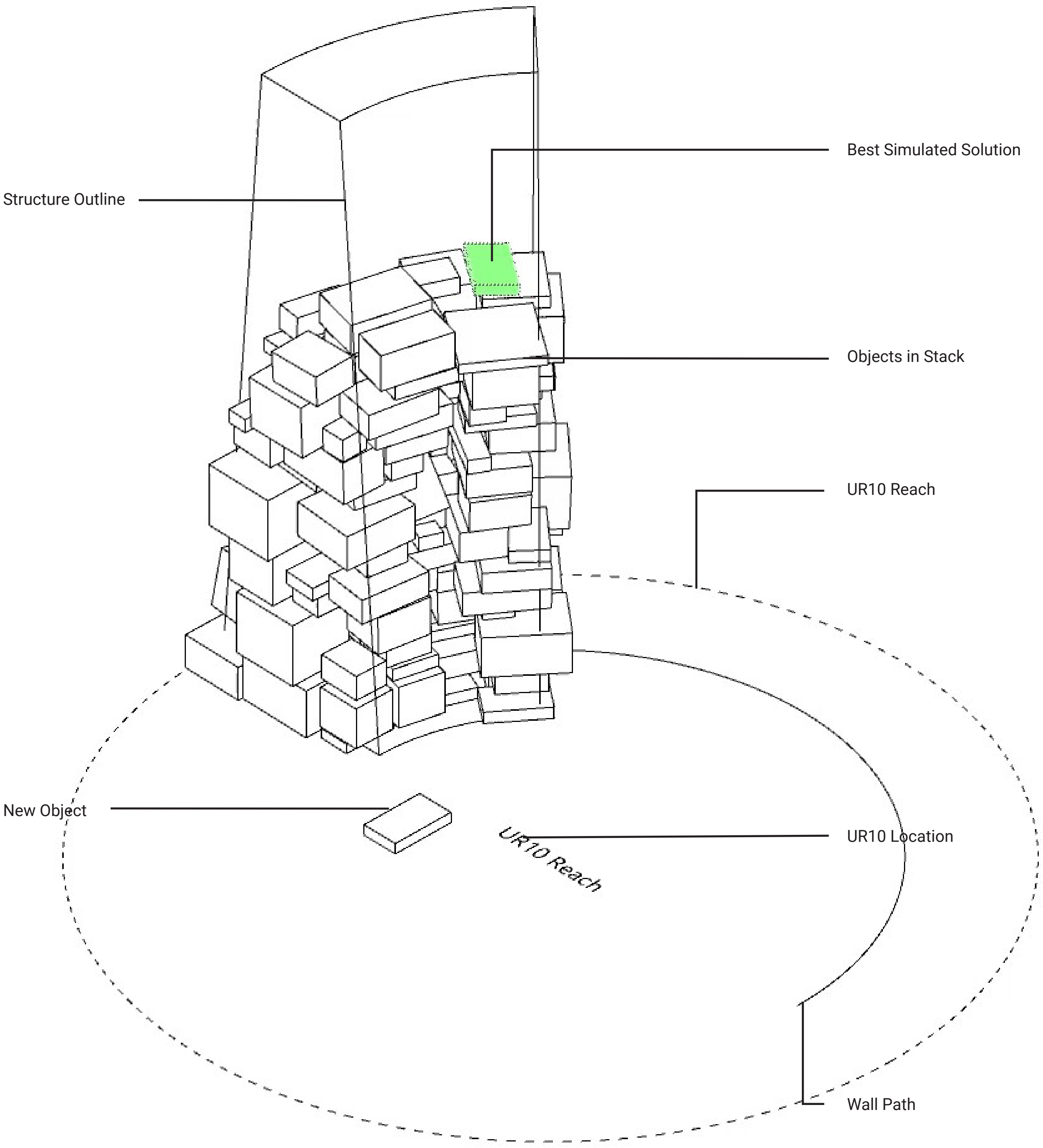
Size of Current Object: 0.05
Next Smallest Object: 0
Next Median Object: 0.3
Next Largest Object: 1

Number of Solutions: 34
Number of Simulated Solutions: 1

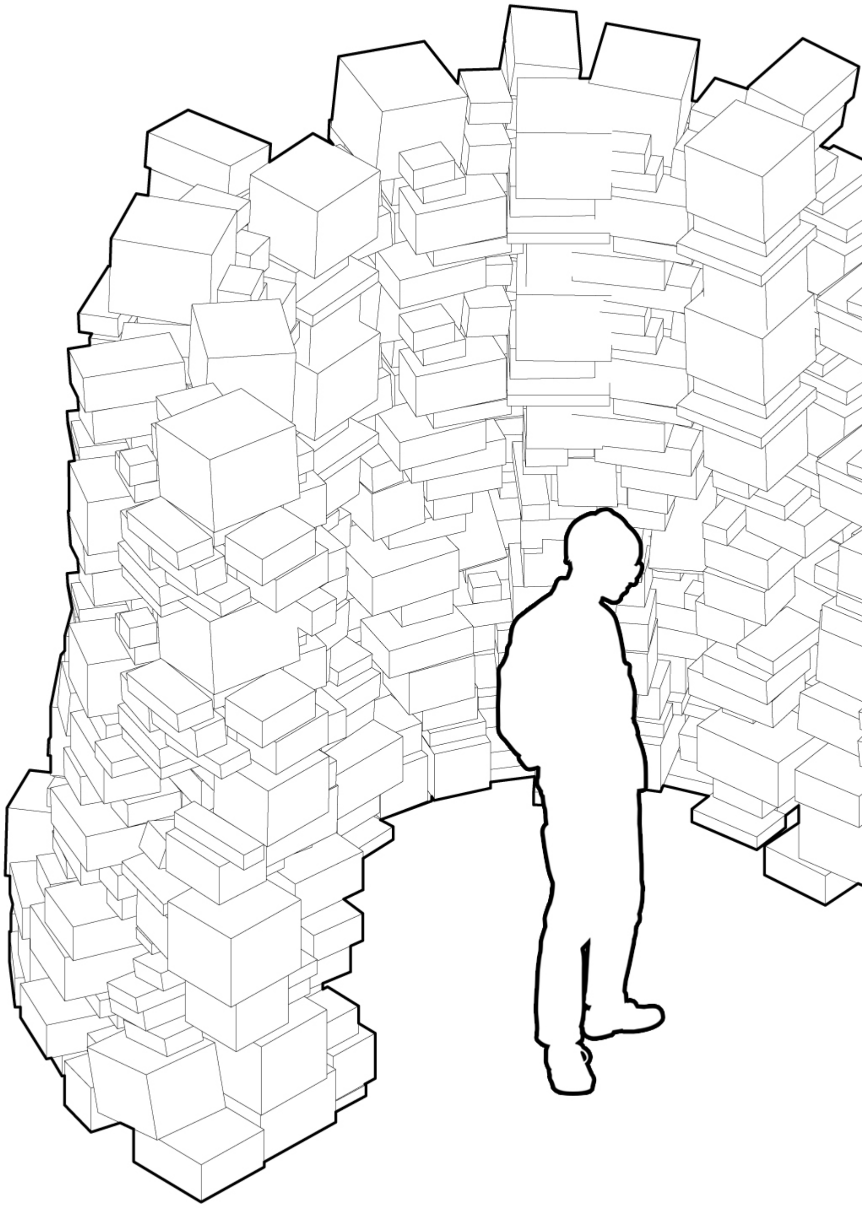
Required Object-Plane Match: 70 %
Required Layer Fill: 70 %
Required Overlapping Surface: 60%

