Upcycling Non-standard Resources as Architectural Elements through Adaptive Digital Fabrication

(非規格材を建築要素へ高付加価値化する適応的デジタルファブリケーション)

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Abstract

Today, almost all modern buildings are constructed with standard materials. Standard materials make design and construction plausible, thus the current trend in material use is down-cycling from unique irregular resources into regular, uniformed pieces. Upcycling, on the other hand, promotes creative re-purposing without processing and has been explored by architects and Human-Computer Interaction (HCI) researchers. In traditional architecture, we also found such re-purposing of materials preserving natural shapes, such as curvy wooden beams and irregularly shaped rocks in masonry walls. The traditional architecture and upcycling share the same challenge: design and fabrication processes must be flexible and dynamic for irregular materials and uncertain behaviors during fabrication.

In this thesis, we explore three different types of non-standard materials and demonstrate feasibility of upcycling them for architectural elements. We propose 'adaptive fabrication' workflow for handling non-standard materials. By augmenting material-awareness for humans and machines, adaptive fabrication recognizes the richness of materials, while enabling to handle materials with complex properties. By implementing material-aware design and fabrication tools, this dissertation aims to solve the challenge with non-standard materials in a resourceful and scalable manner. Three different kinds of material are selected as case studies, and we evaluate a tool developed for each case within the framework of adaptive fabrication.

1. Using rejects from a chopstick-production line, we implemented a human-assisted additive manufacturing system for a large scale architectural pavilion. Material-aware design was achieved by taking the accumulated sticks as the design and modeling the material behavior with unit-volume tested in advance. Material-aware processing was achieved using real-time projection mapping of the work to guide human workers.
2. Focusing on various shapes of tree branches, we implemented a design and fabrication system for irregularly shaped branches. Material-aware design was achieved by scanning and extracting the skeleton and contours of the branches in advance. Material-aware processing was implemented using human-in-the-loop fabrication, where humans position branches on a simple Computer Numerical Control (CNC) milling machine.
3. Within a robotic masonry system placing irregularly shaped stones, the focus was on planning how to place the stones. Material-aware design was achieved through off-line scanning and alignment of real and simulated stones. Material-aware processing was achieved with turn-taking measurement and adjustment of placing pose.

The results are summarized in a taxonomy of valid materials, fabrication methods, and approaches of adaptive fabrication. Based on the taxonomy, we conclude the thesis by discussing the challenges for applying our results to real practices and suggesting the idea of computational upcycling as a field of study where development of interaction and fabrication can contribute to.

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1 Introduction

In this chapter, we first introduce the inspiration and motivation of this work. The inspiration came from material-driven design in art, architecture, and HCI researches. Some of these works intentionally keep materials untouched to express the perspective of non-human entities. Similar presentations of materials can be found in upcycling of used products and traditional architecture with natural raw materials that are conserving original shapes of materials for different purposes. After gathering those various materials use cases, the the idea of non-standard materials and its challenges are addressed. And then, aim, approach, and scope of this thesis are introduced. Our aim is to discover materials that can be upcycled by digital technologies, and grasp an overview of valid design/fabrication approaches. To do so, we set the scope of materials and other conditions, and then conduct three case studies, providing an overview of typology of valid materials and methodology of fabrication. Finally, the conceptual framework of adaptive fabrication is introduced for non-standard materials, and summarize the contributions of this thesis as well as the list of publication.

1.1 Inspirations and Motivation

The initial inspiration was simple *"what can we do with abandoned materials using cutting-edge technologies?"* By just dropping, by joining with simple joinery, or even more simply by placing, our motivation was to explore various design opportunities enabled by modern technologies with those simple manipulations. Currently, digital fabrication primarily uses standardized materials with uniformed properties; we saw an opportunity to demonstrate an alternative fabrication with non-standard materials with irregular but diverse properties. Digital fabrication in architecture has already demonstrated novel designs by Computer Numerical Control (CNC), 3D printers, and robotic arms [39]. In architecture, these machines are linked to parametric modeling software that demonstrates the ease with which architectural elements can be customized (we call the ease as customizability). The customizability of these machines also attracted DIY (do-it-yourself) hobbyists and stimulated the movement of personal fabrication [91]. In reality, we are already using materials with unique properties, such as personalized objects, natural resources, and waste, being customized in a way that they are irregular, unique, and diverse.

These unique materials are already being explored by contemporary artists and HCI researchers inspired by anthropocentric perspective and material-driven approach to design [27]. They refer to spontaneous errors and situations that arise from the material and the environment as 'non-human' entities and actively use them in their design and art. Traditional architecture also uses irregularly shaped, natural, and raw materials, conserving their shapes to their advantage, such as with curvy wooden beams or dry-stack masonry walls with irregularly shaped stones. This may be more due to the limited standardization of methods at the time than from an anthropocentric design motivation. Today, the irregular shapes of material from industrial waste, plastic products, and demolition are also used in design.

The motivation of this thesis is to uncover the design possibilities in these abandoned ma-

terials instead of passively categorizing them as useless. Previous works considered these materials; however, they are scattered in different disciplines such as HCI researches, traditional/modern architectural practices, and art with different motivations. To begin, this thesis will survey these use cases to frame the scope of materials and fabrication methods. For example in architecture, both standard and non-standard materials are used in practice, but non-standard materials are typically reserved for decoration. In construction waste management, the category of non-standard materials exists, but it refers to all materials that are not commonly used; hence the category is not actively defined but is simply the state of not being standard [1]. Currently, upcycling is limited to industrial materials. Throughout the survey, we found that the environmental impact of the construction industry is quite large. In Japan, 40 % of the waste from industrial activities is from construction and demolition (C&D) waste [79], thus the use of non-standard materials could significantly contribute to waste reduction.

1.2 Problems and Challenges

Figure 1 depicts a cascading material flow from the input of irregular resources to the production of regular sized pieces. This process is called down-cycling in waste management (i.e., recycling) [45] or standardization in architectural design [22]. At the end of the flow, regularized middle-product are output delivered as final products. Today, almost all modern buildings are constructed by using these standard materials. Institutions such as ISO and ASTM set standards for building materials and their applications in construction [38, 23]. Buildings constructed with these standard materials and construction methods are valued in the market as legal standardization provides consumer confidence and information for evaluations. Standards are also beneficial for designers and architects, making various tasks more efficient and effective. On the other hand, the standardization process homogenizes materials into uniform objects no matter how rich the features of the input material. In the process, energy and materials are consumed and leftovers are produced. In summary, the problems of standardization in architectural design are that it fails to recognize the richness of the input materials and it fails to conserve energy and materials.

Upcycling non-standard materials is possible approach to address these problems of the lost richness; however, thus far upcycling seems to be lacking a systematic approach. Upcycled materials are various (e.g., tree branches, earth, and industrial rejects and waste as in Figure 2). These materials are considered useless for various reasons, such as irregular shapes and textures or defects, and they are used or old. To preform this research, we must first define the scope of non-standard materials in this context, clarify the challenges they present, and determine how we can make them useful. Second, we need to demonstrate plausible applications that present non-standard material-specific problems. Third, we need to find technical solutions for these problems and summarize them as a methodological framework.

The challenge with non-standard materials becomes clear when we try to make structures out of them, specifically design and fabrication challenges for architectural elements. As craftsman leveraged the original shapes of natural resources in traditional architecture, the fundamental challenge is to use non-standard materials as structure without losing the orig-

Figure 1: *An example of down-cycling material flow from highly variant raw resource or demolition waste to homogenized chips and aggregates. At the end of the flow, standard components and recycled materials are produced with intended functionalities (i.e., standard construction).*

inal features of the material. Historically, the irregular forms of natural, raw resources have been used in traditional buildings; however, this was a consequence of limited standardization methods at the time. Modern architecture also conserves the original forms of upcycled industrial waste into architectural elements (see more details in Section 2.1). In these architectural applications, it is a challenge to come up with creative re-purposing and to make it work. In this thesis, we focus on how to make it work instead of how to come up with it.

1.3 Aim and Approach

This section describes the aim of this thesis that are motivated by the problems of standard materials and challenges with non-standard materials. This thesis is not only about design challenge with unorthodox materials but developing computational tools. Since non-standard materials do not have a clear definition, our research approach is to conduct several case studies with materials that we think non-standard. Through the case studies, we extract essences for framing the scope of this thesis that are introduced in the next section.

1.3.1 Aim

The aim of this thesis is to demonstrate that modern technologies make upcycling non-standard materials accessible and scalable for architectural elements. Figure 3 shows various waste and how they are collected, reused, and recycled. Among these existing approaches, we can provide an alternative material flow alongside down-cycling by developing tools.

Figure 2: *An overview of available building materials, mapped in the one-dimensional axis of low to high standardization from left to right accordingly. We focus on material sets within/around the dotted line. These materials can be an industrial waste, by-products from production, and raw natural resources with irregular shapes.*

Another aim of this thesis is to provide a guideline for design and fabrication with non-standard materials. These guidelines could be used by designers, engineers, and researchers. A taxonomy of the non-standard materials and valid construction/fabrication methods, as well as computational approaches, is necessary to facilitate the discussion. We develop this taxonomy through the case studies in the following section.

1.3.2 Research through Case Studies

Our approach is to present case studies that use a non-standard material, develop a design target with that material, and fabricate the design. We explore the following questions through these case studies: *"what can we make with irregular materials?"*, *"What construction methods are valid?"* and *"what are the challenges for scaling?"* To answer these questions with case studies, we need to carefully select non-standard materials that are different from each other. Once a material is selected, a target is designed that has several criteria. First, the target design should be material-driven. Second, it must satisfy a certain structural performance as an architectural element. Third, fabrication of the target must be technically challenging. After defining the target, a design/fabrication system is implemented. While designing a target involves the finding of problems, the implementation of a system is more a matter of pragmatic problem solving, such as how to control irregular features during fabrication or how to satisfy the intended design geometrically or structurally.

In each case study, we discuss design and fabrication with regard to specific criteria, such as whether or not the rich features of the material are leveraged in the target design and whether or not the developed system provides some control over other design possibilities

Figure 3: *An overview of industrial waste mapped in a one-dimensional axis of low to high value from left to right, accordingly. Down-cycling, collecting and separating are depicted as approaches to increase the values of waste. Our aim is to develop methods and applications to shift the threshold of the resource to the left.*

or are effective for scaling. In the following section, we introduce the criteria used, or the framework of 'adaptive fabrication'.

1.4 Scope

Through the case studies, we have gradually figured out the scope of this thesis. In this section, the scope is presented before each case study for providing the thesis structure. As the scope, we considers the available materials, construction methods, and types of applications. Briefly, we limited our materials, construction method, and target applications. We selected a smaller set of non-standard materials as depicted in Figure 2, and our target applications are less-demanding structures. Within this scope, the construction methods explored in this thesis are summarized as per their material deposition and the assembly of parts. Table 1 summarizes the scope of the construction methods and their descriptions in relation to the features of the materials.

1.4.1 High-level Topics Outside of the Scope

Before we describe what are in the scope, we briefly explain high-level concepts and things that are outside of our scope in this thesis. First, as in the end of the section 1.2, we do not consider automated design system that can take various kinds of materials and suggest upcycling solutions in architecture. Non-standard material and a target design are given, allowing us to focus on developing a fabrication workflow. The target design is defined by multiple parameters that can be tweaked within a range; however, this means the design is

Table 1: *Scope*

Construction Methods	Features of Materials		Description of Construction Method and Suitable Material
	Size	Amount	
Material deposition	Small	Large	Preparation is necessary but scalable to large construction projects.
Assembly of parts	Large	Small	Automation of assembly process is challenging but requires less preparation compared to material deposition.

strictly regulated and a user can not explore designs outside of the range. Second, the upcycling methods of non-standard materials do not aim for competing with standard materials; we are aware that upcycling is a minor and under-development design approach. Third, the thesis does not discuss the performance of developed methods by quantifiable metrics. Before competing existing methods, we need to start from grasping an overview of upcycling non-standard materials by digital fabrication.

1.4.2 Scope of Materials

We established several criteria for our non-standard materials. First, the materials must be less-valued, such as waste, industrial rejects, or previously used building material. Thus, high-valued waste, such as copper wires, are not in our scope. Second, the materials must already be collected and sorted. We think that those tasks are challenging and independent research topics. Thus, mixed waste as illustrated in Figure 2 are outside of our scope. Finally, and most importantly, the materials must have a diverse geometry, morphology, and mechanical specifications, such as weight, rigidity, fragility, and elasticity. The variety does not necessarily have to come from the materials themselves, but could come from the construction methods they were previously subjected to.

1.4.3 Scope of Applications

For the scope of our applications, we consider scales ranging from furniture as object-scale to interior elements or pavilion as large scale. In a pavilion scale, self-supporting structure is our output. In pavilion scale, it is necessary to consider wind loads if the pavilion stands outdoor. For safety reason, we use sub-ordinary, fail-safe structures just in case of the failures of the main self-supporting structure. What we do not consider in this scale is load-bearing structure. Structures such as beams and roofing in a long span are also not in our scope as they are structurally challenging. Design/construction of these structures itself is an independent research topic.
In furniture and interior scale, we include load-bearing structure as an output. This makes our case study more challenging and versatile than purely decorative applications. We also consider decorative applications; however, the material-driven approach itself adds a decorative aspect to the outputs. Note that the developed designs are experimental and not immediately applicable to real architectural practices, because the law regulation does not

include non-standard materials and it takes some time to be approved. To do so, the number of physical tests in this thesis is too limited and more various kinds of tests against weathering and water are required.

1.4.4 Scope of Construction Methods

The scope of the construction methods used in this study was determined by exploring the construction strategies available for the scope of our materials and our target applications. Our methods are categorized roughly in two approaches: material deposition and assembly of parts. Both approaches are not limited in additive or subtractive fabrications, however the shared goal is minimum material processing. We selected the methods used by considering the features of the material, mainly the size of each piece and available amount.

Material Deposition: For materials of a small size but available in large amounts, we considered material deposition. Material deposition combines the material with an adhesive and then deposits the composite material at a position in a certain amount. This method is not limited to use with existing additive manufacturing and 3D printing, but can be used with other technology that can manipulate the aggregation of materials.

Assembly of Parts: For materials of a larger size but available in small amounts, we consider the assembly approach, which observes and distinguishes each individual piece. To be assembled, they need to be connected. There are various ways to achieve material connections, such as ropes, tielaps, joints, bolts and nuts, and screws. We distinguish these connections by whether they require secondary systems, such as screws, bolts and nuts, or require the direct curving of joints on the materials. Recalling our policy to minimize modification of the materials, less preparations was preferable. The simplest assembly is to place an object without modifying them first. Single mono-materials with additional connectors could require less assembly. For a simple appearance, joineries directly milled on the materials could achieve a mono-material appearance.

1.5 Adaptive Fabrication

We propose 'adaptive fabrication' as a framework that are aware of the irregular and rich features of the materials. The goal is to build an intended design without modifying the material's properties and behaviors. The term adaptive appears in various fields from biology to computer science (see in Section 2.3) and each domain formalizes an objective of adaptive system. This thesis sets the main objective of adaptive fabrication to be the conservation of original features of the material. Adaptive fabrication consists of two concepts: material-aware design for recognizing the richness of the material, and material-aware processing enabling the control of complex materials in fabrication. Given the design, the main objective of material-aware processing is set to be the conservation of original features of the input material. If necessary, the target design can be updated taking into consideration the physical constraints of the materials and the cost of both construction and computation; however, it is an open-question whether we prioritize the design or conservation of input materials.

1.5.1 Material-aware Design

The goal of material-aware design is to preserve the diverse properties of non-standard materials and leverage them as design expressions. By scanning materials, the materials are modeled using their key features, becoming available for CAD tools. Another approach is the more conventional engineering approach: take a unit structure and physically test it to extract its mechanical specifications. In other words, the selected material is modeled by the approximation of its actual behaviors. In a developed design tool, a user can play with the key features and complete his/her design directly interpreted in a digital fabrication process. These approaches have already been explored in both architecture and HCI, as we review in Section 2.5. The contribution of this thesis is the focus on upcycling by material-aware design.

Figure 4: *Workflow of the material-aware design process. The design tool is made aware of the material's properties by (1) capturing the shape of the irregular material or (2) modeling the material-unit in advance. Right: feed-forward fabrication is performed after the design is prepared.*

1.5.2 Material-aware Processing

The goal of material-aware processing is to build an intended design with minimum modification of the materials. While the fabrication of material-aware design was depicted as a feed-forward process, material-aware processing implements measurements and adjustments which is an interaction between the material and the machine. Humans can also be included in this interaction as users or to assist the system as a human-in-the-loop. Figure 5 illustrates material-aware processing in comparison with conventional feed-forward fabrication. Measurement and adjustment during fabrication monitors the materials condition during fabrication using sensors and provides feedback to the fabrication process. This process could be fully autonomous system or includes humans, which we call human-assisted fabrication. Human-assisted fabrication adds a human to the measurements and adjustment loop. It takes advantage of observation by human eyes and dexterity of human hands. This also helps to avoid development and integration of a large autonomous system, contributing to accessible digital design/fabrication. Measurement and adjustment during fabrication as

well as human-assisted fabrication both have been explored by precedent works discussed in Section 2.6. The contribution of this thesis is to apply them for upcycling purpose and large-scale applications.