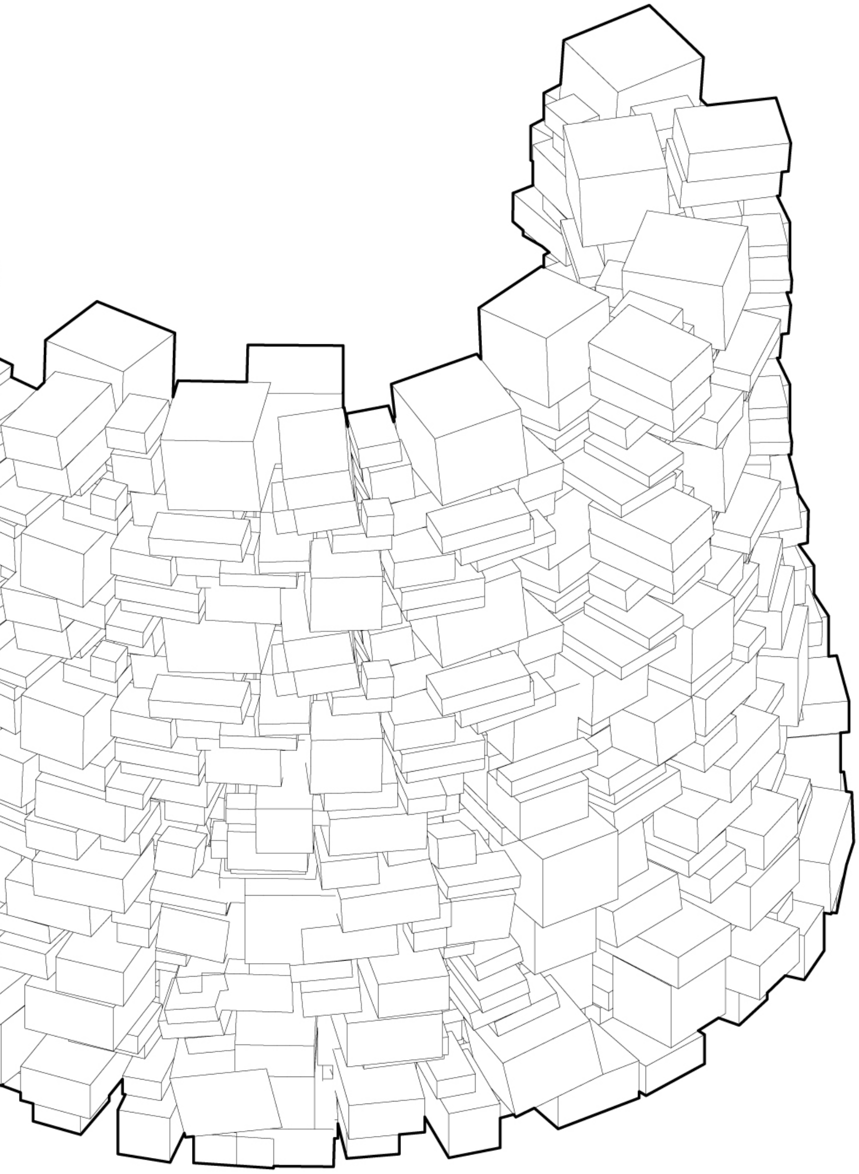
Progress: 48 %

Message: Simulating Solution #0...


Best Simulated Solution
Structure Outline
Objects in Stack
UR10 Reach
New Object
UR10 Location
UR10 Reach
Wall Path

F.87. The geometrical varieties in the introduced set affect the design outcome of the algorithm. The effects of these geometrical varieties can be controlled through Required Object-Plane Match and Required Layer Fill controls in the interface.





CONCLUSIONS & INSIGHTS

- Discussion
- Further Developments
- Future Applications

F

F.88. Machine Vision is one of the aspects of this research requiring further developments

#DEVELOPMENT

#PERCEPTION

#MECHANISM

#ALGORITHM

#EMERGENCY SHELTER

#CONSTRUCTION

#COLLABORATIVE

#EXPEDITION

#RESULTS

#CONTRIBUTION

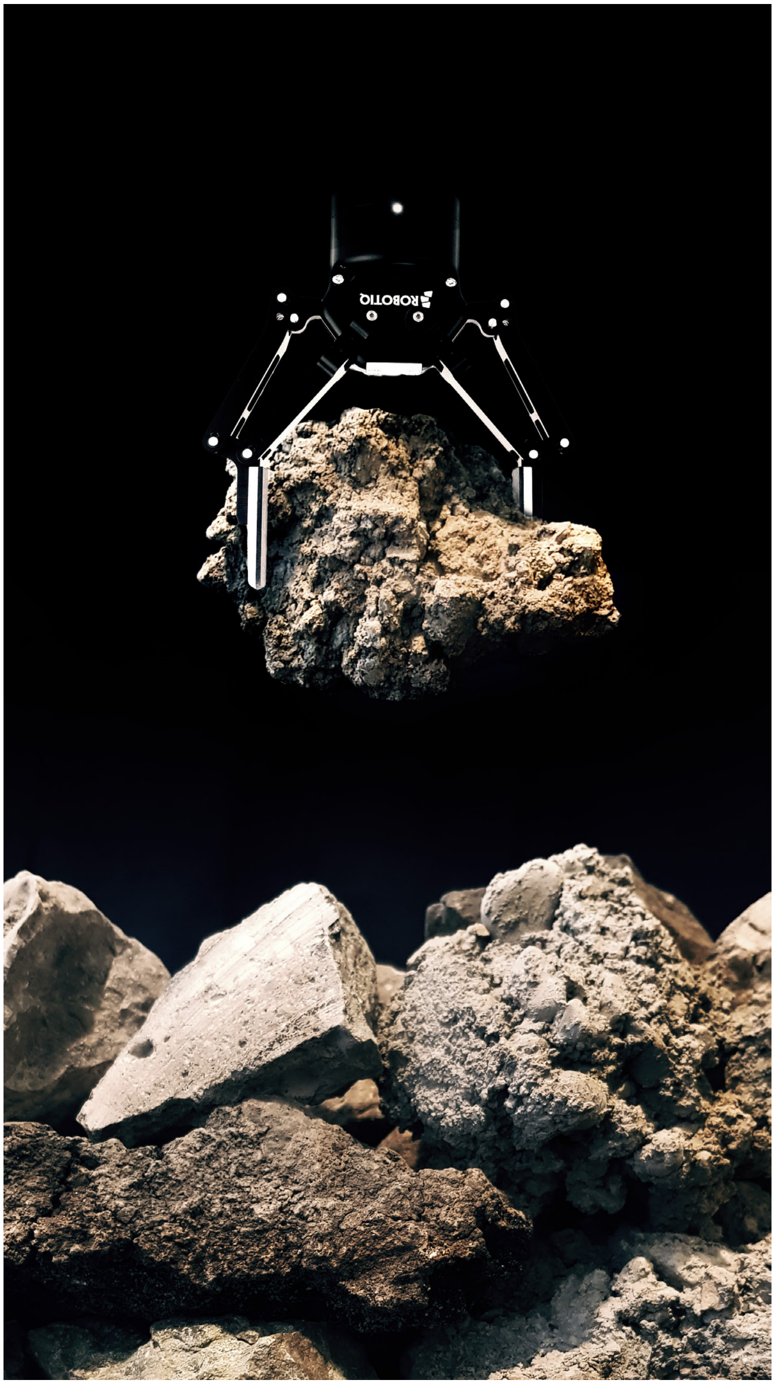
This thesis attempts to reclaim construction and demolition waste through designing a robotic system capable of stacking irregular objects in the form of a self-supporting compression-only structure. This system can be applied to on-site robotic construction to reduce environmental, economic, and cultural impacts of using raw materials. On the other hand, automated assembly of salvaged materials can be used for the construction of safe, cheap, durable, and sustainable emergency shelters. Additionally, using reclaimed materials is the best method of building structures in remote locations such as Mars. This chapter discusses the challenges, contributions, architectural and non-architectural applications, and further developments.

Discussion

This thesis suggests reusing construction and demolition waste as a means to reduce environmental issues, carbon footprint, and material costs. However, repurposing these found materials with minimal transfiguration calls for a complex assembly system. Manual construction of these structures can be a daunting task for a human due to increased complexity and heavy components, nevertheless, an easy feat for computers and machines. Consequently, this thesis develops a robotic stacking system, shown in figure F.89, which scans irregular objects and stacks them to create a materially-informed self-supporting compression-only structure. Finally, the usage rate of the recovered rubble, porosity of the generated structure, and completion rate to assess the performance of the system.

This thesis faced a variety of technical and logistic challenges. First, the nature of this Nondeterministic Polynomial-time Hard (NP-Hard) optimization problem caused a variety of computational problems. Performing a rigid-body simulation with irregular objects became computationally expensive as the number of components increased. To tackle this issue, the best results are isolated at every step to keep the number of solutions to a minimum. Another challenge faced during this research was the real-time optimization. At this time, many, if not all, of the optimization tools and solvers developed for Rhinoceros 3D and Grasshopper 3D operate in an off-line manner; meaning that the results do not update in real-time and user has to interact with their interface for receiving updated solutions. Lastly, this research was conducted in the year of 2020, during the COVID-19 pandemic. Nation-wide lock-down was one of the measures to control the spread of this virus, resulting in the termination of access to the digital fabrication facility at the University of Waterloo. This sudden phenomenon drastically impacted the research plan and decreased motivation levels for a short period. Unable to build a physical prototype, this thesis focused on simulations and computation to fill the gap.

F.89. An abstract photo of Robotic Stacking of Irregular Components in Compression-only Structures.



This research is a continuation to an existent body of literature on digital fabrication using non-standard components. More specifically, *Autonomous Stone Stacking* and *Interfaces for Adaptive Assembly*. However, neither of these precedents succeed in the construction of a wall with irregular objects. *Autonomous Stone Stacking* stops at a dry-stacked tower and *Interfaces for Adaptive Assembly* attempts to construct a wall, however, because of its 2D approach to objects, and lack of a better assembly system, a wall could not be accomplished. This research contributes to this field by merging dry-stacking manual construction techniques with computational 3D bin-packing algorithms, which enables the automated construction of a self-supporting wall with regular and irregular objects.

Robotic fabrication can transform our built environments and the architecture profession as we know it. However, these machines need to become more intelligent to be employed in a real-world scenario. They need to understand different components, devise various assembly methods, and notice errors. These machines need to be able to work with humans and other robots to delegate tasks and boost productivity. Consequently, my research is only a small step towards autonomous materially-informed construction. The interface developed in this thesis is merely a proof-of-concept and is in no way perfect. Further developments are required in all aspects for this system to become deployable. More specifically algorithms, mechanism design, and machine-vision need to be improved.

Further Developments

While this interface successfully generates a column and a wall, there are still many aspects to improve. A custom gripper to facilitate the grasping process, parallel-processing for the rigid-body simulation, and process monitoring could be implemented to get one step closer to on-site employment of robotic fabrication. Ultimately, for the robotic fabrication to influence the architecture industry similar to the advent of CAD programs, these machines need to become more intelligent.

They need to understand different components, devise various assembly methods, and notice errors. These machines need to be able to work with humans and other robots to delegate tasks and boost productivity.

On the one hand, the current algorithm developed in this research is only applicable for building two compression-only structures, a column and a wall. With further developments, construction of arches, domes, and free-form skins will be possible. On the other hand, by integrating tension calculations, this interface will be able to generate tension-only and compound structures, getting closer to the global application of robotic fabrication. Moreover, implementation of parallel-processing and machine-learning into this process is crucial for increasing calculation speed, accuracy, and efficiency.

Mechanism design is another aspect where improvements are necessary. The Robotiq 2F-85 gripper used in this design is not the ideal tool to grasp irregular objects. A Custom end effector that combines suction and pinching with a higher stroke limit can greatly benefit handling non-standard components. The current setup doesn’t allow automated lateral or horizontal movements of the robot. Robot reach restrictions will be lifted provided that this machine can move around freely. Similar to humans, robots should be able to interact and cooperate in order to achieve a goal. The next step to improving the mechanism design in this research is using multiple robots which collaborate with one another to complete a task. For instance, one robot can focus on sorting the materials while the other focuses on construction.

Interacting with the physical environment is an indispensable part of an intelligent construction robot. This part of the process becomes significantly important for handling non-standard components. In this thesis, as-found materials are 3D scanned; however, any change to those materials after they are placed in the structure is unmonitored. The lack of process monitoring feature can lead to the collapse of the structure as soon as a divergence happens between the physical and the digital model. Process monitoring helps update the digital model should any of these unprecedented changes happen. This strategy will make this interface more intelligent and trustworthy when handling irregular objects.

F.90. Robotic assembly interfaces can enable construction with reclaimed materials.


dsm
dsm
dsm
IS TO DO
COME ON YOU SPURS
THE GAME IS ABOUT GLORY
TOTTENHAM HOTSPUR
UNDER ARMOUR
CAT
dsm

Future Applications

There is no questioning that robotic technology will become prevalent in the architecture and construction industry the same way CAD programs did. These machines can be used on construction sites to create a more sustainable industry through reusing waste. See figures F.90 and F.91. This thesis is a small, yet necessary, step towards on-site robotic fabrication. With further developments, this strategy could be applied to decrease or eliminate the need for raw materials. Materials could be collected from the nearby deconstruction site and assembled into a novel structure. This research aimed to "make sense out of nonsense" in that it attempted to construct with completely irregular objects without any prior sorting. In a more practical scenario, the way we deconstruct buildings can play an important role in the form of the construction waste; nevertheless, it is still crucial for these robotic systems to be resilient to change and irregularity.

The second application of these systems is building emergency shelters. See figure F.92. Based on the United Nations guidelines for shelter design, these structures must be compatible with the cultural and climatic conditions of the region. Additionally, affordability, durability, ease of construction, and the possibility of recycling or reusing are the other vital factors in a successful shelter. [116] [117] Recovered materials, more specifically rubble is an appropriate choice that is readily available in many regions of the world. Furthermore, these materials possess significant compressive strength and mass which can increase the durability of the structure. Consequently, automated assembly of recovered components can be applied in the rapid construction of emergency shelters which are safe, affordable, and sustainable.