Figure 5: *Material-aware processing processes (2 and 3) in comparison to feed-forward process (1). While a feed-forward process does not receive feedback from the material during fabrication (1), measurement and adjustment during fabrication constantly monitor the state of the material (2). Humans can be included in fabrication as in (3) human-assisted fabrication.*

1.6 Contributions and Thesis Overview

The contribution of this thesis is that it showed the feasibility of upcycling non-standard materials through three case studies (Chapter 4,5, and 6). We also propose the general workflow of adaptive fabrication and provide a checklist (Chapter 3). With the workflow, the checklist, and case studies, the thesis provides a guideline for those who consider developing own adaptive fabrication systems for their non-standard materials. The results from the case studies was summarized in a taxonomy, providing an overview of relationship among materials, construction methods, and implementation approaches (Chpater 7).

In summary, the contributions of this thesis are as follows:

- Clarifies the opportunities and challenges in using non-standard materials for architectural construction. Architectural applications demonstrated the opportunities for upcycling.
- Proposes 'adaptive fabrication' as a framework for non-standard material, consisting of two concepts as follows.
  - Material-aware design for recognizing richness of complex non-standard materials.
  - Material-aware processing adds measurement and adjustment loop including humans to the conventional digital fabrication.
- Provides three case studies with different non-standard materials and construction methods.
  - Human-assisted deposition of chopstick-rejects from production lines.

- Assembly of tree branches from forestry thinning.
- Placing of stone or rubble from demolition waste.

This thesis is organized as follows:

In Chapter 2, we review the background discussions of architectural design with non-standard materials, anthropocentric design approaches in art and HCI, adaptive fabrication systems, and waste management. Also, we present the recent research regarding material-aware design and fabrication. This chapter gathers work from various domains, such as digital fabrication in architecture, HCI, and robotics.

In Chapter 3, we summarize a generalized workflow of adaptive fabrication and discuss by comparing with other workflows such as conventional digital fabrication and upcycling with digital tools.

In Chapter 4, we discuss the case study involving rejects from a chopstick-production line, in which we used a human-assisted additive manufacturing system for a large-scale architectural pavilion. Material-aware design was achieved by designing with the accumulated sticks and modeling the material with the unit-volume tested in advance. Material-aware processing was achieved by real-time projection mapping of the work to guide the human workers.

Chapter 5 presents the case study using various shapes of tree branches. We implemented a design and fabrication system for irregularly shaped branches. Material-aware design was achieved by scanning and extracting the skeleton and contours of the branches in advance. Material-aware processing was implemented using human-in-the-loop fabrication where humans position branches on a simple CNC milling machine.

In Chapter 6, a robotic masonry system for placing irregularly shaped stones is presented. The focus was on the planning of the placing of simulated irregularly-shaped objects. Material-aware design was achieved by offline scanning and alignment of the real and the simulated environment. Material-aware processing was implemented by turn-taking observation after placement and the simulation of the next placement.

Chapter 7 concludes this thesis. It provides a summary of the material-aware design and the fabrication implemented in each case study and indicates that they complement each other. We also discuss the limitations of this thesis and, finally, describe the possible directions for future research and applications.

1.7 Publications

The following is a list of publications from which this thesis was derived.

- **Paper at The 4th Symposium on Computational Fabrication (SCF 2019)**
  Maria Larsson, Hironori Yoshida, and Takeo Igarashi, "Human-in-the-loop Fabrication

of 3D Structures with Natural Tree Branches."
My contribution in this paper is implementation of the scanning process, the audio-visual guidance system, evaluation of the system by user study, and structural analysis and simulation.

- **Paper at Tangible, Embedded, and Embodied Interaction (TEI 2019)**
  Hironori Yoshida, Maria Larsson, and Takeo Igarashi, "Upcycling Tree Branches as Architectural Elements through Collaborative Design and Fabrication."

  My contribution is implementation of the scanning process, the browser-based game application and its web-interface including database, the workshop.

- Workshop paper at NIPS 2018 (Machine Learning for Creativity and Design) as a mentor
  Azumi Maekawa, Ayaka Kume, Hironori Yoshida, Jun Hatori, Jason Naradowsky, and Shunta Saito, "Improvised Robotic Design with Found Objects."

  My contribution in this paper is writing and supervision particularly in the concept development and scanning in the early phase.

- Invited Paper at IJCAI 2017
  Martin Wermelinger, Fadri Furrer, Hironori Yoshida, Fabio Gramazio, Matthias Kohler, Roland Siegwart, Marco Hutter, "Greedy Stone Tower Creations with a Robotic Arm"

  This paper is an invited paper by IJCAI and thus the content is same as the ICRA paper.

- **ICRA 2017 Best Student Paper Award as an equally contributing author**
  Fadri Furrer, Martin Wermelinger, Hironori Yoshida, Fabio Gramazio, Mathias Kohler, Roland Siegwart, and Marco Hutter, "Autonomous robotic stone stacking with online next best object target pose planning."

  My contribution in this paper is the development of pose searching algorithm as well as its integration in the whole workflow. Furrer worked on the object detection with Zimmerman and Forni, and Wermelinger worked on manipulation. Furrer, Wermelinger, and I are equally contributing authors. Furrer and Wermelinger separately worked on the evaluation of the system.

- **SIGGRAPH 2015 Technical Paper as the first author**
  Hironori Yoshida, Takeo Igarashi, Yusuke Obuchi, Yosuke Takami, Jun Sato, Mika Araki, Masaaki Miki, Kosuke Nagata, Kazuhide Sakai, and Syunsuke Igarashi. "Architecture-scale Human-assisted Additive-manufacturing"

This project was enabled by collaboration among different faculties and industries. I could work as a project lead managing the entire schedule of the project with the support from Obuchi and Sakai. I also managed the construction supported by Umeyama. With Osman, Xu and Jin, I worked on the development of the chopstick-glue composite material and its evaluation with Sato, Aaraki and Miki.

2 Background

This chapter first introduces topics and concepts that form a foundation of this thesis. The topics are architecture, material-driven design, adaptive systems, and upcycling, as they appeared in the title of this thesis. After introducing those fundamental topics, we review related work that are directly relevant to the individual technical contributions of this thesis, namely material-aware design and material-aware fabrication.

2.1 Architectural Design

Architectural design, especially conceptual discussions regarding design theory and strategy, is a large part of this thesis. In the history of architectural design, architects have developed various styles that reflect newly available technologies as well as social/cultural background at each era. In this section, we start from modernist architecture that is the drive of critical regionalism and digital fabrication in architecture. Those two concepts are relevant to our works in the way we presented non-standard materials and the way we use computation and fabrication tools.

2.1.1 Modernist Architecture

As a consequence of the industrial revolution, mechanization in manufacturing influenced not only construction technologies but the form of architectural design known as modernism [86]. Modernist architecture was the name for the style of machine-made materials that was associated with words such as industrial, functional, standardized, and rational. Le Corbuisier is known for his minimalist style as well as his bold attitude toward the use of modern materials, such as reinforced concrete [22]. Standardization and industrial expressions were further developed by international styles. The architect Mies van der Rohe and his minimalist aesthetics is widely appreciated and plays a part in the formation of the contemporary urban skylines.

2.1.2 Critical Regionalism

Since modernist styles became more dominant, its uniform style was criticized as leading man-made world to 'placeless' lacking identity of regions. Critical regionalism was first mentioned by Alexander Tzonis and Liane Lefaivre and later further elaborated by other architects and historians such as Kenneth Frampton [8]. Since then, various architectural styles have been suggested as alternatives. Vernacular architecture is a concept known for the use of locally specific resources and knowledge, typically inspired by and resembling traditional or primitive architecture. According to Frampton, while the concept of vernacular architecture is regionalism, critical regionalism is not a sentimental retrospective attitude but rather has to struggle with the balance between global and local expressions [32]. In Japan, Tadao Ando is known for translating traditional Japanese space using modern concrete material, and today, Kengo Kuma extends this direction with diverse materials from wood to stone and even carbon fibers [31]. Superuse is a concept referring to the re-purposing of locally produced or acquired industrial waste for architectural elements, so it could be

considered a part of critical regionalism if the waste characterizes the location [36]. Before critical regionalism, in the same period of modernist architecture, organic architecture was explored. Originally proposed by Frank Lloyd Wright, organic architecture seeks the balance of man-made space with natural entities [87]. It is important to note that these concepts are not exclusive but rather can be merged or coexist with other concepts, including modernist architecture.

2.1.3 Digital Fabrication

While critical regionalists challenged the "placeless" issue and proposed various styles, some architects focused on enabled aesthetics using cutting-edge processes of design and construction. In the early 1980's, architects started generating shapes using computer programs as a newly available design tool to overcome the repetitive articulation of modernist architecture. In early 2000, it became possible to fabricate these parametrically generated shapes using digital fabrication [39]. Naturally, these technologies cut new paths for creativity, and many artistic expressions were suggested. Greg Lynn [61] explored the aesthetic quality of carved CNC milling paths, and Gramazio & Kohler [16] demonstrated gradient transition in a brick wall by controlling rotations of bricks using a robotic manipulator. In architecture, the use of robotics was also pragmatically justified as robotics makes the number of bricks easier to work with for infrastructure and large-scale architecture [49].

2.2 Material-driven Design

Material-driven design in this thesis is discussed by Karana and colleagues [41]. While they focused on product development from material experience, this section looks into more conceptual background of artistic experiments by contemporary artists and HCI researchers. As we discussed in the Chapter 1, materials we see our living environments are mostly processed and standardized in the ways they are produced and used in construction. This is the problems of standard materials and our motivation in this thesis. Architects addressed this problem as we reviewed the critical regionalism in the previous section. Simultaneously, artists also worked on materials in a similar manner of architects designing their buildings from the development of materials but slightly different purpose. They played with materials as inspirational sources to diversify their works.

2.2.1 Anthropocentric Perspectives in Art and HCI

Art and HCI communities often use materials to diversify design options, which is similar to the motivation of architects seeking expressions from local materials. In HCI, researchers develop design tools and discuss the expansion of design opportunities enabled by their tools. Some are particularly interested in the view from a material or object and call for a shift in perspective in understanding the human and non-human relationship. This approach can be described as material-driven design, which involves letting the materials speak instead of forcing the materials to fit to the artist's idealistic form. Devendorf noted that this approach has been implemented by contemporary artists. For example, a composition called '*4'33"*' by the composer John Cage does not provide any deliberate sound but rather allows the

audience or environment to define the content of the composition [27]. In sculpture, in his work *Hidden Life Within*, Giussepe Pennone presented the geometrically scaled trees inside the timber by carving outside of a growth ring [34]. Simultaneously, Mono-ha (School of Things) are collectives of individual artists in Japan in 1970's, focusing on the individuality of common place objects and demonstrating their perspectives [7].

2.2.2 Form Finding from Aggregation

Some architects use material behaviors and the naturally formed morphology as a main feature of their design. Design by aggregation is a form-finding approach investigated by the architect Frei Otto. He put sand in a container with holes and studied how the sand aggregation behaves with respect to the location of the holes [10]. His study showed that material-driven design is not only limited to materials with countable elements up to the hundreds, but also to those with thousands and millions of countable elements. Based on Otto's experiments, Dierichs et al. [21] aggregated a large quantity of spike-shaped elements and presented the resulting forms, but they were limited to small-scale prototypes. As a large-scale aggregation, Quinze randomly connected 2×4 timber planks and exhibited the output at the Burning Man Festival in 2006 [23]. These studies employed aggregation as an approach to form finding but not as a construction method augmented by computational assistance.

Some architects use material behaviors and the naturally formed morphology as a main feature of their design. Design by aggregation is a form-finding approach investigated by the architect Frei Otto. He put sand in a container with holes and studied how the sand aggregation behaves with respect to the location of the holes [17]. His study showed that material-driven design is not only limited to materials with countable elements up to the hundreds, but also to those with thousands and millions of elements, which becomes uncountable mass of materials as the number of material grows. Based on Otto's experiments, Dierichs et al.[28] aggregated a large quantity of spike-shaped elements and presented the resulting forms, but they were limited to small-scale prototypes. As a large-scale aggregation, Quinze randomly connected 2 x 4 timber planks and exhibited the output at the Burning Man Festival [30]. These studies employed aggregation as an approach to form finding but not as a construction method augmented by computational assistance.

2.3 Adaptive Systems

This section reviews adaptive systems in fabrication, production and robotics. The term 'adaptive' has been used in various fields. In this thesis, as defined in Section 1.5, adaptive fabrication works to conserve the features of the original material. This concept was inspired by the biological 'homeostasis', conserving a certain state from external stimulus. In biology, adaptivity is defined as *"a biological adaptation is an anatomic structure, a physiological process or a behavior' trait of an organism that has been selected by the natural evolution under the assumption that such traits increase the probability of reproduction of an organism"* [63].

2.3.1 Adaptivity in Fabrication and Production

Adaptivity in fabrication is indispensable for arts and crafts. David Pye, a craftsman, designer, and architect, indicated two fabrication modes: *"workmanship with certainty"* as highly regulated fabrication and *"workmanship with risks"* as the capability of flexible fabrication [77]. While highly regulated fabrication uses a controlled environment for lower risks, flexible fabrication can adapt to various types of materials and unexpected errors. Pye used jigs as an example of workmanship with certainty. With conventional workshop machines, such as jig-saws and table saws, a craftsman makes custom jigs for repetitive and accurate production of identical parts. Pye also mentioned that there are still risks involved in the workmanship of making a jig setup.

Adaptivity in production is discussed in various contexts. In a low-level, any production system taking feedback from sensors can be adaptive e.g., polishing machine with a force-sensor feedback or steel rolling process by observing the flatness of metal sheet. In higher-level, production planning with feedback from various sensors in a production line is discussed. In the context of Industry 4.0 in regard to the seamless synchronization of sensors and devices in production lines to cloud computing [47]. Adaptivity in this context includes the collection of data by edge devices and the flexible adjustment of the scheduling of production lines according to sensor data or even to external factors such as market needs. In this sense, the connectivity to a network and the Internet of Things (IoT) from devices that include various sensors in a production line is also considered adaptive production. In the more edge devices in the production system such as sensors, adaptivity considers whether uncertain errors during mass-production can be handled or not.

2.3.2 Adaptivity in Robotics

Many robotics systems are described as adaptive from low to high level. Compliant robots that enable force-control are adaptive in low-level [11]. These robots are already introduced in industries as collaborative robot arms. Unlike position-only control, hybrid position-force control can take external forces but still manage to move a robot arm to a specified position in a Cartesian space [25]. In a higher level, decision making such as task-planning is also a target of adaptivity in robotics. Humans are recently included for such a task-planner for implementation of social collaborative robots [21]. Knowledge required for such social robots is diverse and unlimited, however, some roboticists formulated as a state machine with limited knowledge e.g. current states, a set of goals, a set of actions, a set of human actions, a set of policies, a set of contexts of the situation (e.g., user profile, situation context) and so forth [55]. The challenge for a robot to be adaptive is to be able to generate a new state when the robot faces an unexperienced situation. Reinforcement learning (RL) is a widely used approach, continuously updating a policy that selects an action based on observation of an environment or current state. By updating the policy through exploitation and exploration, an agent can be adaptive within the given environment.

2.4 Waste Management and Upcycling

Upcycling is a new concept in waste management motivated by the way materials are recycled through down-cycling; however, upcycling is still experimental and under-development to be socially implemented. The clear thing is that down-cycling consumes energy and efforts, and the resources are limited. It is natural to think our down-cycling activities lead us to the state where all materials are mixed. This section first introduces such a experimental thought by economists, and then reviews how waste is managed especially with construction and demolition (C&D) waste are managed.

2.4.1 Waste Management and Environmental Economics

Waste is an important subset of non-standard materials discussed in this thesis. In environmental economics, goods are the things produced and distributed in markets, and *"bads"* are the waste in markets to be collected and processed in order to avoid polluting an environment. Considering the process from raw resource to homogeneous material, economist Nicholas Georgescu-Roegen noted that human economic (or industrial) activities lead to resource scarcity where all the resources are dissipated through industrial processes. He was inspired by entropy in thermodynamics and applied it to economics; however, his formulation was later proved to be false [51]. Using case studies of PET-bottles, ore, and used paper, Hosoda describes how *"bads"* can turn into goods for various reasons and external factors, such as location, time, economic situations, availability, and available technologies [37]. While the economics around waste and explanations for the bad-to-good turn have been studied, methodologies such as how to make goods out of bads have not been concretely proposed.

2.4.2 Construction and Demolition (C&D) Waste and 3Rs

Among all industries, the architecture and construction industry produces the most waste, and its recycling rate is low depending on the materials used. It is one of the most important challenge faced by sustainable development to manage C&D waste. In Japan, while the ratio of C&D waste accounts for 40% of all industries, its recycling rate is 20% [79]. The U.S. Environmental Protection Agency describes three major approaches for managing C&D waste: reduce, reuse, and recycle [4].

While reuse is a one-time event, recycling can occur several times in a material's lifetime; however, the process of down-cycling is involved in recycling. In architecture, while reusing/upcycling requires removing parts from a building without damaging them, recycling is an easier process, as it involves shredding the material into small pieces. According to Hosoda [37], the decision to reuse or recycle is based on the size and cost of removing/separating/collecting/sorting. Reuse and recycle both start by collecting a certain amount of waste in one place and then sorting it. It is important to mention that material collection alone is a big technical challenge; ZenRobotics developed an automated sorting system that is in current use [60]. After sorting material types, it is much easier to reuse and recycle them. Down-cycling itself consumes energy and other resources and also produces waste as a bi-product. For example, in architecture, concrete waste from a demolition

site is first collected and the steel reinforcement bars are separated using magnetic crushing machines. The crushed aggregate is further processed for a uniformity in size [90, 3].