In remote areas, robotic construction with found materials might be the only option. Transporting skilled labor and materials are both expensive and time-consuming. In many cases, it is preferable to build with local materials. For instance, in the extreme case of mars colonization, we need to use the resources found on that planet; supplying materials from earth is nearly impossible.

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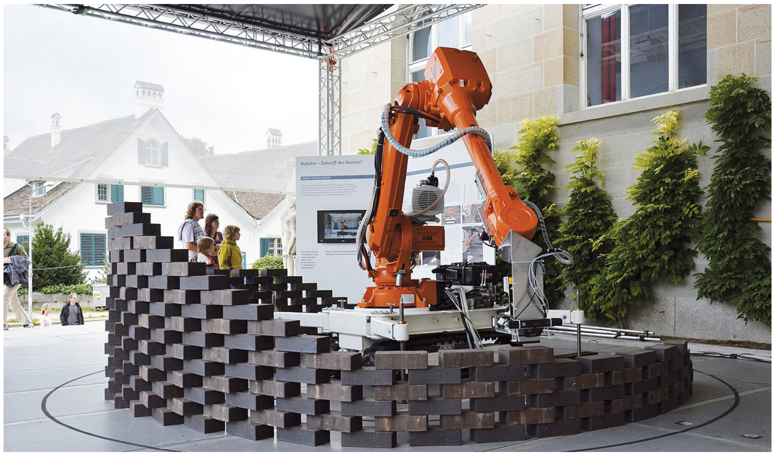
116. United Nations High Commissioner for Refugees, Shelter Design Catalogue (United Nations High Commissioner for Refugees Geneva, 2016).

117. Abdulrahman Bashawri, Stephen Garrity, and Krisen Moodley, "An Overview of the Design of Disaster Relief Shelters," Procedia Economics and Finance, 4th International Conference on Building Resilience, Incorporating the 3rd Annual Conference of the ANDROID Disaster Resilience Network, 8th – 11th September 2014, Salford Quays, United Kingdom, 18 (January 1, 2014): 924–31, https://doi.org/10.1016/S2212-5671(14)01019-3.

F.91. Robots can decrease construction costs and increase completion speed in the future.



F.92. Emergency shelters can benefit from robotic construciton systems.

F.93. Construction on Mars is possible with reclaimed materials.

BACK MATTER

- Letters of Copyright Permission
- Bibliography
- Appendices
- Glossary

G

Letters of Copyright Permission

From: Nima Karami

Sent: Friday, October 2, 2020 10:46 AM

To: Sandy Pirouzi; Florian Heinzelmann

Cc: sayhello@sanrokstudio.com; info@shau.nl

Subject: Re: Copyright Permission Request - Bima Microlibrary / SHAU Bandung

Hi,

Thank you!

Best,

Nima

Nima Karami

M.Arch. Candidate

School of Architecture I University of Waterloo

From: Sandy Pirouzi <sandy@sanrokstudio.com>

Sent: Friday, October 2, 2020 6:19:32 AM

To: Florian Heinzelmann

Cc: Nima Karami; sayhello@sanrokstudio.com; info@shau.nl

Subject: Re: Copyright Permission Request - Bima Microlibrary / SHAU Bandung

Hi Nima,

It’s no problem too from our side. Good luck with your thesis!

<Sanrok_Studio_.jpg>

<Sanrok_Studio.jpg>

Sandy Pirouzi

SANROK Studio

Photographer / Founder

On Fri, Oct 2, 2020 at 8:32 AM Florian Heinzelmann <f.heinzelmann@shau.nl> wrote:

Hello Nima.

From our side no problem. From Sanrokstudio's side I hope it won't be an issue either (they are the holder of the copyright of the photos after all). I hope they will answer too.

Best regards,

Florian Heinzelmann

Ph.D., M.Arch., Dipl.-Ing., Architect (SBA)

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On 2 Oct 2020, at 06.02, Nima Karami <nkarami@uwaterloo.ca> wrote:

Hello,

I hope this email finds you well in these troubled times. I am contacting you to request copyright permission for academic use.

I am an M.Arch. student at the University of Waterloo, Canada. I would like to use the attached images of the PET pavilion project in my thesis document.

My thesis is titled “Reclaiming Construction Waste: An Interface for Robotic Stacking of Irregular Components in Compression-only Structures”

These photos will complement the case study and the literature review section of my thesis book. I would appreciate if I could use these photos without any modifications.

Thank you in advance.

Best regards,

Nima

Nima Karami

M.Arch. Candidate

School of Architecture I University of Waterloo

From: LOOS.FM <info@loos.fm>

Sent: Wednesday, September 23, 2020 2:24 PM

To: Nima Karami

Subject: RE: Copyright Permission Request - PET pavilion

Hello Nima ,

Ok , fine , you can use them

Kind regards ,

architectuurbureau

PROJECT.DWG

Michiel de Wit

Architect / eigenaar.

06-30647976

mdewit@projectdwg.com

www.projectdwg.com

Avast logo

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www.avast.com

Van: Nima Karami <nkarami@uwaterloo.ca>

Verzonden: woensdag 23 september 2020 14:43

Aan: info@projectdwg.com; info@loos.fm

Onderwerp: Copyright Permission Request - PET pavilion

Hello,

I hope this email finds you well in these troubled times. I am contacting you to request copyright permission for academic use.

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My thesis is titled “Reclaiming Construction Waste: An Interface for Robotic Stacking of Irregular Components in Compression-only Structures”

These photos will complement the case study and literature review section of my thesis book. I would appreciate if I could use these photos without any modifications.

Thank you in advance.