2.4.3 Cradle to Cradle and Upcycling

Reducing can be achieved in the way we design products and buildings. Cradle to Cradle (C2C) is a design guideline coined by McDonough and Braungart that refers to closing the loop from resource to product [64]. The main concept of C2C is to reduce waste as much as possible with a goal of zero waste. This not only pertains to the materials of products and buildings, the energy must also be from a reproducible energy source. C2C also emphasizes upcycling over recycling. Upcycling is similar to reusing but it is described as a creative reuse as its re-purposing target is not obvious; hence it has been used by several designers and architects [50, 36]. Architects and interior designers re-purpose various products for architecture, such as containers, bottles, plastic water tanks, or tires.

2.5 Material-aware Design

This section collects precedent works that take non-standard materials into computational design tools such as CAD. Nowadays, 3D scanning became much more accessible than it used to be with expensive high-end devices, thanks to inexpensive commercialized depth cameras. This section also reviews more conventional methods to represent objects not only shapes but also mechanical specification. Before those approaches, non-standard materials were simply not considered to be elements we can design with, or only skilled and experienced workers with a specific materials could handle the material. Material-aware design provides a methodology to handle irregular non-standard materials, while material-driven design focuses on conceptual design methodology.

2.5.1 One-time Scanning Materials with Feed-forward Fabrication

As digital scanning and fabrication became available, some works experimentally combined them for artistic expressions. These works are generally from the field of architecture and design, and tends to present full design systems from material collection to built object. Greg Lynn extended his CNC work and framed in the social issue of mass-production and consumption. He collected mass-produced kids plastic toys and virtually stack them in CAD modeling. He then extracted intersections of the toy models and used those curves for CNC milling [61]. In furniture scale, Schindler scanned tree branches and created experimental furniture designs [83]. In a larger interior scale, Boleoor commercialized the idea by combining scanning and CNC for customized flooring production [72]. In an even larger pavilion scale, the wood barn project as a student design/fabrication project at Architectural Association in London extended the concept to three-dimensional while Bolefloor was in two-dimensional. They worked on grafted tree trunks carefully selected by experts and leveraged the grafted tree as a truss structure[62].

Some research scanned rigid irregularly shaped stones for designing walls and tiling. The SmartScrap project measured leftover stone slates from a quarry and organized them two-

dimensionally for a facade design proposal [35]. Simulation with a physics engine was explored by Nielsen et al. [71], but their construction input was to place the next stone at the lowest possible location. As for design with irregularly shaped stones, Lambert and Kennedy developed an application for guiding masonry construction with a geometric packing algorithm in two-dimensional convex shapes, but it is limited to two dimensional tiling [53].

The HCI community is actively combining real-world with fabrication. Focusing on real-world based modeling, Lau and colleagues developed the idea of 'situated modeling' whose interface is based on the real world objects. These objects have AR markers and their models are known. They used those objects as tangible interface for users freely place and combine those objects in a virtual space. They conducted user study to compare with an existing interface (Daichi tool) [54]. For more user-friendly CAD, MixFab also included real-world objects with gesture inputs. Instead of requiring AR markers, it can take objects by capturing with a depth camera [95]. Similar to Greg Lynn, Truss-fab developed a design interface that can formulate a truss structure using collected PET-bottles [50]. Their construction method is the assembly of pet-bottles using 3D-printed custom joint parts.

2.5.2 Modeling Material Behavior and Computational Design

Modeling material behavior using material testing is a conventional approach in architecture and construction, and is still actively used in the industry, such as flexural testing of a newly designed pre-fabricated component [19]. This approach is based on an assumption that the pieces of the material are homogeneous; thus, its properties can be approximated by mathematical models. If a material/component is heterogeneous, it is necessary to test it in multiple directions.
Compared to one-time scanning, measuring the mechanical specifications takes more time and effort. However, once a component unit is extracted and modeled properly, it is useful to diversify the design options. For example, Bickel et al. used 3D printers and focused on micro-structures to demonstrate how to control the macro-behaviors of printed objects [13]. To measure deformations in non-linear materials, some previous works have proposed a capture and model method for non-linear heterogeneous soft tissue [12, 40, 44, 73]. These studies mainly discuss methods of capturing the deformations of a real object and modeling them as finite-element models.

Similarly, some works have focused on other functionalities with real-time user feedback. Umetani et al. developed a guided exploration for furniture design [94]. Umetani explored real-time simulation feedback for CAD and tried to reduce the computational cost of conventional Finite Element Modeling (FEM) based simulations [93]. Zhou and Lu proposed a 3D printing method that analyzes an input 3D model and creates a structurally durable model [102, 59]. Pereira et al. [75] focused on the propagation of light inside a solid object and proposed a manufacturing method that prints an object with embedded optical fibers that route light between two surfaces. Prevost et al. [76] proposed a method to assist users in producing properly balanced designs for 3D printing so that the model can stand without support. Cali et al. [18] proposed a method to print objects with movable mechanical joints. These works were from HCI and graphics community and successfully demonstrated the

capability of modeling material behavior in computational design and fabrication; however, they are limited in product scale whereas this thesis included architecture scale.

In architecture, researchers in graphics and computational design worked on masonry structures to make self-supported structures out of rigid discrete elements [98, 24, 56]. Historically, Livesley [57], [58] set the foundation of a numerical method for a limited analysis of discrete rigid-block structures. Block et al. employed graphical statics in interactive design tools with structural analysis feedback [14], and Whiting et al. [97] extended the limited analysis by Livesley to design a guidance system by adding infeasibility metrics. We discuss this topic further in Chapter 6. Panozzo et al. [74] proposed a method that allows the end user to create free-form, self-supported masonry structures, and then Deuss et al. [26] optimized the construction process by reducing the number of supports. Song et al. [85] described an interactive computational tool for designing a reciprocal frame structure. These proposals are novel modeling methods employing conventional construction processes and materials, however none address a drastic change in building materials.

2.6 Material-aware Processing

This section summarizes precedent works augmenting fabrication by interaction and robotics technologies. Instead of feed-forward digital fabrication, researchers have demonstrated more intuitive fabrication tools by various interaction modes from turn-taking to real-time. While these works focused on tool development for novice users, this thesis take similar technical approaches for the challenge with non-standard materials, namely enabling the control of complex materials during fabrication.

2.6.1 Measurement and Adjustment during Fabrication

HCI community explored augmentation of digital fabrication, increasing the usability of modeling and fabrication systems. 'Interactive fabrication' presented a series of elements for fabrication tools, monitoring material condition on-the-fly and updating the actuators of fabrication devices [99]. The 'Constructable' project extended the idea and created a user interface for laser-cutters. Unlike the conventional batch processing for the preparation of a cutting path and the execution of a laser-cut, it accepts user interruption during fabrication. The user can specify inputs at the object-level with physical input devices [67]. While the interaction model of 'Constructable' was turn-taking rather than on-the-fly, the 'FormFab' project accepted direct manipulation on-the-fly to adjust a feature of an object [68]. Mueller summarized a series of interactive fabrication works and categorized them by interaction models (i.e. batch processing, turn-taking, and direct manipulation), that are analogies of early human computer interaction and recent real-time user interfaces [66]. Another approach for achieving material-aware processing is to embed sensors in materials and monitor them instead of monitoring the materials using external cameras. The 'Shape-aware material' project embeds sensors in materials, monitors the materials state, and updates it on a CAD software [96].

2.6.2 Human-assisted Fabrication

Human assisted fabrication approaches are mainly explored in HCI community. The 'Crowd-sourced fabrication' project developed a user interface that allows users to freely contribute to the large scale construction of a pavilion. Construction was roughly divided into two: production of each component and their assembly. Humans carry and assembly a component that is produced by a robot arm [52]. In a smaller scale, augmenting CNC routers with human mobility were explored by Rivers and Zoran. In the topic of computer guided fabrication, Rivers et al. presented 3D-sculpting aided by computer feedback, where a camera-projection system analyzes the current shape compared to a target and projects colors that indicate where material should be added and subtracted [81]. Rivers also developed a mobile router with an actuated milling bit where a user roughly places the router on the material while the router fine-tunes the milling bit position in 2D [82]. Similarly, the MatchSticks project asks humans to attach a mobile router to fabricate wood joints [92]. Zoran presented a 3D-sculpting tool where the user moves the router freely and the milling bit automatically stops when the user carves too much [103]. These projects create powerful applications by combining the reachability of the human with the precision of a CNC-machine.

2.7 Summary

This chapter first reviewed the various backgrounds that motivate this thesis from different perspectives; namely architectural design, material-driven design, adaptive systems, and waste management. Although these topics are diverse in domains and motivations are different; however, they are common in working on non-standard materials. Sections 2.5 and 2.6 introduced precedent works that are directly related to adaptive fabrication and its approaches: material-aware design and fabrication. These works are more technical rather conceptual. In summary, there are only few precedent works that focused on digital fabrication with non-standard materials. We saw several works of material-aware processing in large scale architecture; however they are mostly for one-off projects or blackboxed, whereas works in material-aware processing put emphasis on technical contributions but mostly limited in product-scale.

3 Workflow for Adaptive Fabrication

This chapter introduces a general workflow for adaptive fabrication. Before we discuss the details of the workflow, we share prerequisites for readers who consider developing their adaptive fabrication systems, working as a checklist preventing unnecessary developments. Also, this chapter compares workflows for conventional digital design/fabrication, upcycling with non-standard materials, and adaptive fabrication. If conventional digital fabrication is a top-down approach from idea to fabrication, upcycling is a bottom-up process regulated by the available materials at hand. While both workflows are based on feed-forward fabrication, adaptive fabrication is a branch of upcycling but slightly modified in a way that hardware and human involvements are leveraged for the sake of measurements and adjustments during fabrication.

3.1 Prerequisites

In this section, we first confirm the scope of materials, construction methods, and applications, and then describe prerequisites and preparations to get hands on adaptive fabrication workflow. The following table provides a checklist for those who consider adaptive fabrication.

Criteria	Applications	Materials	Hardware/Software equipment
Questions	Which application are you thinking of, in which scale?	Do you have enough amount? Standard or non-standard?	Have certain equipment/facilities and experiences?
Considerations	Object-scale • Personal fabrication • One-off objects > 3.2/3.3 depends on the number of available materials Architecture scale • Several furniture production • Interior • Pavilions > 3.2 or 3.4 depends on standard or non-standard Large scale construction of buildings > Not the scope	Few standard materials > Consider one-off objects production manually or design in CAD. 3.2 is also relevant. Few non-standard materials > Follow 3.3 or manual fabrication without CAD, requiring skills and less-regulated design target. A bulk of standard materials > 3.2 A bulk of non-standard materials > 3.4	Digital/manual fabrication hardware • A laptop • CNC router, laser cutter, 3D printer • Band-saw, grinder, chop saw, worktables etc.. For Scanning • RGBD camera • Rotary table For tool development • Microcontroller such as Arduino board • Wiring/Soldering materials and facilities Software • CAD/CAM software that can provide output files such as g-code. • Other programming environment such as Processing, Python, ROS

The scope of applications is set with construction of architectural elements ranging from furniture and interior to pavilion scale. They are similar targets of personal fabrication but slightly different in scales and the numbers to be fabricated. On the other hand, applications that are outside of the scope are large scale construction such as infrastructures and critical

load-bearing structures.

The scope of materials is set with separated mono-materials with irregular sizes, specification, and behaviors during fabrication. 'Adaptive fabrication' provides solutions for these irregularities in scalable manners. For scalability, the materials should be available with certain amount. We need a bulk of materials to explore fabrication methods with trials and errors. During fabrication, the workflow also makes errors and mistakes resulting in fixes and replacements.

For standard materials, conventional digital fabrication workflow (see Section 3.2) is suitable, further discussed in the next section. In case of few non-standard materials, 5-10 individual pieces, it is not necessary to implement an adaptive fabrication workflow but normal upcycling procedures with digital scanning is suitable (see Section 3.3.) In this case, output would be more artistic one-off objects such as sculptures or conceptual furniture using found objects.

As for minimal hardware for fabrication, we expect basic digital fabrication equipment such as a desktop digital fabrication machine and laptop for experiments. For scaling the developed workflow, it is recommended to have a certain size of space for real scale construction materials such as 4 $\times$ plywood sheets. For this scale, a set of fabrication machinery is recommended to be equipped such as table saw, band saw, grinder, polisher, CNC, chop saw, power drills, and some other storage with small tools, depending on materials. It is also recommended to have a workshop space for prototyping electric devices with micro controllers and sensors/actuators, requiring wiring and soldering.

Computers and other devices are dependent on materials and projects though, a RGB-D camera is useful for 3D scanning as well as monitoring fabrication process. A rotary table for scanning is useful as well. A laptop does not necessarily process heavy computation but natural interaction for human-in-the-loop with image input requires a certain computational resource. For connecting multiple devices, a computer with multiple USB ports is preferable. As for skills and knowledge regarding design/fabrication, basic CAD experience as well as experience to use DIY tools such as hand-held power drills and jig-saw are recommended. In the beginning, empirical trials and errors are unavoidable.

3.2 Conventional Digital Fabrication with Standard Materials

In this section, conventional digital fabrication process is reviewed, depicted as Figure 6. The workflow is characterized by the simple cascading process from exploration to assembly. The use of standard materials enables the simple workflow based on the assumption that the feed-forward fabrication will be executed without errors.

The workflow begins with abstract design exploration of functionalities and abstract sizes by considering contexts of use and environments the object is placed in. This exploration is a common process for most design/fabrication activities. High-level design concepts that characterizing the design such as unique functionalities or composition of materials are also

Figure 6: *Workflow of conventional digital fabrication (the top row) and digital tools used in each phase (the bottom row). The solid arrows are the main and the dotted arrows are occasional processes.*

explored in this phase. After a rough idea of size and material is planned, the design process defines more details for fabrication. More concrete details of the design, such as sizes for each component and how these they are assembled, are defined. Materials are also selected in this phase, and then fabrication methods for independent parts, connection methods for assembly are subsequently determined based on the selected materials. While there is no definite tool for exploration, CAD is set as a standard tool in design phase especially for digital fabrication. It is helpful to validate the plan in more details as CAD provides rich visualization and simulations such as structure or assembly.

Before fabrication phase, most of fabrication-related parameters such as tool paths and tooling speed can be defined in the CAD software. Parameter-tuning with such a high-end CAD is called Computer Aided Manufacturing (CAM). With CAM software, a user can simulate fabrication process with the selected material. In this way, most of errors during fabrication are filtered out in the design phase. Once fabrication starts, digital fabrication machines execute motions defined by G-Code or other forms of commands. In fabrication machines, some basic sensors are equipped for controlling simple actions.

Some errors during fabrication is fixed when a user notice them. It is usually destroy the work due to the feed-forward nature; therefore it is common to redo from the beginning once it failed. There is no direct feedback to design. This is also characterized in the cascading workflow, especially the clear division between design and fabrication [99, 66].

After the whole or partial assembly of parts, the global design can be evaluated. Some digital tools for assembly are useful e.g., visualization of assembly process such as Building Information Modeling (BIM) or other procedural guidance interfaces. The challenge of digital fabrication is that major mistakes are found when parts are assembled each other in the end of the flow, which is depicted as evaluation in Figure 6. Various reasons for errors of assembly can be listed e.g., clearances between parts are not appropriate, materials behave different

way from simulation, or simple mistakes in design etc. In case major mistakes are found during assembly, it is necessary to redesign the whole, requiring significant efforts.

3.3 Upcycling with Non-standard Materials

If conventional design process is an inductive, top-down approach from abstract ideas to exploration of possible materials, the design process of upcycling can be described as a deductive, bottom-up approach from the selected material to exploration of possible designs. More concretely, in a conventional design process, the workflow first starts from designing a target with specific sizes, and then searches for suitable materials among available products in the market. On the other hand, when we decide to go for upcycling, we start from the material at hand and probably have an abstract idea what to build; however, sometimes the idea is found to be infeasible with the available set of materials. Among various upcycling workflows, this section intentionally focuses on a minor case with digital tools for better understanding of the adaptive fabrication workflow in the later section. Note that digital fabrication, especially feed-forward fabrication process as in the previous section, is not suited for upcycling in general.

The biggest difference from digital fabrication is that the workflow begins with physical materials, which is represented as 'preparation' phase in Figure 7. Preparation includes digital scanning and other measurements of the materials to take digital representation in CAD. The selected material regulates possible designs with their physical constraints. Fabrication method can be defined once the material and design are fixed. In this way, upcycling is bounded by the physical constraints of the selected material.

Figure 7: *Workflow of upcycling (top row) with digital tools (bottom row). Preparation and design phases go through several iterations, and errors during fabrication are not easily recovered. The same phases and tools with digital fabrication workflow are grayed out. The solid arrows are the main and the dotted arrows are occasional processes.*

After the functionality is defined, a global design can be explored with the selected materials by importing scanned geometry into a CAD software. Unfortunately, the feedback arrow from design to preparation in Figure 7 occurs frequently in upcycling workflow since some design concepts are found to be infeasible with the selected materials during the design process. In fact, CAD is not mandatory for most upcycling upcycling with small number of materials. In this case, it is quicker to manually explore design configurations with the

physical materials. Whether in both virtual and manual designs, the challenge is to select and assign materials and define the feasible global design out of the selected materials.

Fabrication of upcycling with non-standard materials is another challenge due to the irregular nature of individual materials. In case with feed-forward digital fabrication, it is mandatory to calibrate the planned machine paths and the material, requiring careful alignment for each material. This is one reason upcycling is difficult with digital fabrication. Recovery from mistakes due to the misalignment or unexpected material behaviors during fabrication is problematic with feed-forward fabrication. Even though small mistakes could be covered by modifying the tool-paths, it is tedious to calibrate the machine and the material again. If your materials has irregular material property, more chance to have unexpected errors.

In case of more significant mistakes, the entire design might be affected and require modification of the global design. The worst case is that the piece of materials is so unique that we cannot replace the material with others. If we cannot find a similar material within the prepared materials, it is necessary to redo from the preparation as the dotted line from evaluation to preparation in Figure 7. One approach to avoid such a situation is to design a standard component out of the available materials; however, such a design requires many trials and errors. It also does not solve the problem fundamentally because many digital fabrication machines only accept supported materials and the unit component is anyway built out of the irregular materials. Another approach is to relax the precision of the design target. As a result of assembly, the whole shape might not satisfy the intended design. We can positively take the gap between the target and the built result as a design character; however, it limits possible applications due to the unreliable results. These are the main reasons upcycling with non-standard materials is not active and mostly processed by manual skilled labors for one-off artistic creations.

3.4 Workflow for Adaptive Fabrication

The workflow for adaptive fabrication is almost same as the one of upcycling with digital tools. As in Figure 8, the only difference is the measurement and adjustments during fabrication and updating design if necessary. Adaptive fabrication puts emphasis on the explicit implementation of this measurement and adjustments with minimum hardware and software with interactive and autonomous systems.

In adaptive fabrication, design and fabrication phases are closely connected more than what CAD and CAM. During fabrication, more sensors including cameras are used to observe the result of material processing. In feed-forward digital fabrication, some basic sensors also observe materials at the beginning of fabrication to avoid critical errors such as a tool crashing into the material. It is same for upcycling but it requires humans to pay attention on the machine-material calibration. In this way, upcycling takes advantage of the human's capability for measurement and adjustment, while adaptive fabrication explicitly includes humans in the process. The feedback from fabrication to design also became explicit as design and fabrication are closely connected in adaptive fabrication. In this way, the global design can be dynamically updated within the range defined by the user.

Figure 8: *Workflow of adaptive fabrication. Measurement and adjustment are depicted in the design and fabrication phases. The same phases and tools with upcycling workflow are grayed out. The solid arrows are the main and the dotted arrows are occasional processes. The corresponding chapters are also depicted next to the digital tools in the bottom raw.*

In the previous workflows, simulation in the design phases filtered out potential errors and mistakes during fabrication and assembly processes. In adaptive fabrication, simulation is not only for humans to predict errors but also for machines to decide next actions during fabrication. With material models from preparation phase, a simulator can predict few steps of actions to prevent critical errors and recover from small mistakes. In case of irreversible errors are found, the design is slightly modified and updated as we described above. In this way, errors and mistakes can be minimized without making critical influences on the assembly.

3.5 Summary

In this chapter, we first shared the checklist for the ease of selecting a suitable workflow, and then reviewed three digital fabrication workflows. The conditions of input material, standard/non-standard and available amount are important to select the right workflow. For standard materials, it is natural to take conventional digital fabrication as errors can be recovered by replacing the work and redo the same process. Upcycling forces its workflow to start from physical materials at hand. In case of upcycling with digital fabrication, a solid preparation, such as scanning and modeling, is indispensable. Based on those workflows, adaptive fabrication workflow was introduced and the concept of measurement and adjustments during fabrication was introduced. Most of fabrication situations, adaptive fabrication is not necessary for various reasons, mainly because the application is targeting one-off object or the selected material is standard. In case the application requires a large amount of use of non-standard materials more than 10-100, it is reasonable to consider the development of adaptive fabrication workflow.

4 On-the-fly Guidance for Human-assisted Chopsticks Deposition

As the first case study, this chapter presents a material deposition method with specially developed material composite with chopsticks and glue. The material composite is suitable for large-scale additive manufacturing due to its porous structure. As a material-aware design approach, we take the jammed chopsticks pointing at random directions as a material expression. The challenge of the material-aware design was to fulfill structural and functional performance while preserving the expression, and our approach was to model the material composite's mechanical specification by specifying the required number of sticks and glue per volume. Another challenge was to implement a method that can extend the material to large scale and challenging geometry. To do so, we developed a material-aware processing method with on-the-fly projection mapping as guidance for human-assisted material deposition. We also developed stick dispensers in order to guarantee glues are evenly applied to sticks. For validating the developed adaptive fabrication method, experimental pavilions were designed and built as experiments. We evaluate the performance by measuring the difference of target and fabricated shapes, cost, and construction duration.

4.1 Project Overview

This project was enabled by a collaboration among different disciplines in architecture, structure, and computer science (see more detailed contributions in section 4.5.3). Design by aggregation has been explored by several architects based on the interest of naturally defined forms without manipulation by humans (see Section 2.2.2). In architectural design, Frei Otto studies how sand dunes are naturally formed, and explored forms generated by the material behavior [17]. What if we drop stick-like elements such as chopsticks? The form-finding eventually leads us to the large-scale 3D printing method that can control the random aggregation of sticks. Our material composite was initially developed through design exploration of forms enabled by aggregated materials. Stick-like element has an advantage in logistics. However, it is not possible to keep the form and control how each element lean on others.

Digital fabrication has become more prevalent in recent years due to the increased accessibility of a range of personal digital fabrication tools. In the architectural domain, such tools have been in use for years in both professional practices and educations. However, unlike CAD software, which entirely replaced conventional drafters, applications of these tools are limited either to custom component fabrication or scale model making. Additionally, these digital fabrication tools can never fully replace the role of humans in construction and development processes. Human labor is still essential when dealing with uncertainties in on-site construction processes because humans can flexibly determine case-by-case solutions. The involvement of human labor is primarily due to the one-off nature of the architectural design. Moreover, digital fabrication tools were initially designed for factory automation in controlled environments, not for use on construction sites [15].

There have been some attempts to 3D print buildings with a large scale printer. D-shape scaled the CNC gantry base up to 6 m by 6 m with 300 array injection nozzles, to solidify sand layers with 1.0 mm resolution [19]. The study illustrated the challenge of working with a printing material too fine for efficient large-scale printing. Contour Crafting developed a nozzle for concrete extrusion and controlled it with a CNC gantry [46]. This example also exemplified the challenge of large scale construction, indicating that such a project requires a massive CNC gantry base, resulting in extremely high costs. Applicable sites are limited for such machines due to the complexity of CNC operation at large scales and the requirement of a controlled environment. Additionally, available printing materials in the market are expensive and too fine for such large-scale objects.

Our proposal for scaling up 3D printing mechanisms was inspired by recent works related to computer-assisted digital fabrication processes [103, 82], especially the Sculpting by Numbers project, which supports complicated sculpting works by projecting simple colors on a work [81]. This process is applicable to additive manufacturing, letting workers hold a printing nozzle, and guiding them where to print. Because one of the primary challenges for large-scale printing is the determination of a material solution, a related challenge is the development of a hand-held printing nozzle and a corresponding guidance system.

In this chapter, we present an architecture-scale computer-assisted digital fabrication method consisting of three technical components: (i) a porous printing material composite consisting of chopsticks and wood glue, (ii) a specially designed printing device called a stick dispenser, and (iii) a printing guidance system. For large-scale 3D printing purposes, the simple, straight geometry of chopsticks has advantages in terms of efficiency, production, and logistics. Chopsticks and wood glue are utilized together to form randomly aggregated porous structures, which are evaluated through volume-based analyses. The mechanical specifications of aggregated chopsticks are obtained through physical tests, and these specifications are then used to inform the subsequent pavilion design process. The developed dispensers guarantee consistent feed of the stick-glue composite and controlling the aggregation process. The projector-camera system was developed to evaluate shapes in real-time and to indicate to human workers where to print, all through the use of a simple color code. The system enables the materialization of digital models with minimal use of fabrication equipment.

With the developed method, we designed and constructed an experimental architecture as a case study; the STIK pavilion (a 50 m^2 footprint and a 3.8 m height). This project includes insights into the construction process used to create the pavilion and will also discuss limitations of the presented methods, along with future developments. The proposed method is exploratory and is not immediately applicable to real practices. However, we believe the individual components of this work advances state of the art. Furthermore, the method as a whole, (including the construction process), provides insights and inspirations for future advancements in architecture-scale digital fabrication.

Figure 9: *An overview of our method: (i) Aggregation of printed chopsticks solidified with wood glue; (ii) A specially developed hand-held printing device to consistently feed a chopstick-glue composite; (iii) Print guidance system implemented by a projector-camera system; (iv) The constructed pavilion as a case study.*

4.2 Material-aware Design

We choose the combination of chopsticks and glue as a construction material because of the following reasons. Firstly, it forms a highly porous structure. The porous structure is desirable because one can produce a large structure out of less material, benefiting less operation time. Secondly, the rectilinear shape has advantages in production and logistics. Finally and most importantly, chopsticks are cheap and easily obtainable. Each stick costs less than a dollar, and in China alone, over 80 billion chopsticks are produced annually. Costs and environmental impacts can be further reduced by using imperfect chopsticks (chopsticks resulting from errors in the manufacturing process).

This section includes a report on our study of the proposed material for design and construction purposes. Making a number of test samples with a dispenser, we empirically studied the form-ability and the constraints of aggregated sticks, referring to them as geometric properties. Testing these samples, such as compression and bending tests, we obtained mechanical properties of sticks per volume. We eventually used these geometric and mechanical properties to design the pavilion and simulate its structural capabilities.

4.2.1 Aggregation as Design

This section examines the form-ability of stick aggregation and its limitations. Stick geometry contributed to quick printing operation, for example, chopsticks with 220mm length can add 100-200 mm per layer, depending on the rotation of the sticks at the point from which they are dropped. Stick aggregation can grow not only vertically (see (i) in Figure 10) but also obliquely upward without any support underneath by changing the dropping angle. A 60cm overhang could be built at 150cm height as (iii) in Figure 10 illustrates. The overhang without form-works is a strong advantage for construction.

Figure 10: *Geometric properties: A vertically printed sample (i) with jammed structure (ii). An obliquely printed sample (iii) with stratified structure (iv).*

Mode of aggregation: We distinguished two modes of aggregation: jammed and stratified (see (ii) and (iv) in Figure 10, respectively), determined by the angle at which sticks were dropped (see Table 3). When sticks were dropped vertically, the sticks landed in random locations and formed a jammed aggregation. When creating a porous and lightweight structure, this process results in quick aggregation, thus we usually print in jammed aggregation. For oblique growth, sticks need to be dropped at a certain angle and slower speed. This forms a stratified aggregation with layers of aligned sticks (Figure 10). We build an oblique wall carefully by stratified aggregation and then drop sticks in a jammed manner. In this way, the oblique wall works as a form-work.

Table 3: *Input factors and resulting geometry*

Factors of control	Aggregation mode	Growth direction
Tilted dropping angle, Spiked geometry at landing point	Jammed	Straight
Straight dropping angle, Flat geometry at landing point	Stratified	Oblique

Factors of control: Among a range of factors of control, dropping angle and speed influence the aggregation mode, as previously explained (and as illustrated in Figure 15). Stratified aggregations require slower speeds for accurate deposition, whereas vertical dropping can be accomplished at higher speeds. However, to prevent sticks from bouncing at the landing point, the speed at the drop point must not be too fast. For the same reason, the drop point must be raised as the aggregation grows in order to maintain a constant distance between the drop point and the landing point. In addition to controlling parameters at the drop point, the initial geometry at the landing point also influences the aggregation mode. Dropping sticks onto flat surface results in a flat and dense aggregation, whereas dropping onto non-flat surface results in a jammed, porous structure. In our experiments, we prepared a container to initiate jammed aggregation (Figure 10 (ii) - (iv)). Table 4 summarizes major factors of control during dropping sticks.

Table 4: *Input factors explored in sample fabrication*

	Factors	Parameters
Dropping Factors	Dropping angle	0 (vertical) to 45 degree
	Dropping speed	Slow <->High
	Dropping height	Fixed <->Variant height
External factors	Glue drying speed	Fast (liquid-like) <->Slow (Sticky)
	Landing point geometry	Spiked <->Flat

4.2.2 Modeling the Behavior of the Stick-glue Aggregation

Through the exploration of the material behavior, we found that it is challenging to develop a model of individual contacts of sticks. Instead, we take the modeling approach by approximating the material as homogeneous volume. Mechanical properties were acquired through a variety of loading tests performed on aggregated sticks. Seven samples were prepared, which varied in the number of sticks and the amount of glue per volume. These samples were used for compression and three-point bending tests (Figure 11). Figures 12 and 13 show the results of the compressive and bending tests, respectively.

Figure 11: *Material tests: Compression test (left) with a 40cm x 40cm x 30cm sample. 3 points bending test (right) with a 25cm x 27cm x100cm sample*

We set a required density for constructing the pavilion to be $\rho = 0.06(\mathrm{tf/m^3})$, considering the average density of samples and multiplying a safety factor. To achieve this density, 33,000 chopsticks and 33(kg) wood glue was consumed per cubic meter. The stress-strain curves did not show a clear yielding point, which was varied in each test. However, they showed relatively similar values for young's modulus. We set the yielding point and young's modulus from the averaged values. Table 5 compares the mechanical specifications of stick aggregations with different materials. The data indicates that the material is quite weak, but it is also lighter than standard materials. The material exhibiting properties most similar to the aggregated stick material is styrene foam.
The bending test demonstrated that the material is stronger than the result of the compression tests. The sticks themselves have an anisotropic nature due to their geometry, and thus

Figure 12: *Stress-strain curves from compression tests. Early three samples with less glue on the left graph and improved samples with more glue on the right.*

Table 5: *Comparison of mechanical specifications of stick aggregation and other materials.*

	Density (t/m^3)	Young's modulus (MPa)	Yield stress (MPa)
Stick aggregation	0.060	0.1	0.0106
Styrene foam	0.013	8	0.1
Balsa wood(across the grain)	0.140	150	1
Balsa wood(with the grain)	0.140	4000	10
Ceder wood(with the grain)	0.380	8000	25
Steel(SS400)	7.800	205000	400

become more variant in mechanical properties following various directions of applied force. Furthermore, the direction of the applied force determined the amount of friction on the jammed structure. The results suggest that the material is capable of withstanding bending forces. This information helped design the pavilion and implied that a uniform surface (such as a shell) could be compatible with the material properties.

4.3 Material-aware Processing

The material-aware processing for chopstick-glue materials consists of two technical elements: specially developed dispenser and on-the-fly guidance projection-mapping.

Figure 13: *A bending load-deformation curve from a 3-points bending test.*

4.3.1 Stick Dispenser for Human-assisted Fabrication

After creating a series of prototypes, we arrived at the design of a hand-held stick dispenser, a machine capable of consistently depositing the stick-glue composite (Figure 14). There were three critical design criteria for the dispenser: (1) Capable of consistent material deposition when combining stick and glue feeding processes, (2) Ease in handling (regarding its size and weight), and 3. Capable of controlling both dropping angle and speed for free-form construction.

Figure 14: *A series of hand-held dispensers.*

Material supply and feeding mechanism: A bundle of 300 sticks is supplied to a sliding container on the dispenser, which pushes sticks against a feed roller for feeding at any angle (Figure 15). The feed roller feeds ten sticks at once through a slit and then passes the sticks

to glue coating rollers that can evenly coat wood glue on sticks. Both feed and coating rollers are powered by a DC motor with variable speed control. When considering the wood glue, it was essential to determine the viscosity of glue, factor in the pumping pressure required, friction encountered within the hose, and glue drying speed. In particular, glue drying speed affects the aggregation mode. Thicker glue dries faster and thus holds the sticks where they are dropped, but makes it difficult to control the dropping angle. Thinner glue takes more time to dry (and thus hold the sticks in place), but it allows precise control in terms of dropping angle and speed. Our results indicated the optimum glue viscosity is 2.0 $Pa \cdot s$, with water and glue being mixed at a ratio of 1: 3.25, respectively. A gear-pump with a pressure of 3.0 MPa can feed the glue.

Operation: During operation, a worker needs to adjust the height of the dispenser in order to keep a constant distance between the dispenser and the top of the current work. A dispenser can feed 150 sticks and 1 liter of glue per minute (capable of printing one cubic meter in 1.5 hours). In oblique growth, users need to adjust the rotation of the dispenser in order to follow the growth direction. Through the use of a guidance system, users can check the growth direction. Multiple dispensers can be operated within the guidance system.

Figure 15: *Left: An overview of a dispenser. Right: Operation of a dispenser.*

4.3.2 On-the-fly Projection-based Guidance for Human-assisted Deposition

The workflow of our guidance system was developed based on the Sculpting by Numbers project [81] (see Figure 16). As for precedent works, projection-based augmented reality

has been used for various purposes (e.g., for displays, entertainment, and task guidance), and many works have advanced its performance [9].
The system captures the current work using a depth camera, compares the scanned geometry with the target shape, and then projects the guiding information based on an evaluation. Our contributions here are the real-time tracking and feedback using a depth camera, and an operation workflow on an architectural scale. The workflow includes a calibration procedure which supports the relocation of the camera-projector system, thus allowing the guiding system to cover large objects.