Best regards,

Nima

Nima Karami

M.Arch. Candidate

School of Architecture I University of Waterloo

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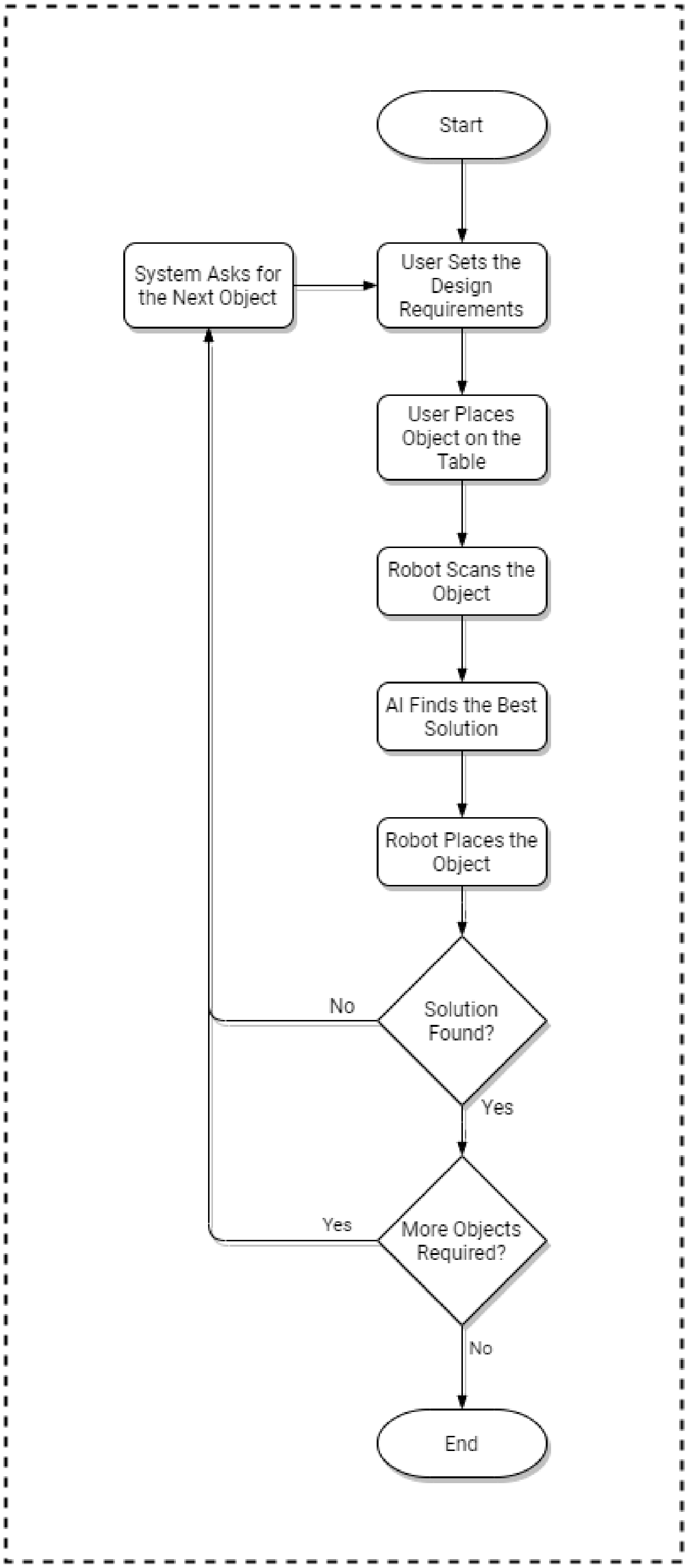
Appendices

In this section, a number of computational flowcharts are listed to reflect the different steps in the design of the algorithm. The first drawing, figure F.94, depicts the overall process at a macro level, including the user-device and device-device interactions. The following drawings analyze each section of this process in more details. F.95 is related to the design parameters set by the user that define the type of the structure, its length, width, height, and other properties. F.96 moves to how the robot and other electronic devices work cooperatively to scan the new objects. Next, F.97 describes the strategy used by the algorithm to find the best possible solution as the target pose. F.98 decpicts how the observed initial pose and the calculated target pose can inform the robot to grasp an object and place it in the desired location while avoiding obstacles.

LEVEL 00

OVERALL PROCESS

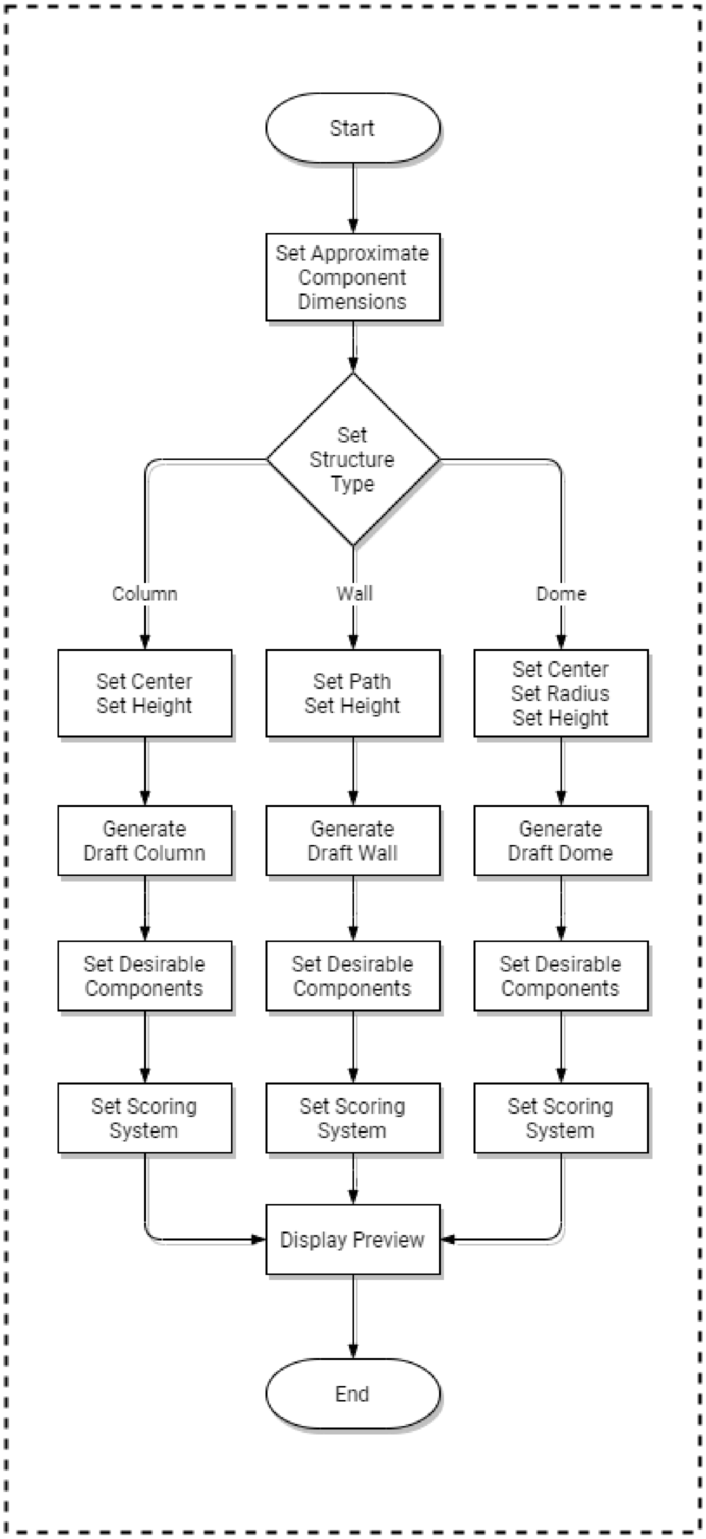
F.94. The overall process flowchart of the interface developed in this thesis.