Figure 16: *The workflow of the guidance system.*

Hardware setup: We set a projector-camera system on a 3.5 [m] high scaffold. A short-range projector, BenQ MX823ST, was selected for its wide projection area (approximately 4.0 [m] by 5.5 [m] at 3.3 [m] height). We used KINECT version.2 for the depth camera at a resolution of 512×424 at 30 fps. The Kinect2 was easy to use and was also capable of outdoor use due to the TOF (time of flight) measurement mechanism.

User Interface: The captured current work and a target model are represented by voxels. The system evaluates each voxel, determines whether the current shape matches the target model or not, and then returns differences by displaying the evaluation results on each voxel. There are three types of evaluation results, as indicated in Figure 17: (1) Insufficient: The detected voxel matches the target shape but requires additional printing. The color gradient (from green to blue) indicates how close the shape is to the desired shape. (2) Sufficient: The detected voxel matches the target shape. (3) Excessive: The detected voxel is outside the target shape. Results are displayed as 3D volumetric models and are also projected onto the current shape (Figure 17).

4.4 Experiments

To validate the feasibility of the proposed method and to clarify issues for real application, we designed and constructed two pavilions as experiments. The first experiment was conducted indoor, fully constructed by additive manufacturing, whereas the second experiment was partially panelized which is described in the later section.

Figure 17: *UI and coordinate systems: Viewer UI on the left. Projected image is on the right. The model coordinate is in the bottom-center of the target model.*

4.4.1 Experiment 1: Indoor construction test

As a preliminary study, we built a pavilion with customized stick materials. The length of the stick material is 200 [mm] with 5 × 5 [mm] section. The construction was performed indoor with one dispenser. The duration of the construction took three days. The construction was all executed by the additive manufacturing with the developed guidance system, unlike the experiment 2 partially built by assembly of prefabricated panels. After the construction was completed, we scanned the built shape by a FARO laser scanner and compared with the target shape. As a result, most of the accumulated sticks were fitted in the target volume.

4.4.2 Experiment 2: Outdoor construction with panels

As the second experiment, the STIK pavilion was constructed and exhibited on a university campus. The design of the pavilion was not determined in the pursuit of functional architecture but instead aimed to test the developed methods, particularly in terms of free-form printing and on-site construction. Because the projector system could not be operated in daylight, we split the pavilion into panels, most of which were printed in controlled indoor environments. The pavilion was constructed over 20 days, which included placement of scaffolding, creation of a foundation, and clear coat spraying. The structure was exhibited for 12 days. One million chopsticks were used to create the structure. Visitors were attracted to the exhibition from a distance but expressed surprise upon discovering that the pavilion was made of chopsticks.

In addition to addressing the daylight issue described at the beginning of this section, panelized construction also proved to be effective for minimizing the required printing operations outdoors, where we encountered rain and other weather-related difficulties. The first meter of the pavilion was attached to weights, which made the form impractical to carry. For this reason, the first meter (red part in the inset figure) was printed on-site with multiple guidance systems. For the remaining portions of the pavilion (which reached 3.8 m in height), the geometry was divided into 35 panels, which were printed indoors (blue part in the inset figure). When modeling the panels, we created gaps between panels and filled them in on-site, much in the way mortar is used in brickwork.

4.4.3 Lessons Learned

In many cases, workers needed to check the growth direction of a target shape to adjust the dropping angle. It was impossible, however, to determine the growth direction purely through the use of the guidance system because the system only indicated whether the current work matched the target model or required additional sticks. For addressing this issue, a board placed at an arbitrary height could be used to check the results of the guidance system (on the board rather than on the work on progress) (Figure 18). The board shows an invisible volume in mid-air. By moving the board up and down, workers were able to understand the growth direction of the current work intuitively.

Unfortunately, the guidance system was used in a few areas during on-site construction for a number of reasons. Due to daylight, there were limited periods of time during which the projector could be operated. Although it was possible to operate the system at night, this was avoided for safety reasons. Another issue encountered was related to the calibration space; space, which was defined by fixed physical markers, was often blocked by other objects (such as scaffoldings) on-site.

Due to the limited operation of the guidance system, some areas or panels did not match the targeted shapes. In these cases, panels were aligned using conventional drawings and measurements. This process, however, created tedious work and necessitated repetitive measurements over uneven surfaces followed by re-positioning of panels. In crucial areas of the structure or in locations that were difficult to print (such as the openings), printing operations were physically guided using nets or boards as form-works.

4.5 Conclusions

This chapter reviewed the case study of the chopstick and glue material and construction of the two pavilions. The developed adaptive fabrication workflow leveraged human assisted fabrication for materials deposition as a construction method. This section first reflects on this case study based on the generalized workflow in Chapter 3, and then individual technical contributions together with limitations and future work are summarized.

Figure 18: *A user checking the growth direction of the target model.*

4.5.1 Review of the Developed Adaptive Fabrication Workflow

As Figure 19 shows, we put corresponding tasks of this case study in the general workflow from chapter 3 (Figure 8).

Figure 19: *The workflow of the case study based on the general workflow from Figure 8. Notable actions are directly depicted in the diagram and other corresponding actions are listed below. MAD stands for material-aware design and MAP is material-aware processing, that are tagged on the upper-left of relevant actions. Arrows that happened only few times are grayed-out.*

At the beginning of this project, we have already decided to work on the concept of 'aggregation as design', which defined the overall direction including the decision of material deposition as a construction method. The concept contributed to achieve material-driven design with the random orientation of sticks, therefore, the concept itself is counted as material-aware design. Precedent works explored randomly oriented stick-like materials with larger wooden planks. *The Gathering* project constructed a pavilion out of hundreds of wooden planks that are following a vector field [70]. To achieve the flow of materials with the standard planks, they put extra efforts on each material connections that were precisely designed and fabricated. Similarly, Arne Quinz manually built a pavilion with randomly oriented wooden planks with metal fittings without digital fabrication [30].

In the preparation phase, we also developed technical elements, namely the material, the

dispenser, and projection-mapping. The development of these elements required countless trials and errors represented by the feedback arrow from design to preparation phase (Figure 19). The main factors through the material development were the mechanical properties and the aggregation modes (randomly oriented and layered). Those extracted factors informed the design by various simulations including FEM, that is a typical material-aware design process. Although simple walls could be constructed to validate the workflow, we intentionally selected the challenging shape with undercuts to demonstrate the developed technical elements. In the design phase, we decided to embed metal wires in case of strong winds. The mechanical properties and the metal wires for safety were included in FEM that informed feasible shapes in the design process.

The hand-held dispensers and the guidance system were successful regarding leveraging human capacities. The feedback loop of fabrication in Figure 19 is a local adjustment of the hand-held dispenser by human workers. The global adjustment of the target shape rarely happened as depicted as grayed out arrow in Figure 19.
Similarly, we evaluated the fabricated results once or twice during the construction of each experiment. First the shape was scanned by a FARO scanner, and then compared the scanned shape with the target shape. The arrow from evaluation to design is grayed out in Figure 19. Locally, human workers were able to choose aggregation modes by titling the deposition angles. Globally, the guidance system was sufficient to provide necessary information for human workers to achieve a global target shape. Additionally, we also tested the guidance system for the assembly of panels outdoors.

4.5.2 Contributions

The technical proposals consist of three elements: use of a chopstick-glue composite as a printing material, a stick dispenser as a printing tool, and a guiding system which indicates printing locations to workers. We have explored the geometric and mechanical properties of the created porous structure (which consists of chopsticks and glue) through several physical tests and a comparison of constitutive factors with several other materials. We have presented the mechanism of the stick dispenser and its operation method and have demonstrated the guiding system, which uses a projector-camera system, to scan the current work and project the guidance onto the work with a simple color code. The STIK pavilion was designed and constructed with our proposed method, which provided further insights and findings through the construction process.

4.5.3 Limitations and Future Work

Compared to conventional building materials such as timber and steel, the chopstick-glue composite without reinforcement is relatively weak as a structural building material. Stronger binders, such as hot-melt glue, can improve strength and provide higher resistance against weathering. If printing with threads or nets, the material's tensile strength can be reinforced. These additions can be applied locally after printing, reinforcing structurally critical points. Due to the roughness of the material, it is challenging to achieve geometries requiring high degrees of precision (such as flat surfaces). For such precise work, physical jigs or form-works

are useful for guiding approximate outlines. However, the resulting surface loses the "spiked" material texture. In these cases, flexible nets can serve as form-works while also working to maintain the material texture.

An analysis of the material indicated that the stick-glue composite is anisotropic, but our physical tests were limited to one direction. The material suggested resistance to bending forces rather than axial loads on samples. However, more samples are necessary to validate this tendency. Aggregation behaviors were distinguished into two modes (jammed and stratified); however, this may be an oversimplification. Further investigation of input factors and output results is highly recommended.

The guidance system cannot be operated in daylight. Implementation of a temporary enclosure for use throughout the construction period is highly recommended to block all sunlight and rain. Intelligent power tools with built-in interfaces and sensors could also provide workers with information regarding construction processes [103, 82]. Our hand-held dispenser could be developed as an intelligent power tool, but sharing information among multiple tools would be a challenge for large-scale construction. Additional work would be required to set up a motion tracking system on-site. AR devices such as HMDs (Head Mounted Displays) could serve as interfaces but would require calibration on each device. The proposed projector-camera guidance system can be prepared with a simple calibration process, and can also allow for intuitive information sharing among workers.

Adaptive modification of the target shape could be useful in cases where the current work is significantly different from the target shape. Zoran et al. explored the fabrication of dynamic models [103], which could apply to architecture scale construction. Especially it is practical to share an update model among several workers co-operating on-site.

Project Contributors

This project was enabled through the collaboration of different disciplines in architecture, engineering. Prof. Yusuke Obuchi who directed the Digital Fabrication Lab (DFL) at the Faculty of Architectural Design organized a series of pavilion projects and this project was one of them. I was luckily able to involve in this project as a project manager with supports from other course assistants. Among all the contributors, I contributed to stick-glue material development, construction, and project leads to integrate all the components. All contributors and contents are as follows (the professors and students are all affiliated to the University of Tokyo).

- Prof. Yusuke Obuchi for providing the educational setup of the DFL with course assistants Toshikatsu Kiuchi and So Sugita. Thanks for their efforts, we could manage 8-10 master students constantly focusing on the development of this project.
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- Structural engineering was managed by Prof. Jun Sato, Mika Araki, Masaaki Miki from the Department of Socio-Cultural Environmental Studies/Graduate School of Frontier Sciences.
- The design of the pavilions were developed by Kevin Clement, Ornchuma Saraya, Benjamin Berwick from the DFL under the supervision of Prof. Yusuke Obuchi, Toshikatsu Kiuchi, and So Sugita.
- The dispenser was developed by Anders Rod, Kosuke Nagata from DFL.
- The exhibition was documented by Toshihiko Kiuchi, Ryusuke Wada, Yanli Xiong, JanVranovsky from the DFL.

5 Human-assisted Design and Fabrication of Tree Branches Assembly

This chapter presents an assembly of branches with directly milled custom joints on individual tree branches. We first introduce the challenges for working with tree branches, and then review our material-aware design and fabrication approaches, and finally share the results of two experiments. Tree branches are too small and fragile to make a structure, thus no application has been suggested except for chipping and burning. Our goal is to construct a structure by conserving the shape of tree branches, and our basic strategy is the simple combination of digital scanning and feed-forward fabrication with a CNC router as we reviewed in Section 2.5. To make structures out of tree branches, there was an incremental but heuristic development from 2D to 3D structure that brought another challenge in fabrication. As a preliminary study to explore possible layout patterns, we first collected a number of 2D layouts of tree branches designed by multiple users through a collaborative design interface. After learning from the first study, we shift our focus to construction of 3D structures out of tree branches, leveraging a loop unit and extending it as a structural pattern. The loop pattern create reciprocal frames, increasing structural performance validated through physical tests. The 3D structure brought a fabrication challenge, thus we developed a human-assisted fabrication approach with audio-visual guidance. Finally we share the results from those developments.

5.1 Project Overview

Tree branches are found almost everywhere but not recognized as construction materials so far. They are too small and fragile to make a structure; therefore no industrial application has been proposed except for chipping and burning. On the other hand, branches are often used in arts and crafts or in DIY communities. These communities build sculptures, furniture, and architectural elements. In these works, joints used for assembly are challenging as the branches could be from a hard wood and the roundness makes mechanical connection difficult. For example, to build a lattice of branches for an outdoor fence, DIY hobbyists typically assemble them using ropes to create rigid joints. In cases that do not require rigid joints, artifacts using tree branches tend to be decorative and without structural performance. In this work, we directly fabricate custom shaped rigid joints on the intersections of branches. These joints showcase the precise control of the fabrication process and the integrity of the design.

Another motivation of this work is sustainable development. Wood is particularly promoted as a sustainable construction material [100]. At the same time, the preference for industrial wood production is even-aged and monospecies conifer forestry. Such forests produce straight tree trunks which are suitable to cut into standardized pieces. The broadleaved forest, on the other hand, produces small and curvy tree trunks and branches that are difficult to systematically use for higher value applications in construction and manufacturing. As tree branches account for a quarter of a whole tree, structural application with branches can contribute to effective use of natural resources [2].

As for fabrication with natural wood, previous work generally uses a 3-axis CNC router for 2D structures [72], or a 6-axis robot for 3D structures [62]. The main difference with those works is the focus on upcycling low-valued tree branches. Also, we focused on less hardware requirement with a conventional CNC router, and our human-in-the-loop fabrication system makes it possible to fabricate 3D structures. On a conceptual level, the difference between our work and *Wood Chip Barn* is that their target is a large structure requiring expert skill and professional tools such as crane and industrial robot arm. Our work, on the other hand, leans towards personal fabrication. The tree branches can be handled by humans during both fabrication and assembly.

Our motivation is to upcycle abandoned tree branches and construct structures with the assembly of parts approach. As for connection detail, we carve out cross lap rigid joints directly on a tree branch. Branches are digitally scanned and modeled in order to generate custom joints at intersections and its milling paths in a CAD system. We implement this process by combining digital scanning and fabrication. The basic workflow is described as following. Branches are first collected and cut in manageable lengths. After scanning branches, geometric properties such as skeletons and radii are extracted for modeling branches. Skeletons are used for computing intersections and radii are for modeling joint geometries. Joint geometries are translated into milling paths and G-Code is generated for CNC milling process. Finally, we assemble branches manually. This workflow is also summarized in Figure 20.

In this chapter, the incremental development process from 2D to 3D structures is introduced. We started from a preliminary design exploration in 2D. We developed an interface that collects layout designs from multiple users. Learning from this study, we found a strategy to build a 3D structure leveraging curves of branches. To increase structural performance, a reciprocal frame unit was developed and its structural performance was evaluated as a unit frame. We applied the acquired mechanical specifications for FEM analysis and compared simulation and real load bearing capacities. The reciprocal frame structure made joint milling process more challenging, as joints are facing different directions on a branch. Typically this is solved with 5 axis CNC milling machine or 6-7 axis robotic arm. Rather than depending on those high-end fabrication machines, we take a human-assisted fabrication approach with accessible hardware requirements. A user positions a branch with the help of audio-visual feedback. Voice commands, a beeping sound, and visual feedback guide the user to orient the branch correctly before fixing it in a vise. Then, a 3-axis CNC router mills out the joint.

In summary, our key contributions are:

- Upcycling abandoned tree branches for 3D structures.
- Material-aware design with digital scanning and the mechanical specification of unit reciprocal frame.
- Human-assisted fabrication with audio-visual guidance for placing material on a 3-axis CNC router.

5.2 Material-aware Design

Tree branches are selected as a non-standard material. Our objective is to minimize the modification on branches for material-driven design purpose. The design challenge how to arrange unique components is shared by precedent works. They take different approaches. Schindler and colleagues let users "manually" design furniture with commercial 3D modelling software [83]. Similar to this work, our first approach presents exploration of branch layout designs with cross lap joints. We developed a game interface for this exploration. Second we present a reciprocal frame unit that can be extended to 3D. The unit was tested and mechanical specifications were acquired, enabling us to design larger structures.

5.2.1 One-time Scanning for 2D Branch Layout Game

We discuss an entire workflow from collecting branches to assembly with fabricated joint.

Figure 20: *An overview of the workflow of preliminary study: 1.fix branches on plates 2.scan the plates and upload the model 3. play the game with scanned branches 4.fabricate joints by a CNC router. The way branches are attached on the plate (1) and the restricted milling direction of CNC router (4) provide a constraint for BranchConnect*

5.2.1.1 Collecting and Scanning Branches : Branches are cut to be shorter than a certain length, determined by the work surface of a CNC router, and then they are attached to a plywood plate. They need to be firmly fixed to stay in place during the milling process. We use metal fixtures and screws to attach them. We scan multiple fixed branches on the plate at once and acquire textured mesh models of branches. From the mesh models, we extract contours and skeletons with radius at each skeleton point as simplified representations of the branches. First the branches are segmented from a plate and contours are extracted. These contours are further used for clustering vertices in the mesh model and for extracting

the branch skeletons. In this process we need to consider the case of a grafting branch (Y-shaped) consisting of multiple segments. To avoid metal fixtures during milling process, their locations are specified by mouse-clicks and marked with a red dot. The left of Figure 21 shows a textured mesh model on the left, and corresponding contours and skeletons on the right.

Figure 21: *Left: A and B show an interface of branch importer. Right: diagram of our joints. 1. A layout design 2. Branches on a plate with milling paths in red 3.An assembled pair of branches 4. A close-up joint geometry.*

5.2.1.2 2D Branch Layout Game : The entire workflow is introduced in the previous section as well as in the Figure 20. Here, we focus on the implementation of the game *BranchConnect*, specifically scoring system of the game. In the game, users are asked to connect several target points on an frame by given set of branches by moving and rotating branches in 2D. Users can pick a branch from the available set displayed on the bottom and create layouts by moving, rotating, and mirroring branches. A user continuously receives visual feedback with update of the score, guiding the user to a feasible design. The game is completed when all the target points are connected. It is, however, still possible to keep modifying the layout to improve the design and to try to reach a higher score. Joint and group evaluation are the two key functions of the game, and the basis for the scoring system.

Joint Condition Score: A joint is created when two branch skeletons are intersecting. An important constraint of the game is that every other branch needs to be flipped, i.e. mirrored, in order to make a valid joint. This is caused by the way branches are fixed on a plate (see Figure 20 top left image) and the restricted milling direction of a 3-axis CNC router. Mirrored branches are indicated by a thicker outline in the game. A user can make non-orthogonal joints with angle restriction (see Figure 22.2). The developed system only handles the lap joint of two intersecting branches. It is not possible to connect two edges with a terminal connection (Figure 22.3). Neither is it possible to connect the end of one branch to the body of another, with a T-shaped connection (Figure 22.4). Figure 22 presents other joint conditions for calculating score.

Figure 22: *Joint conditions. 1. Valid joint. 2. Invalid - angle out of range. 3. Invalid - terminal connection. 4. Invalid - metal fixture point. 5. Invalid - T-shaped connection.*

To describe the joint update process, let each branch b_i be a member of a set of the branches $\mathcal{B} = \{b_1, \ldots, b_{Br}\}$ dropped inside of the target frame by a user. The user freely selects $\mathcal{B} \in \mathcal{B}_{\text{plate}}$, where $\mathcal{B}_{\text{plate}}$ is the branches fixed on a selected plate. Note that we accept one joint with a pair of branches, but a branch can have multiple joints with other branches. The process starts from the selected branch b_i and updates joint conditions of the selected branch with paired branches. When an intersected pair is detected on a branch b_i, the intersection is firstly evaluated as in Figure 22, and then labeled as valid joint j_{valid} or $j_{invalid}$ and stored in b_i. The number of target points T_{all} is different on each target frame. Note that we also take one target point per branch. The branch connected to the target point is trimmed at the target point. The trimmed length $l_{\text{trim},i}$ is stored in b_i and used as a penalty for score calculation. In this way, the user tries to position the branch as inside of the frame as possible.

Iterating all branches in a frame $\mathcal{B}$, we get the number of all valid/invalid joints and connected target points, N_{valid}, $N_{invalid}$, $Ntarget$ respectively. When a branch $b_i \in \mathcal{B}$ is connected to one of target points, the number of the connected target points N_{target} is appended and the branch is trimmed at the target point. The trimmed length $l_{\text{trim},i}$ is stored in b_i and used as a penalty for score calculation. This process is iteratively executed while a user is positioning a branch while dragging. We calculate the score of joint conditions $\mathcal{S}_{\text{joint}}$ as follows.

$$\begin{aligned} \mathcal{S}_{\text{joint}} &= w_1 N_{valid} + w_2 N_{invalid} + w_3 N_{target} \\ \text{s.t. } & w_j \in \mathbb{R} \ \wedge \ \forall j \in 1, \ldots, 3 \\ & N_{target} \leq T_{all} \in \mathbb{R} \end{aligned} \tag{1}$$

Group Condition Score: Major group conditions are detected as in Figure 23. If a branch is connected to a target point, colors of the branch and its belonging group are updated, informing users about the validity of their layouts. Taking each branch as edge and joint as node, the graph structure of layouts is analyzed. If cyclic structure is detected, the number of cycle N_{cycle} is updated. When a group bridges a pair of target points, a special score is added and displayed with an animation. After updating the group, group condition and the connectivity of target points are evaluated. Denoting a group and a set of groups as g_k and $\mathcal{G}$ respectively, we check each branch $b_i \in g_k \in \mathcal{G}$ whether it has a connection with a target point or not. If it has, the target point is stored in the group g_k. Denoting the number of groups as N_{group}, the number of islanded groups as N_{island}, the number of bridged target

Figure 23: *Left: valid group with two target points connected. Middle: valid but non-optimal because there is more than one group. Right: invalid due to Islanded situation.*

points as $N_{bridged}$, the sum of distance of bridged target points as $Dist_{bridged}$ the score of group conditions $\mathcal{S}_{group}$ is calculated as

$$\begin{aligned} \mathcal{S}_{\text{group}} &= w_5 N_{island} + w_6 N_{bridged} + w_7 Dist_{bridged} + w_8 N_{cycle} \\ \text{s.t. } & w_j \in \mathbb{R} \ \wedge \ \forall j \in 1, \ldots, 4 \\ & N_{bridged} \leq T_{all} \\ & N_{island} \leq Br \end{aligned} \tag{2}$$

The game is completed when N_{group} is one, and all the target points are connected to the group without invalid joints. The state of completion $\mathcal{C}_{\text{complete}}$ is binary and described as

$$\mathcal{C}_{\text{complete}} = \begin{cases} 1, & \text{if } N_{group} = 1 \wedge N_{bridged} = T_{all} \wedge N_{invalid} = 0 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

We calculate the score S_{all} by adding the results from Eq 1, Eq 2, and Eq 3. Note that the weights $w_1 \ldots w_9$ are non-negative weight coefficients pre-adjusted in advance by the authors.

$$\begin{aligned} S_{\text{all}} = \mathcal{S}_{\text{joint}} + \mathcal{S}_{\text{group}} + w_9 \mathcal{C}_{\text{complete}} \\ \text{s.t. } w_9 \in \mathbb{R} \end{aligned} \tag{4}$$

5.2.1.3 Fabrication and Assembly : After a design is selected for fabrication, fabricability of the design is further analyzed in a high-resolution model as shown in the left image of Figure 21. If an invalid joint is detected, the layout can be modified by adjusting the branch positions using the mouse. Users can also control fabrication parameters such as milling bit diameter, joint depth, cutting speed, moving height and so on. After confirming the fabrication settings and joint validity, G-Code is exported. The joint is a lap-joint with full side cuts and a half-way-down center cut. The resulting geometry creates rigid joints, adapted to the unique branch shapes and angles of intersection (the right of Figure 21).

5.2.2 Modeling the Behavior of the Reciprocal Frame Unit

To make a structurally sound structure out of relatively thin and fragile branches, a reciprocal frame pattern was developed. Such pattern effectively distributes forces across multiple branches. [1] In this thesis, I discuss how to model the structural behaviour of the reciprocal pattern of branches.

Figure 24: *Reciprocal frame unit.*

Figure 25: *The two types of joints of the reciprocal frame unit.*

We conducted flexural tests on two basic loop components of four branches. The experimental setup is shown in Figure 26-1 and 2. Figure 27 shows how the two samples deform with increased input load until they break. In the beginning, the plot is oscillating as the structure settles down with increasing input load. The samples yielded at 2.3 and 2.4 $[kN]$, respectively. Both samples were yielded in the same way - the shortest span between joints split along the direction of the fibers (Figure 26-3). Another finding is that the settlement of the structure was relatively smooth, demonstrating that the joints were precisely fabricated.

Flexural modulus is calculated as $E = L^3F/48I\delta$ where δ is displacement, L is the length of the beam, F is the maximum load, and I is the area moment of inertia. We simplify

[1] Larsson and Cavalli developed the reciprocal frame pattern.

Figure 26: *Flexual test. 1,2: Experimental setup. 3: Failure mode.*

Figure 27: *A displacement-load graph of the two specimens.*

the model with the uniform diameter of 50 $[mm]$ and isotropic material property. The calculated E is 4.0 $[kN/mm^2]$ with 20 $[mm]$ displacement. Considering that the Young's modulus of hard wood is 8.0 $[kN/mm^2]$, it is reduced to half. The bending strength σ_{yield} is calculated by $\sigma_{yield} = M_{max}/Z$, where M_{max} is the maximum bending moment and Z is moment of inertia of area. The bending strength σ_{yield} is 8.78 $[kN/mm^2]$, which is about 5 % of bending strength of other types trees. The reduction in strength was expected, because joints on wooden material are known for drastically reducing bending strength.

5.3 Material-aware Processing

5.3.1 Human-assisted Fabrication with Audio-visual Guidance

Fabricating 3D joints on a branch is challenging since they appear on various sides of the branch at various angles. High-end fabrication machines such as industrial robot arm or 5-axis CNC milling machine can cut 3D joints, however, they are expensive and their work space are limited. On the other hand a 3-axis CNC router is not capable of cutting joints in 3D, therefore, we take human-assisted fabrication as a material-aware processing approach. A user can position a branch with the support of audio-visual feedback. Voice feedback, a beeping sound, and visual feedback guide the user to orient the branch correctly before

fixing it in a vise. Then, a 3-axis CNC router mills out the joint.
We are inspired by works in Section 2.6.2 and try to combine the flexible way in which a human hand can orient a piece of material with the power of the machine. But rather than using the machine to "correct" the sloppiness of the human, we let the computer guide the human to precision. Compared to these precedent works, in our case, the human does not have to work constantly, but only spot-wise when re-positioning is necessary. Furthermore, we try a different mode of guidance compared to precedent work - namely audio-visual. It is, to our best knowledge a novel approach in the field of fabrication; although, it should be noted that audio guidance has been extensively used for other applications such as aircraft operation [29], surgical tools [80], and aids for people with impaired vision [43].

5.3.1.1 Fabrication Setup : The fabrication setup is a CNC router with a vise to fix branches for milling (Figure 28). A board of AR markers is installed on the work surface of the router. These markers correspond to the coordinates of the CNC machine. A camera captures the scene and read the pose of the marker cube on the branch in relation to the machine.

Figure 28: *Fabrication setup. Receiving image input, a PC (personal computer) gives audio-visual guidance to a user. The PC also controls the CNC router.*

5.3.1.2 Audio-visual Guidance System : Each joint on one branch has a unique cutting direction defined by vector $\vec{v}_{cut}$ (Figure 29). As long as we use a 3-axis CNC router,

it is then necessary to position the branch for every joint cut. We take a human-in-the-loop approach for this positioning task, asking the user to place the branch at a specific orientation. More precisely, the branch needs to be oriented so that $\vec{v}_{cut}$ is aligned with the Z-axis of the CNC router. The "roll" and "pitch" angles needs to be set by the user. The the "yaw" angle, which is effectively the rotation around the Z-axis of the machine, and translation do not need to be set by the user - the milling path is automatically adjusted to those parameters after reading the pose of the fixed branch. To place the branch correctly, the user receives audio-visual guidance in the form of speech hints and a stepped sound with a variable frequency. Furthermore, the user is asked to do a fine calibration of the milling bit position on the physical branch during fabrication. The reason is that the automatized pose recognition system with AR markers has an accuracy in the range of centimeters, but millimeter accuracy is required to achieve desired fabrication quality.

Figure 29: *Example of a branch with unique cutting angles for each joint.*

5.3.1.3 User Study of Audio-visual Guidance We conducted a user study to evaluate the audio-visual guidance system for material positioning, where participants were asked to position a branch to a target pose. As a baseline we compared the audio-visual system to a visual-only system. We compared audio-visual guidance to visual-only guidance. We also run a follow-up study to see the feasibility of audio-only guidance.

Participants: Prior to this study, we ran pilot study with two users to improve the audio-visual guidance. We also confirmed that five times of training could be enough for most users to get used to the guidance. 20 participants joined the study, varying in age from 21 to 54 years old, consisting of 4 females and 14 males. They have various backgrounds including computer scientists, students, researchers, engineers, a secretary, and lawyers. Their backgrounds vary from students and researchers from computer science to some engineers, a secretary, and lawyers. The participants were first given a brief instruction of how audio-visual guidance works. We then asked them to get used to the audio-only guidance prior to the main study.

Procedure: Each study with one participant takes approximately 20 minutes. First, we introduce the overall idea of the task as well as the concept of roll and pitch angles, and then demonstrate the task. After the demonstration, a participant practices 2-3 times. We use

audio-visual guidance for this demonstration and practicing. After the practicing, the participant continuously work on the task with visual-only and audio-visual guidance without breaks. After finishing the task, the participant also tries audio-only guidance once or twice.

To avoid learning bias, half of the participants were asked to first follow the visual-only guidance for 5 times, and then follow the audio-visual guidance another 5 times. For the other half of participants, the order was reversed; they first did audio-visual 5 times and then visual-only 5 times. The study was conducted using the same tree branch with a randomized target orientation vector for each trial. Lastly, both groups were asked to follow audio-only guidance. This task corresponds to the initial positioning (Fig. 16-1) and there is no mark on the branch. The tolerance of the correct angle was set to ± 0.01 [$radians$] (0.6 [$degrees$]). meaning that the quality of the result is assured. The frame-rate of the guidance was set to 5 [Hz].

Quantitative Results: All the participants successfully completed the task with both visual-only and audio-visual guidance. Figure 30 shows the result of completion times of participants with each mode. Table 6 summarizes the result with average completion times on each trial with two modes. While participants gradually get used to the system with visual only, audio-visual did not show the tendency that is shown on p-values on each trial. Taking the fifth trial of visual-only audio-visual guidance, average completion times are 31.8 [sec] and 24.4 [sec] that do not show statistically significant difference. All the participants also successfully completed the task with audio-only guidance, but the average completion time was significantly longer.

Figure 30: *Results of the user study of our guidance system, showing average (thick line) and individual completion times for visual-only (left) and audio-visual guidance (right). Visual-only and audio-visual were counter balanced regarding the order in the study.*

Qualitative Results: After finishing the positioning task, participants freely discussed their impressions, feelings and suggestions for improvements. Regarding audio-guidance, all of the participants agreed that it is effective for the task. P1 stated that the strength of multimodal guidance was that *"It was clear which direction and how much I should rotate the branch."* P6 also stated that *"Audio, especially beeping sound was helpful for fine-tuning"*. As for weakness of audio-guidance, P3 mentioned *"At the beginning, the direction by speech*

Table 6: *Average completion time and p-values on each trial with visual-only (V/O) and audio-visual (A/V) Placement*

Trial	1	2	3	4	5
Avg time of V/O [sec]	40.2	37.5	36.4	33.7	31.8
Avg time of A/V [sec]	26.0	27.7	26.8	28.2	24.4
P-value	0.005	0.012	0.038	0.171	0.172

feedback was not intuitive. For example, pitch up could mean either moving the AR marker up or my hand up, which results in different opposite actions." P6, P13, P14 and P15 suggested that different audio feedback for roll and pitch angle would make the operation easier. Similarly, P17 suggested that playing invariant sound for target angle with variant sound for current angle would be effective as well as playful. P16 and P17 pointed that experiences in playing games and instruments would make difference in the completion time. Regarding visual-guidance, many participants suggested that it could benefit from a higher resolution. P8 also claimed that *"In fine-tuning, audio guidance gives direction mostly in speech, however, it could be better just providing beeping sound".* P3 stated the weakness of visual guidance that *Distance to the goal was clear but the direction of rotation was not."* P15 had difficulty with visual-only guidance due to the near-sighted eyes. P7 suggested an improvement for the visual guidance as *"The pitch slider could be shown vertically, corresponding the reality"*. Most of them were ready for the study after three times of trials as preliminary training. Additionally, P9 commented that the appraisal sound feedback was motivating. We observed that many participants had issues with occlusions of AR markers. All the participants mentioned that higher frame-rate of the guidance can help preventing overshooting.

Discussion of User Study: The study indicates that audio-visual modality is more user-friendly than visual-only mode. While audio-visual mode did not show a clear learning curve, visual-only mode showed users get used to the system gradually. Audio-only guidance can guide users to place object but it take more time. We received several ideas that immediately improve the system e.g. playing a monotonic invariant sound with a variant sound linked to angles is feasible and seems to be effective. The organization of the user study could be improved by eliminating systematic errors due to occlusion and other causes.

Regarding the discussion of the functionality of audio-visual guidance, we selected the modality for a variety of reasons. The fabrication setup poses some limitations. The user holds the branch in one hand, and the lever of the vise in the other, hence the user needs to have two hands free. The user also needs to keep visual attention at the fabrication scene. Considering these constrains, we out-ruled options including holding a smartphone and wearing a VR headset. AR glasses, projection mapping, and audio feedback were identified as suitable options. We choose audio over the other modalities. AR glasses was expected to be lagging. A projection system was expected to be slow at launching. Since the system is used for just a few minutes at the time, with up to an hour break in between (while the CNC router is milling), it would be tedious to turn on a projector and wait for it to warm up every time. This can be solved by using a laser projector, which turns on and off instantly. However, we

found the more basic setup using audio feedback sufficient for the task. We simply use the built-in speaker of the PC on which the pose-tracking system is running. With this mode of guidance, the user has both hands free and can look at the branch while placing it. It instantly turns on and off. And even when there is some latency, audio lag is less irritating than visual lag. Later, we did however extended the system by adding visual guidance on the PC screen, so that the user can glance over to the screen if he or she feels lost.

5.4 Results

In this section, we first share the results from the design exploration through the collaborative layout design interface *BranchConnect* [2]. And then, we share the result of the 3D Dome fabrication with tree branches with the audio-visual guidance system.

5.4.1 Experiment 1: Design Exploration with 2D Branch Layout Game

With the developed workflow, we conducted a workshop that builds a 2D fence together with participants, and later extended the workflow for building a larger screen wall for exhibiting SXSW 2018. Figure 31 shows outcomes from the preliminary study.