LEVEL 01

USER SETS THE DESIGN REQUIREMENTS

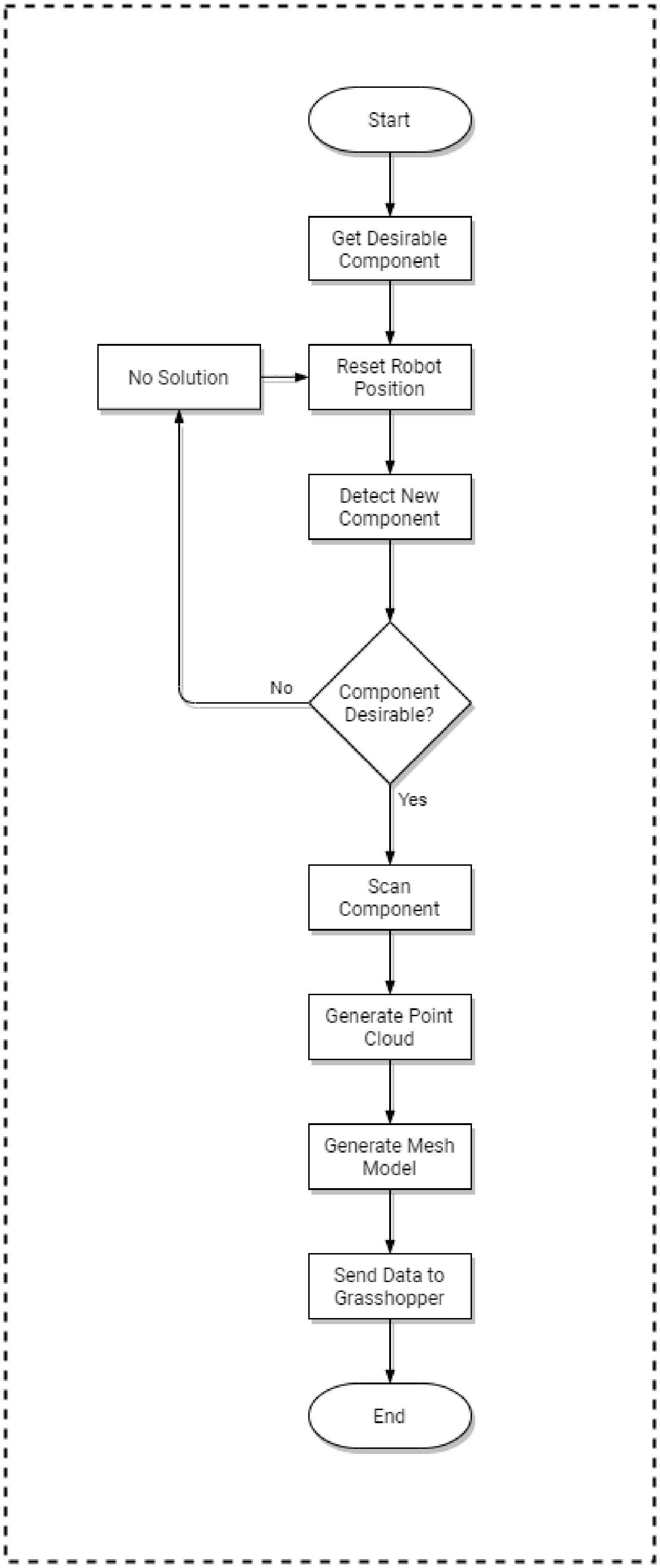
F.95. The flowchart diagram of the design requirements setup by the user.



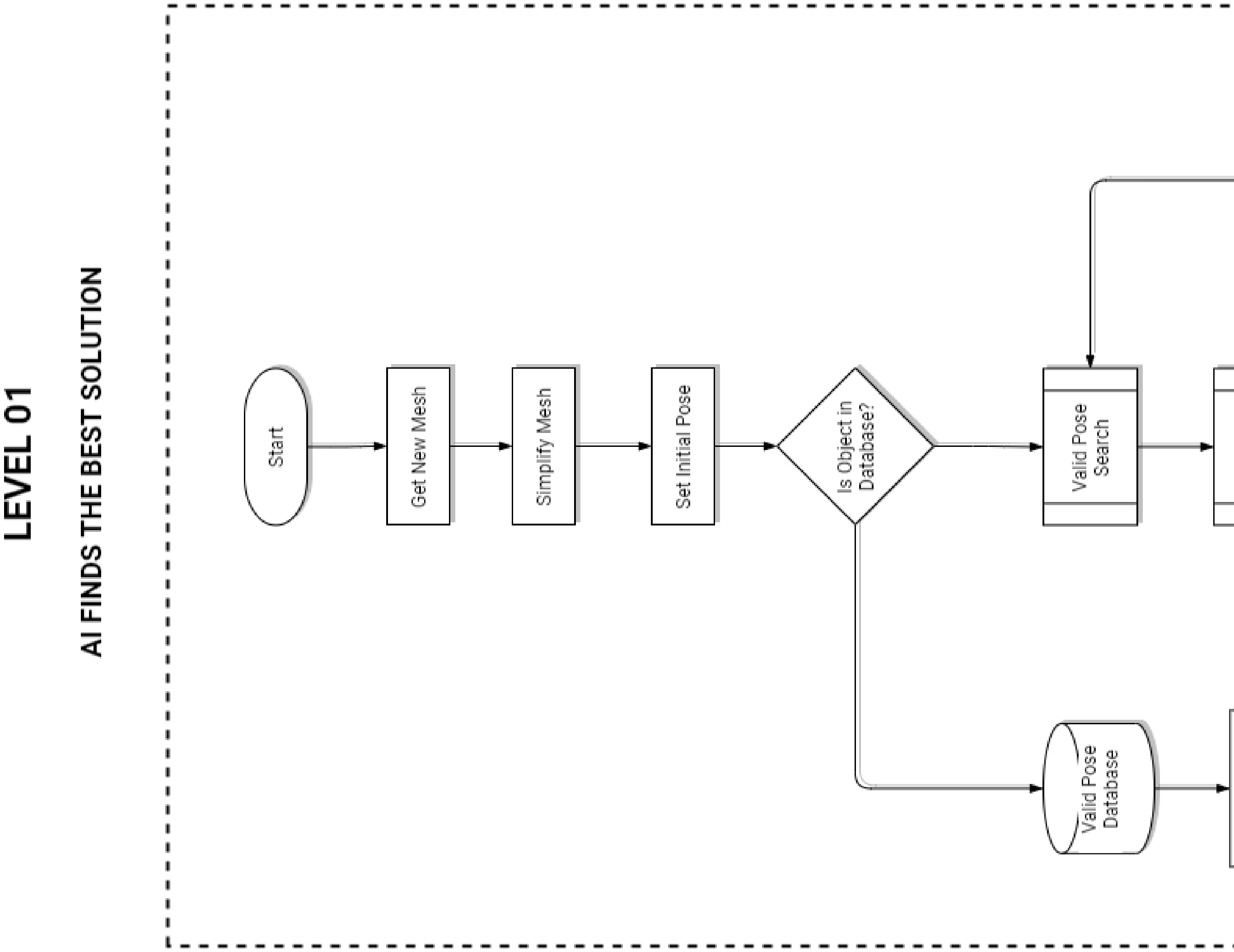
F.96. The flowchart diagram of steps involved for the robot to scan an object.

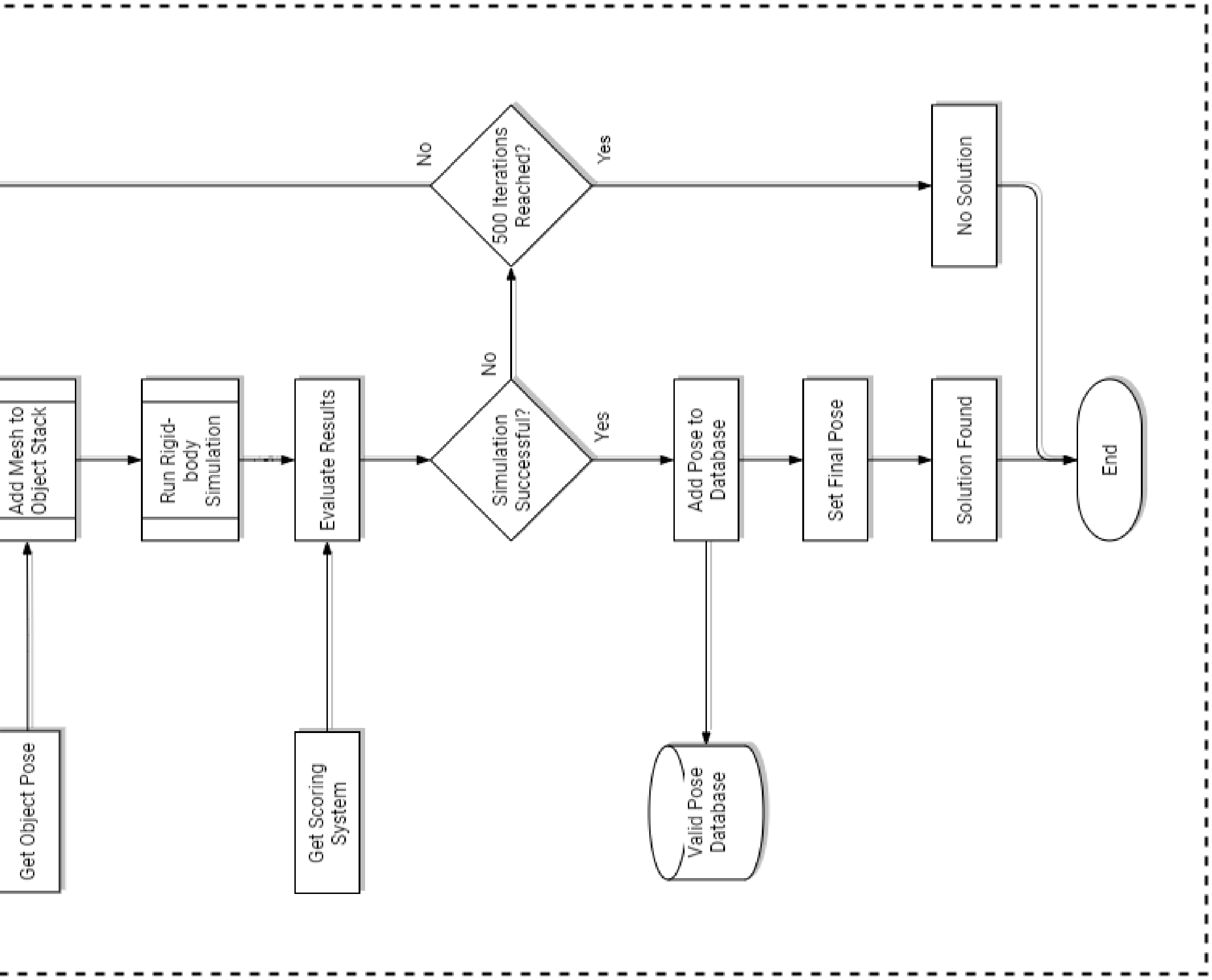
LEVEL 01

ROBOT SCANS THE OBJECT



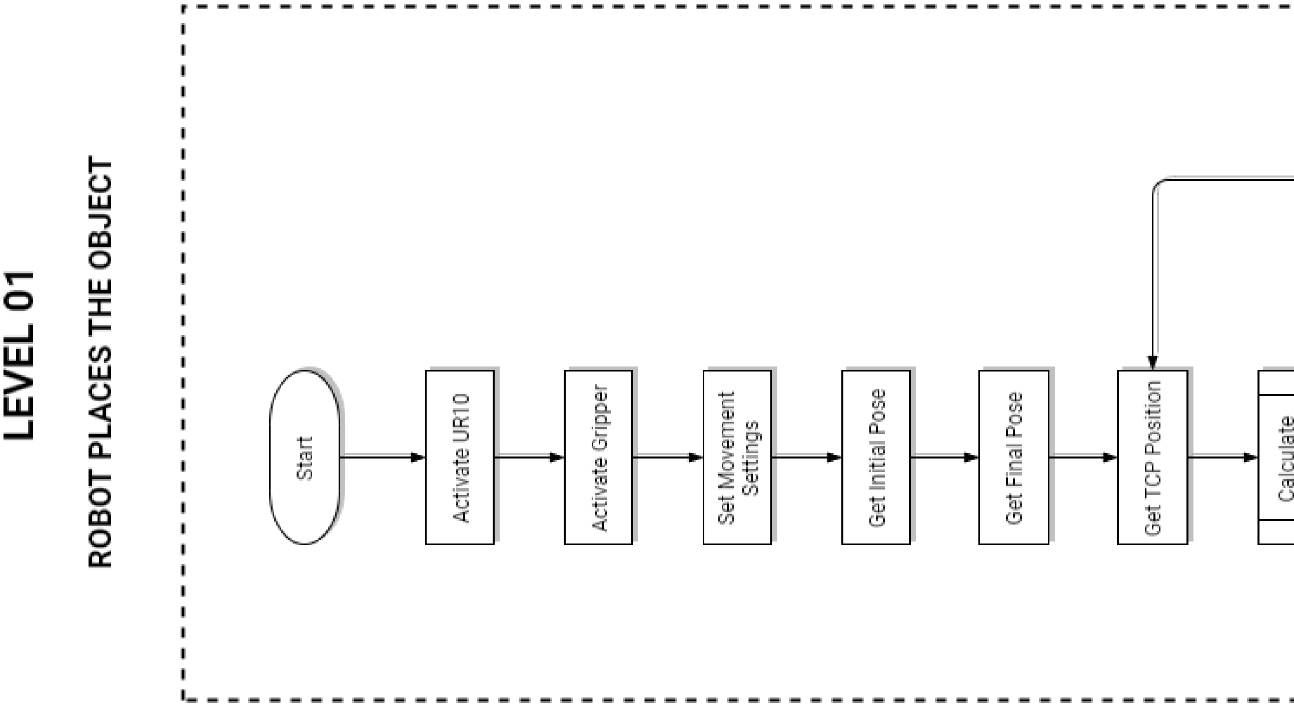
F.97. The flowchart diagram of steps involved for the algorithm to find the best solution.