Figure 31: *Outcomes from preliminary studies. Left: A layout of the fence (top) and the fabricated fence (bottom). Middle: A layout of the large fence exhibited in SXSW 2018. Right: the fabricated large fence.*

5.4.1.1 Building a Fence Workshop We organized a design and fabrication workshop to examine the feasibility of our system. It was hosted in a public community house close to a forest. The participants were four children (aged 4, 7, 9, and 10) and two parents. We set the goal to create a screen wall (2000 mm x 900 mm) divided into 8 sub-frames (500 $mm \times$ 450 mm). Each step of the process was explained and supervised by the author.

[2]The game URL: `https://branchconnect.herokuapp.com/game`

Figure 32: *An overview of the workshop. 1. The overview of the space. 2. Collect branches. 3. Cut in specified lengths 4. Attach on a plate 5. Scan the plate 6. Play the game 7. CNC milling.*

Procedure of the Workshop: Firstly the participants were asked to collect branches with 2-7 *cm* diameters. The collected branches were cut in appropriate lengths, maximum 50 *cm*. Branches were manually cut using a saw. They could construct two plates by themselves and the rest plates were built by authors. Each plate was scanned using iSence camera running on iPad minis. Figure 33 the left shows the scanned branches on plates. When the plates are scanned, simplified branches were uploaded to the game. We set 30 minutes for playing the game, including practicing.

Results of the Workshop: The entire workshop took 4.6 *hours* to complete the whole process, including introduction, moving, and pauses. Table below shows duration of each task. The biggest fraction was preparing plates. Including collecting branches and moving from site to site, which took about half of the time. Scanning including geometry processing, layout design, and CNC milling took about 10 % each. As for scanning, we scanned 15 plates in total (see the left image of Figure 33). As for layout designs with the game, we received 27 layouts from six participants for half hour (see the right image of Figure 33). The average time spent per layout was 71.4 seconds, and average click count was 48.5. Figure 33 the right shows example layouts in score-descending order. For this workshop, we set the weight coefficients in Equation 4 as follows.

Table 7: *Weight settings for the workshop*

Weights	w_1	w_2	w_3	w_4	w_5
Our settings	100	-100	-1000	500	-5

Lessons Learned from the Workshop: Through the workshop, we learned that the participants were excited by seeing the branches they collected by themselves, however not necessarily with own designs. Some participants complained that the workshop was too long and suggested to divide design and fabrication. Another learning from the workshop is that participants preferred to complete a large wall without subdividing frames.

5.4.1.2 Large Wall Fabrication for SXSW : Taking those points, we conducted improved version of the preliminary study that focuses on building a larger wall that can

Figure 33: *Results of the workshop. Left: An overview of all the 15 scanned plates. Ortho-top views of scanned mesh models and segmented branches are shown for each raw, top and bottom respectively. The plates with red rectangles are built by participants in the workshop. Right: Example layouts created by the authors in score-descending order. The highest score is top-left and the lowest score is bottom-right.*

demonstrate its architectural application exhibited at SXSW 2018 where more than a thousand of visitors came. We designed a wall with 2 by 2 m in size and consisting of 74 branches. Compared to the workshop, we used diverse types of trees and a wider range of shapes. The CNC milling process took two weeks in total, however the assembly took less than an hour with three people. The main challenge of this study was to decide the best layout of over 70 branches all to be fitted in a frame. At the beginning, a designer focused on the layout task, but we soon realized that it was overwhelming for one person. Eventually we overcame the issue by virtually subdividing the frame into several work areas and restricting the number of branches per area. Each area became a micro-task, thus multiple designers could work collaboratively. For international shipping, branches went through fumigating process to eliminate insects in the branches. The final outcome is shown in the middle and right images of Figure 31. It was therefore important to set a clear and fair framework from the beginning.

5.4.2 Experiment 2: Design and Fabrication of 3D Dome

The goal of this case study is to build a 3D structure leveraging curves of branches. Another emphasis of this case study is evaluation of 3D structure and informing computational design with acquired mechanical specifications. We show the feasibility of the fabrication system by fabricating a dome-shaped surface (Figure 34).

Figure 34: *System overview. 1: Input surface. 2: Set of scanned real branches. 3: Best found fitting branch assigned to a reciprocal pattern of target curves. 4: Joints fabricated by audio-visual guided positioning by human and a computer numerical control (CNC) router. 5: Fabricated and assembled result. Among them I worked on the step 4 and structural evaluation.*

5.4.2.1 Structural Evaluation : We modeled the sample and simulated in a finite element analysis (FEA) with the CAD software *Rhinoceros* and its plugin *Karamba Physics*. Taking the parameters we obtained through this test, we compared a model of 3D dome and the fabricated dome by compression test (see Figure 36). Fixed supporting points are set at the four corners of the dome. An input load was applied as in Figure 35. Figure 36 shows the result of the real compression test of the dome.

Figure 35: *The result from FEA with mechanical specifications from preliminary flexural test of loops (left), and the real compression test of the dome (right).*

In the simulation, the structure could take the maximum total load 2.5 $[kN/mm^2]$, causing a 19.2 $[mm]$ displacement, while in the compression test with the real dome it broke at a load of 2.28 $[kN]$ and with a displacement of 66 $[mm]$ (see Figure 32). The difference of displacements between simulation and the real test came from the way structure was settled by compression load in the real test. In the simulation, joints were modeled as continuous nodes whereas the real joints are disconnected at the beginning of compression, resulting in

Figure 36: *Load-displacement graph of the compression test of the dome.*

more displacements and jumps on the graph at the beginning. It is also a rather simple beam model excluding details about the joints and variety of species of wood. There is a potential to improve the simulation and integrate the structure analysis feedback in the design process. However, we did not explore that direction, as the purpose for this evaluation is to show that fragile and irregular branches can form a simulatable structure.

5.5 Conclusion and Future Work

This chapter presented two experiments of structures with tree branches; the preliminary study for exploring branch layout design, and 3D shape design and fabrication with the audio-visual guidance. The preliminary study organized a design and build workshop where participants follow the entire workflow: collect, scan, mill, and assemble branches by themselves. The layout was designed by the participants through the online game 'BranchConnect'. The study only confirmed the feasibility of the workflow, and explored variation of layouts by branches. In the second experiment, we applied human-assisted placement method to augment a 3-axis CNC router by asking users to fix a branch on the work surface of the router. In this section, first we review the developed workflows based on the Figure 8 in Chapter 3, and then, we summarize contributions, limitations and future work of this chapter.

5.5.1 Review of the Workflows

In this section, we first review the workflow for the preliminary study shown in Figure 37, and then reflect on the workflow for the second experiment presented in Figure 38. The first workflow is developed based on a feed-forward digital fabrication without major feedback nor evaluation. The preparation includes digital scanning of the plates with tree branches and the early development of the layout game. The design phase implemented the game guiding users to feasible layouts within a highly constrained design space. Before moving to the fabrication phase, we check the fabricability of the layout and adjust it if necessary

as shown in the left image of Figure 21. This fine-tuning of the layout is depicted as the feedback arrow from fabrication to design in Figure 37.

Figure 37: *The upcycling workflow of the first experiment based on Figure 7. Irrelevant arrows are grayed-out, and corresponding actions are remained as solid arrows. Major tasks are listed below. MAD represents material-aware design, tagged on the left of the relevant action.*

Figure 38 shows the workflow of the second experiment. In the preparation, it requires attaching AR markers on each branch and then digital scanning. Also, we conducted physical tests with loop unit samples. In design, the mechanical properties from the tests are used for FEM simulation to predict deformation under an input load, achieving material-aware design. The audio-visual guidance for placement leveraged human's mobility. Noteworthy point is that the feedback arrow from design to preparation happened several times for searching better fits on target curves. After fabrication of all joints on a branch are completed, we check the fit of the branch in the whole assembly. Through this quick manual evaluation, we found some branches were easily broken or simply not fitted well with other branches. In these cases, we follow the arrow from evaluation to preparation to search better branches. Once the materials is fixed, the rest workflow is same as feed-forward fabrication.

5.5.2 Limitations and Future Work

As for the collaborative design interface in experiment 1, further investigation of the gamification approach is valuable. There might be undiscovered branch layouts that are structurally performative and aesthetically pleasing. As a collaborative process, the entire workflow was too long for participants; therefore, we could have focused a specific problem with narrower user groups such as DIY hobbyists or designers. The material collection process itself can be further elaborated. More concretely, the interface for material collection can visualize various information such as when/where/how the material is found by who, and how the collected materials can be used. Regarding the organization of the workshop for larger project, it might be advantageous to separate the workshop into several occasions as follows: 1) Collecting branches, 2) Playing the game together, and 3) Assembly.

As for experiment 2, much effort was spent on material handling, i.e. to build and attach each marker cube, and to scan the branches one by one. For the sake of scalability of the

Figure 38: *The workflow of the case study based on the general workflow from Figure 8. Notable actions are directly depicted in the diagram and other corresponding actions are listed below. MAD stands for material-aware design and MAP is material-aware processing, that are tagged on the upper-left of relevant actions. Arrows that happened only few times are grayed-out.*

workflow, these steps should be simplified. Scanning a bulk of branches at once, rather than one by one, is technically feasible. As for the AR markers, it would be quicker to use off-the-shelf 3D physical markers. Furthermore, it would be even smoother for users to use marker-less tracking without compromising on accuracy.

The fabrication itself is rather time-consuming as most of the time is spent for milling the joints. That is not unique to our system, but equally time-consuming with engineered wood. Using multiple CNC-machines parallel is one possibility to speed up the fabrication. As for the human task of positioning, it is rather quick and, we find, an enjoyable way to part take in the fabrication. The calibration steps after the positioning also rather quick but tedious. The user has to stand up and look closely at the branch from multiple angles to visually assess the position of the milling bit. This step would be easier if the user was assisted by a second camera capturing only the zoomed in area under the milling bit. Then the user could adjust the milling bit position while looking at a screen. With such engineering improvements of our prototypical system, it would be more feasible to scale up production.

Considering the structural tests, the reciprocal pattern was effective to absorb the irregular nature of tree branches. The test with the fabricated dome showed more displacement than the simulated result. This result shows that the modeled dome was not accurate due to the continuous connections at nodes. The branches were weakened by milling out the joints as well. Further study on precise joint modeling is necessary. For architectural applications, there is an abundant diversity of reciprocal and other structurally sound patterns that we have left unexplored. For furniture applications, it would be possible to make furniture such as chairs and tables out of tree branches. It would just require a more diverse portfolio of joint types.

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6 Turn-taking Pose-searching for Irregularly-shaped Stone Stacking

As the last case study, this chapter focuses on irregularly-shaped stones that have been used for masonry walls in traditional architecture. Focusing on the challenges with the diverse shape of stones, we implement a robotic placing system that constructs a balancing vertical stack tower without mortars and adhesives. Material-aware design is the offline one-time scanning of stones, and adequate modeling considering realistic behavior with feasible computation cost in simulation. Material-aware processing is the next best pose searching algorithm that is integrated in a closed-loop manipulation. The implemented system is not on-the-fly but rather turn-taking considering the update rate of the loop. Collaborating with roboticists, we evaluated the system through eleven consecutive trials of constructing a vertical tower. Note that the implemented stacking system is experimental and limited in a controlled environment and pre-scanned stones with a limited number. Also, note that the author's contribution to this implementation is on the stacking pose searching algorithm as well as integration with other processes, i.e., object detection and manipulation.

6.1 Introduction

This chapter spotlights stones as non-standard materials and implements an autonomous placing system for the construction of vertical stone towers. Researches in digital fabrication in architecture explored controlling various materials and their behaviors to develop novel designs; however, most of them are limited with standard materials [39]. While the scope of this thesis in construction methods covers most of the production methods that appeared in precedent works, the focus on non-standard materials of this thesis differentiates from the precedent works. Especially irregularly-shaped rigid stones and rubble are attractive in both architecture and robotics. Packing and organizing irregularly shaped components is not an explored topic. Robotics in construction studies automation technologies and emphasizes on-site operation scenarios. Napps and colleagues worked on cluttered and unstructured environments and onsite material deposition in such environments [69]. The on-site material deposition also takes standardized phase-changing materials, for instance, cement used for large scale 3D printing [49]. Instead of getting into the clutter environment, this chapter focuses on the problem when we plan to place an irregularly shaped object, especially in a balancing manner. We limit the topic in this chapter due to the complex problem of placing as robotic manipulation; hence, our objects are known, and the environment is controlled lab setup. Similarly, we limit the target design to a simpler and smaller toy problem compared to the ones from previous chapters.

Focusing on irregularly shaped stones, our goal in this chapter is to construct dry-stuck structures without mortars and adhesives. This goal has many constraints but allows us to focus on specific technical elements for irregularly shaped objects. The use of non-standard, irregularly shaped materials reveals the following challenges. Firstly, individual object instances need to be identified. Secondly, grasping and stacking poses are not visible, requiring a novel algorithm to select the next best object and find a feasible next pose in the continu-

ous space of the object. Thirdly, the stacking task may be performed in unstable situations; for example, vertical tower stacking in our case, requiring a structural evaluation and target re-planning after each object placement. Within the above-mentioned workflow, this chapter mainly describes a planning algorithm for placing objects while maintaining the target structure in static equilibrium using a robotic manipulator. Due to the instability of a vertical tower, it is natural to observe errors between the desired target pose and a stacked pose in the real world. Hence, it includes evaluation of the resultant pose after manipulation and re-planning of the target pose. The process is integrated in the closed-loop workflow from observation to manipulation. [3]

6.2 Material-aware Design

For building a structure with irregularly-shaped objects, we need to find the next best object and its pose. A placing pose is not as obvious as the one with simple geometries e.g., box or cylinder. We need to test many sample poses and find a feasible one; therefore, a light process of contact generation is necessary. Our approach for fast contact generation is to use dynamic simulation e.g., physics engine. For static structural analysis, numerical methods were developed with rigid discrete elements, as in Section 2.5. While these works analyzed a static equilibrium of given geometric configuration with distinct contact surfaces, in our case with irregularly shaped elements, we need to start from contact detection, which is a core function of physics engines, and then acquire a contact surface. In this section, we first summarize precedent works regarding design with discrete rigid bodies, including picking systems and structural analysis and then describe one-time scanning of stones for the simulation environment.

6.2.1 One-time Scanning of 3D Irregularly Shaped Stones

River stones (Figure 39) are selected for challenging materials property due to low friction. The size of objects is selected to be fitted in finger stroke of the Robotiq Three-finger gripper. For object detection and pose searching, 3D digital models of stones are acquired by; first, dense point cloud using Agisoft PhotoScan [5] or ATOS Core high precision scanner, and then we reconstructed surface using MeshLab [20].

6.2.2 Alignment of Stone Models in Simulation to the Realworld

Different mesh resolutions (from 10 to 10000) were tested in the simulation, considering reasonable computation cost and a correlation between the real world and physics engine (see Figure 40). Notably, the generated contacts in the simulation were compared with contact situations in the real world by inserting a carbon-copy paper between stones, shown in Figure 41. For our purpose, homogeneous triangulated meshes with 500 faces are reasonable in cost and correlation. In the physics engine, rigid body objects are constructed with these digital models. The weight, CoM (Center of Mass) position, and moment of inertia of each

[3] Fadri Furrer, Luca Forni, and Yves Zimmermann worked on object detection, Matrin Wermelinger worked on manipulation

Figure 39: *River stones used in the workflow*

object were measured and specified in a URDF [4] model. We also empirically found that homogeneous friction (0.2) and restitution (0.1) values are suitable for simulation.

Figure 40: *A comparison of mesh models with different mesh sizes. We selected the size of vertices with 500 considering computation cost and the alignment with the real world.*

6.3 Material-aware Processing

Our construction method is simple placing, and our material-aware approach is turn-taking observation of the current state and searching for the next best object and its pose. We simplify the placing problem by handling known objects only and vertical tower stacking as a toy problem. The vertical tower stacking is actually harder problem for robotics due to the instability of placed stones. Our challenge here is to select the best stone and its pose without destroying the tower. For this issue, stacking pose is simulated based on the current work of a vertical stack. In fact, physics engines, such as Open Dynamics Engine (ODE), have been used for evaluating structural stability of object compositions [10]. Similarly, our algorithm employs a physics engine to extract the CoM position and dynamic characteristics,as well as the contact points between the irregularly shaped objects. The key hacks are avoiding jittering motions in the dynamic simulation, more concretely, the whole

[4] URDF is the most commonly used robot description format within ROS.

Figure 41: *Development process with dynamic simulator. A carbon-copied sheet is inserted between real stones to extract real contacts. We compare the extracted support polygon to the one in physics simulation.*

algorithm performs physics engine update steps only when it is necessary. Also objects in an existing stack are set to be immobile in the whole process, except when the cost is calculated.

Integrated autonomous systems dealing with object detection and picking these objects with robotic arms have been proposed for industrial applications [48], [89]. These works have successfully detected irregularly shaped stone-like objects for geometric packing, however, they are limited to place these objects in containers, and hence, did not need to consider structural stability.