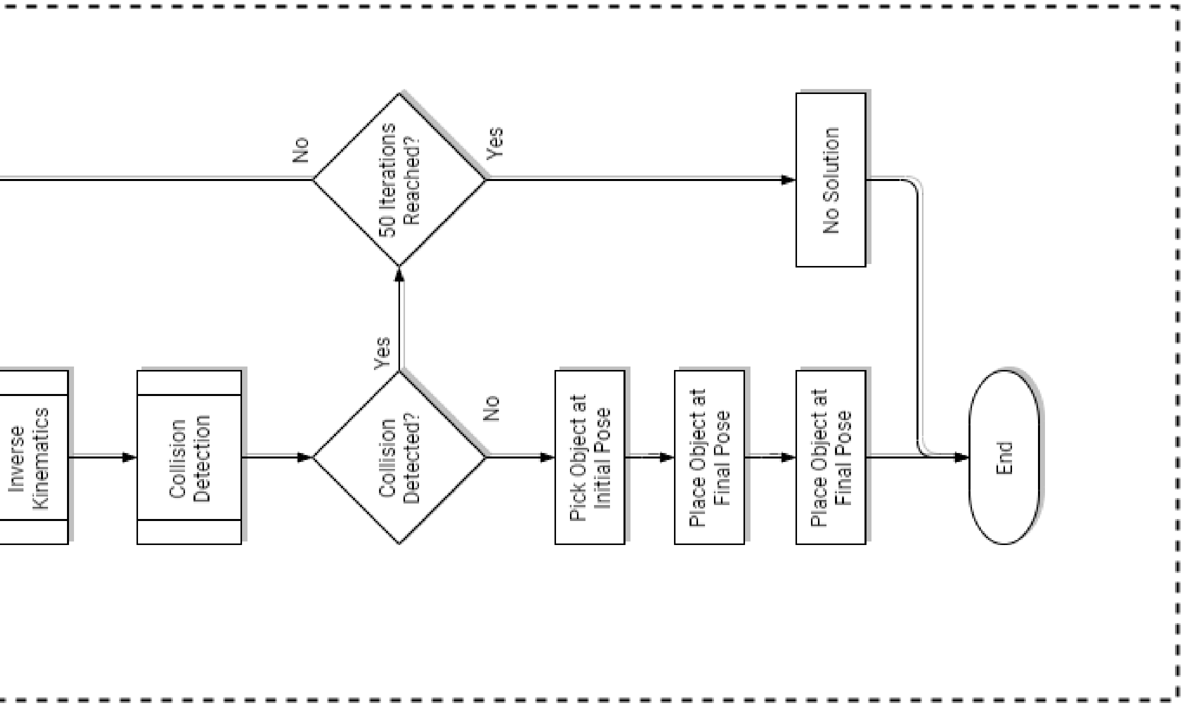




No
500 Iterations Reached?
Yes
No Solution
Add Mesh to Object Stack
Run Rigid-body Simulation
Evaluate Results
No
Simulation Successful?
Yes
Add Pose to Database
Set Final Pose
Solution Found
End
Get Object Pose
Get Scoring System
Valid Pose Database

F.98. The flowchart diagram of steps involved for the algorithm to find the best solution.




Inverse Kinematics
Collision Detection
Collision Detected?
Yes
No
50 Iterations Reached?
No
Yes
No Solution
Pick Object at Initial Pose
Place Object at Final Pose
Place Object at Final Pose
End

Glossary

ACTUATOR

Actuator is part of a system that controls components of a mechanism, in other words, an actuator is a “mover”

ADAPTIVE ASSEMBLY

As opposed to zero-tolerance assembly, adaptive assembly adjusts design or fabrication based on the newly presented conditions. This process can be used for bottom-up designs.

ALGORITHM

A set of rules and conditions employed in computational operations to undertake calculations or solve certain problems.

AS-FOUND MATERIALS

Existing items which are used in an art or architectural project without modification. Reclaimed materials. Reused materials.

BOTTOM-UP DESIGN

An approach that involves assembling smaller elements to create more complex systems. The results of this goal-oriented process is an effect of the small components and is not pre-planned.

C&D WASTE

Construction and Demolition waste includes any rejected material that is produced directly or indirectly in the process of a new construction or demolishing existing structures.

COLLABORATIVE ROBOT

Cobot. These machines are designed for cooperation and operation alongside humans. These devices often have safety measures that prevents hazardous accidents.

COMPUTATIONAL DESIGN

Development of new concepts and strategies using computing and algorithms in the design process.

COMPUTER VISION

Machine Vision. An interdisciplinary field enabling machines with high level understanding of the physical environment through image and video analysis.

DIGITAL FABRICATION

The production or invention of an item or structure using novel technologies such as additive, subtractive, or robotic manufacturing.

END EFFECTOR

In the field of robotics, an end effector is the actuator manipulating the physical environment. An end effector is the last element of the mechanism that interacts with the objects.

GRASSHOPPER 3D

Grasshopper is a visual programming language integrated within the Rhinoceros 3D application. This program is widely used by architects and industrial designers.

GRIPPER

A device that grasps or facilitates the process of grasping objects. This device is an end effector acting as the “hand” of the robot

HARDWARE

The physical tools and devices used in an interface and computational process.

INTERFACE

In computing, an interface is a system across which distinct components communicate. This communication can be among software, hardware and humans.

MACHINE VISION

Computer Vision. An interdisciplinary field enabling machines with high level understanding of the physical environment through image and video analysis.

MANIPULATOR

In robotics, a manipulator is an electronic device capable of interacting with its environment. Robotic arms.

MATERIAL RECLAMATION

It is a process of extracting value out of waste without major modifications. Material recovery.

MECHANISM DESIGN

The act of designing different components of a robotic system including body, control systems, manipulators, and drivetrain.

MOTION PLANNING

In computing, motion planning is the process of calculation the path to move an object from point A to point B.

NONDETERMINISTIC POLYNOMIAL TIME

NP (nondeterministic polynomial time) is a complexity class which describes various decision problems in computational complexity theory.

OPEN-SOURCE

A software program, the original source of which is publicly available. These programs can be freely modified and redistributed.

PERCEPTION

In robotics, perception enables the robot to observe, analyze, and understand the physical environment.

PLANE

In mathematics, a plane is a two-dimensional limitless surface. In 3D environments, planes often have a normal direction (Z) in addition to length (X) and width (Y) axis.

POINT CLOUD

A set of data points in space which can be used to scan the physical environment. These points are often generated through 3D scanning hardware or photogrammetry software.

POSE

In robotics, the pose of a robot includes its two- or three-dimensional position as well as its orientation.

PYTHON

Python is a high-level programming language.

REACH

Reach is the distance from the center of the robot to the furthest point the robotic arm can reach while maintaining full operability.

RECYCLE

The act of transforming waste to a new product through chemical or physical processing.

REDUCE

The practice of optimizing a process in order to decrease the amount of waste generation.

RESILIENCY

In complex systems theory, resiliency is the ability of a system to tolerate stresses and the capacity to learn and adapt to new circumstances.

REUSE

In construction and waste management, reuse is the practice of using waste with minimal or no modification.

RHINOCEROS 3D

It is a 3D computer-aided design software program created by Robert McNeel & Associates. This program is often used by industrial designers and architects.

RIGID-BODY SIMULATION

Rigid-body simulation is the computational study of interconnected bodies under external forces. This type of simulation greatly benefits the study of mechanical systems.

SALVAGED MATERIALS

Reclaimed materials. Recovered materials.

SOFTWARE

The digital tools and algorithms used in an interface and computational process.

STOCHASTIC PROCESS

Random process. A decision-making process based on a set of random variables.

STROKE LIMIT

The maximum length that an end-effector can grasp.

SWARM ROBOTICS

In the field of robotics, swarm robotics refers to the practice of coordination of many robots relying on collective behavior.

TCP

Tool Center Point. A point used to move the robot end effector to a desired position.

TCP/IP

Transmission Control Protocol and the Internet Protocol. Internet protocol suite. A set of communication protocols used in the Internet and computer networks.

TOP-DOWN DESIGN

An approach that involves carefully strategizing everything with a preset outcome in mind.

UDP

User Datagram Protocol. In computer networking, UDP is one of the major components of the TCP/IP.

USER

An individual who uses or operates a system, especially an electronic device or a machine.

ZERO-TOLERANCE DESIGN

A strict design approach where variations are not accepted. Top-down designs often employ a zero-tolerance strategy to ensure the results.