6.3.1 Pose Searching Algorithm

The global goal is to construct a vertical tower consisting of irregularly shaped objects from a subset $\mathcal{S}$ of available objects $o_i \in \mathcal{S} \subseteq \mathcal{O}$, where $\mathcal{O}$ denotes the complete set of given objects. Within the set $\mathcal{S}$, we want to find the best object and its target pose. The search space is twofold: discrete object space and continuous pose space. To find a stable pose on a vertical stack, our pose searching method places each object o_i on the top object of the existing stack in a dynamic simulation using a physics engine. For evaluating each object's 'goodness' with a certain pose $\mathbf{p}_i$, we introduce a cost function that maximizes the support polygon S_i's area A_i of the newly placed object o_i and minimizes other considerable parameters, such as kinetic energy. Throughout this process, several initial poses are tested with fixed initial positions but randomized orientations. We are sampling our initial orientations randomly, to keep the problem viable in large problem sets, where a holistic pose sampling would become intractable. The returned cost value is interchangeable among available objects in $\mathcal{S}$, thus we find the best object o^* with the best pose $\mathbf{p}^*$.

An Overview of the Algorithm and the Initial Object: The pose searching algorithm iteratively evaluates poses with valid contacts (support polygon) between a newly placed object o_i and the existing stack. Once a pose with valid contacts is found, the algorithm refines the pose with gradient descent. To find a valid contact pose, we set the object to an initial pose in simulation that is close to the existing stack, but not yet touching it. The initial pose

$\mathbf{p}_{\text{init},i}$ of a new object $o_i \in \mathcal{O}$ consists of its initial position $\mathbf{r}_{\text{init},i}$ and its initial orientation $\mathbf{q}_{\text{init},i}$. The initial position is set with an offset from the centroid C_j of the last placed object's support polygon S_j along the normal direction $\mathbf{n}_j$ of S_j (see Figure 43). To obtain the initial orientation, the detected object orientation is rotated around a randomized axis with the random angle $\theta \in [-\theta_{\text{init}}, \theta_{\text{init}}]$.

Figure 42: *A flowchart of our pose searching algorithm to find the best pose for object o_i. The valid pose search subroutine is described in Algorithm 1 and the cost calculation in Algorithm 2. The gradient descent sub-routine is further depicted on the right.*

Initial pose: The initial pose $\mathbf{p}_{\text{init},i}$ of a new object $o_i \in \mathcal{O}$ consists of its initial position $\mathbf{r}_{\text{init},i}$ and its initial orientation $\mathbf{q}_{\text{init},i}$. The initial position is set with an offset from the centroid C_j of the last placed object's support polygon S_j along the normal direction $\mathbf{n}_j$ of S_j (see Figure 43). To obtain the initial orientation, the detected object orientation is rotated around a randomized axis with the random angle $\theta \in [-\theta_{\text{init}}, \theta_{\text{init}}]$.

Based on the initial pose $\mathbf{p}_{\text{init},i}$, the valid contact pose $\mathbf{p}_{\text{contact},i}$ is found by a sub-routine named *valid pose search* by applying an attraction force $\mathbf{F}$ parallel to a thrust line input (in our case along the gravitational axis). We then run gradient descent (see the right in Figure 42) to iteratively improve the contact pose $\mathbf{p}_{\text{contact},i}$ using the cost function presented below. After the local optimum pose $\mathbf{p}^*_{\text{local},i}$ is found, the orientation of the initial pose $\mathbf{p}_{\text{init},i}$ is randomized again to find the next valid contact pose $\mathbf{p}_{\text{contact},i}$. After computing certain number x of local minima, we find the pose $\mathbf{p}^*_i$ with the lowest cost as the solution pose of o_i. We iterate the process over the available subset $\mathcal{S}$ to find the best object o^*.

Figure 43: *(1) Initial position for the new object based on the existing support polygon. (2) Spawn the new object with random pose and apply attraction force. (3)Get the new support polygon and other parameters for stability check.*

Valid Pose Search: For evaluating physical stability of object o_i, it is a valid approach to analyze whether P_i', the projection of the position P_i onto the support polygon S_i, is inside the support polygon or not (see Figure 43). In order to find a valid support polygon S_i for an irregularly shaped object o_i, we consider the contact points of the object to other objects. The assumed contact situations are simple; either on a flat surface for the first stack, or collision between two rigid body objects with parallel contact normals. The valid pose search method is detailed in Algorithm 1. To assure that $\mathbf{p}_{\text{init},i}$ results in a valid contact pose $\mathbf{p}_{\text{contact},i}$, we apply an attraction force $\mathbf{F}$ along the thrust line direction vector $\mathbf{v}_i$ to the object o_i (see Figure 43). During this process, we continuously check whether the projection P_i' of the CoM position lies within the support polygon (see Figure 43).

Algorithm 1 Valid pose search algorithm

```
function ValidPoseSearch(o_i, p_init,i)
    set o_i's pose to p_init,i
    do
        apply force F to o_i
        step physics simulation once
        if P'_i ∉ S_j then return false
    while N_contact(p_i) < 3
    pause physics simulation
    p_contact,i ← current pose
    if E_kin(p_contact,i) < E_kin,stable then return true
    else return false
```

As soon as the number of contacts $N_{\text{contact}}(\mathbf{p}_i)$ between o_i and the existing stack is at least three (see Figure 43), the resulting pose $\mathbf{p}_{\text{contact},i}$ is evaluated by o_i's kinetic energy $E_{\text{kin}}(\mathbf{p}_{\text{contact},i})$ with a threshold value $E_{\text{kin,stable}}$. By evaluating the kinetic energy, we limit the viable set of poses to the ones that cause minimal motion of the existing stack. This approach for finding a valid contact pose $\mathbf{p}_{\text{contact},i}$ guarantees to satisfy the following constraints:

$$
\begin{aligned}
E_{\text{kin}}(\mathbf{p}_{\text{contact},i}) &\leq E_{\text{kin,stable}} \\
P_i' &\in S_j \\
N_{\text{contact}}(\mathbf{p}_{\text{contact},i}) &\geq 3.
\end{aligned} \tag{5}
$$

Cost calculation: We assign a cost to each valid contact pose $\mathbf{p}_{\text{contact},i}$ to compare its 'goodness' in terms of a robust object poses, which allows further stacking. Therefore, we maximize the area of the support polygon S_i as well as minimize other considerable parameters, such as kinetic energy E_{kin}, and surface normal deviation from the thrust line $\mathbf{n}_i$ for reducing sheer forces. To robustly find the support polygon S_i from the sparse contacts between o_i and the existing stack, contacts over several simulation update steps, in our case 10 steps, are collected and simplified [6]. After acquiring 3D point sets, principal component analysis (PCA) is performed for dimension reduction from 3D to 2D point set. Processing the 2D point set with Delaunay triangulation [42], the polygon mesh S_i is created for calculating its area A_i and surface normal $\mathbf{n}_{c,i}$ (see Figure 43).

Given the area A_i of the support polygon S_i, the kinetic energy $E_{\text{kin}}(\mathbf{p}_{\text{contact},i})$, the dot product $\|\mathbf{n}_i \cdot \mathbf{v}_i\|$, where $\mathbf{v}_i$ is the thrust line direction vector, the length $\|\mathbf{r}_{P_j P_i}\|$ between P_i and the CoM of the previously stacked object P_j, we define the cost function as

$$
\begin{aligned}
f(\mathbf{p}_{\text{contact},i}) = w_1 A_i^{-1} &+ w_2 E_{\text{kin}}(\mathbf{p}_{\text{contact},i}) \\
&+ w_3 \|\mathbf{r}_{P_j P_i}\| + w_4 \|\mathbf{n}_i \cdot \mathbf{v}_i\|, \\
\text{s.t. } w_j \geq 0 \; \forall j \in 1, \ldots, 4
\end{aligned} \tag{6}
$$

where w_j are manually selected weights of the individual energy function components. An overview of the cost calculation algorithm can be seen in Algorithm 2.

After assigning the cost to the valid contact pose $\mathbf{p}_{\text{contact},i}$, gradient descent is performed for searching the local optimum pose $\mathbf{p}^*_{\text{local},i}$, as depicted in the right of Figure 42. In this process, we iteratively calculate a small pose step $\Delta\mathbf{p}$ consisting of $\delta\hat{\mathbf{r}}$ and $\delta\hat{\mathbf{q}}$, as given in Eq. (8) and Eq. (9), to obtain an updated initial pose for valid contact pose searching: The next pose $\mathbf{p}_{n+1,i}$ is acquired with the current valid pose as $\mathbf{p}_{n,i}$ and $\Delta\mathbf{p}$.

$$
\begin{aligned}
\mathbf{p}_{\text{local init},i}[n+1] &= \mathbf{p}_{\text{local contact},i}[n] + \Delta\mathbf{p} \\
\text{s.t. } \Delta\mathbf{p} &= (\delta\hat{\mathbf{r}}, \delta\hat{\mathbf{q}})
\end{aligned}, \tag{7}
$$

where $\mathbf{p}_{\text{local contact},i}[0] = \mathbf{p}_{\text{contact},i}$. The translation $\delta\hat{\mathbf{r}}$ assigns a positive constant offset z_{const} in contact normal direction to avoid placing the object o_i at invalid poses overlapping with the existing stack. Given ϵ_r as a small value, $\mathbf{T_i}$ as a homogeneous transformation matrix from world frame to the thrust line aligned frame at C_j (see Figure 43), and z_{const}, we obtain $\delta\hat{\mathbf{r}}$ as:

Algorithm 2 Cost calculation

```
function CALCULATECOST(o_i, p_contact,i)
    set all objects in stack mobile
    contactsArray[] ← 0
    for k ← 0, k < 10 do
        step physics simulation once
        contactsArray[] ← current contacts set
    contacts ← simplify(contactsArray[])
    contactPlane ← PCA(contacts)
    contacts ← projection(contacts,contactPlane)
    S_i ← 2D DelaunayTriangulation(contacts)
    get A_i(S_i), E_kin(p_contact,i), ||r_{P_j P_i}||, ||n_i · v_i||
    reset poses of all objects in stack
    set all objects in stack immobile
    cost ← f(p_contact,i)
return cost
```

$$\delta\mathbf{r} = \mathbf{T_i}\left(\frac{\partial f}{\partial r_x}^{-1}, \frac{\partial f}{\partial r_y}^{-1}, z_{\text{const}}\right),$$
$$\text{and } \delta\hat{\mathbf{r}} = \epsilon_r \frac{\delta\mathbf{r}}{\|\delta\mathbf{r}\|}, \quad \text{s.t. } z_{\text{const}} \geq 0. \tag{8}$$

For rotation, we describe the orientation with a quaternion $\mathbf{q}$ in axis-angle representation as (axis, angle). Given ϵ_q as small rotation angle, and $\mathbf{T_i}$, we obtain $\delta\hat{\mathbf{q}}$ as:

$$\mathbf{v}_{\text{axis}} = \mathbf{T_i}\left(\frac{\partial f}{\partial q_x}^{-1}, \frac{\partial f}{\partial q_y}^{-1}, \frac{\partial f}{\partial q_z}^{-1}\right)$$
$$\text{and } \delta\hat{\mathbf{q}} = (\mathbf{v}_{\text{axis}}, \epsilon_q) \tag{9}$$

For minimization of the cost, we iterate the process described in Eq. (7) until the difference of returned cost becomes smaller than the threshold γ as $f(\mathbf{p}_{\text{local contact},i}[n]) - f(\mathbf{p}_{\text{local contact},i}[n+1]) < \gamma$. We write the optimization process as,

$$\mathbf{p}^*_{\text{local},i} = \underset{\mathbf{p}_{\text{local contact},i}}{\text{argmin}} \; f(\mathbf{p}_{\text{local contact},i})$$
$$\text{s.t. } A_i(S_i) \geq A_{\text{min}} \tag{10}$$

After finding a local optimum pose $\mathbf{p}^*_{\text{local},i}$, a new randomized rotation is assigned to the initial pose $\mathbf{p}_{\text{init},i}$ and the process is repeated until x local solutions are found, as shown in the left of Figure 42. The pose with minimum cost is selected as a solution $\mathbf{p}^*_i$ for object o_i. We iterate the entire process over all objects of the available subset $\mathcal{S}$, returning the best object o^* with the best pose $\mathbf{p}^*$.

6.4 Evaluation

To evaluate the proposed method, we construct vertical stacks out of randomly placed objects on the table. Therefore, we are using a robotic arm with a three-finger gripper, as depicted in Figure 45. The arm is mounted on a table where a set of natural stones are available to build such a vertical stack. The stones are scanned in advance, and their shapes and behaviors in a simulator are confirmed manually. A subset of the scanned stones gets arbitrarily distributed on the table surface. The object detection pipeline finds the current poses of the objects that are in the scene, and the pose searching algorithm finds the best target configuration, according to Eq. (10).

6.4.1 System

As in Figure 44, firstly, the limited number of objects are scanned offline. The workflow starts from detecting objects, then pick a proper object and search a stable stacking pose, and finally place it on a vertical stack. Each process is implemented as a node of the Robot Operating System (ROS)[78] and available libraries within the frame. For example, the pose searching algorithm is built on Open Dynamic Engine (ODE) [84], and MoveIt! [88] to plan the manipulation tasks required to achieve the desired target composition. This process is depicted in Figure 44. MoveIt/ROS solves motion planning in the workflow. The geometry of each object is known, scanned offline by a high-resolution laser scanner. The geometric information of stacking objects are used for object detection and pose searching with physics simulation.

6.4.2 Case Study Setup

We use a set of six natural lime stones Figure 39 as objects because they show challenging properties for the stacking task like irregular shape and slippery surface. The point cloud and mesh model of the object's geometric shape were previously acquired with an ATOS Core high precision scanner. These models are used for object detection and placing planning. To lower the computation cost, we reduced the mesh model for the pose searching algorithm to a homogeneously triangulated mesh with 500 faces. The mesh size showed to be a reasonable trade-off between reducing the computation cost and being able to generate a contact situation that correlates with the real world. The weight, CoM position, and moment of inertia of each stone were measured and added to the geometric model description. The friction coefficient was estimated with a low value of $\mu_{stone} = 0.1$. For manipulating the objects, we use a robotic arm equipped with a three-finger gripper, as depicted in Figure 45. The object detection is performed with an RGB-D depth camera mounted on the robot arm. The size of the objects is selected to fit in the finger stroke of the gripper. A force-torque sensor mounted at the attaching point of the gripper is used to detect impact during the placing of the object. The workflow of autonomously creating a vertical stack of arbitrarily placed stones is shown in Figure 44. This task is performed by continuously executing a loop consisting of object detection, pose searching and object manipulation.

First, the objects are detected and localized in the scene, resulting in a set of available stones $\mathcal{S}$. For each trial, we used an alternating subset of four stones from the complete set of the six

Figure 44: *Turn-taking process of detection, planning, and manipulation. In an offline step we scan a set of objects (top). These objects, or a subset of it, can be distributed arbitrarily on the work-space and get detected by our object detection pipeline (middle-left). From the detected objects, the presented pose searching algorithm proposes a vertical stack (middle-right). A motion planner (bottom-right) is used to plan the next steps to replicate the proposed stack with the robotic arm (bottom-left). During all execution steps the objects' poses are measured and if the deviations to the desired poses are too large the pose searching algorithms is rerun.*

lime stones. From this set $\mathcal{S}$, the presented pose searching algorithm proposes the next stable stack. A collision-free grasping configuration from a predefined set of feasible configurations is chosen, and a motion planner generates executable trajectories. After placing the stone at the proposed pose, we detect the updated pose and validate if the stacking was successful. The updated stone pose is used as a foundation for the next pose searching step. If the robot could successfully execute the proposed stack, the next proposed stable stack is computed from the remaining set of stones. The stacking task is terminated once the pose searching does no longer find a feasible solution from the available objects or the stacking was not

Figure 45: *An overview of case study setup: a ROBOTIQ 3 finger gripper, a FT150 force torque sensor, and a Intel®RealSense^{TM} SR300 RGB-D camera are attached to the UR10 arm.*

successful.

6.4.3 Results

The robotic system performed the vertical stacking task in eleven consecutive runs with an alternating set of four stones. In two of these runs, the system succeeded in constructing a stack out of all four available stones. In six cases, the system was able to stack three stones vertically but failed to place the fourth stone, and in three cases, the system did not succeed to stack the third stone. For the pose searching algorithm presented in the previous section, we used the parameters given in Table 6. The average cost of the last pose the system was able to successfully stack was 0.7425. Whereas, in the case of failures, the average cost was 1.8018. The gap between those numbers indicates that these poses were already identified as less favorable compared to the ones that were successfully stacked. If the cost at a previous step is high, the probability increases that the following stone placement will fail. See, for example, the high cost of the second stone in run 6 and 7 (see Figure 46). Table 7 shows the mean execution times of the different parts of the presented

Table 8 : Parameters

Parameter	Value	Parameter	Value
w_1	0.179	A_{min}	$1e^{-5}\,\text{m}^2$
w_2	0.472	F	100 N
w_3	0.094	$E_{\text{kin,stable}}$	20 J
w_4	0.255	θ_{init}	$\frac{\pi}{4}$ rad
x	5		

approach, although computational and execution speed was not a focus of this paper. On average, a trial to construct a vertical stack lasted 271.0s. The main fraction of this time is spent on the manipulation task that includes path planning, arm, and gripper motion. The duration of manipulation is mainly because the robot, for safety reasons, is operated with reduced speed. The remaining time is spent on the pose searching algorithm itself, object detection, and other tasks, such as visualization and stopping the motion before capturing depth images. The stacking workflow is not yet optimized in terms of construction time and could be significantly improved by parallelizing manipulation with pose searching and object detection, and by increasing the operation speed.

Table 9 Mean execution times.

Task	Mean time (s)	σ time (s)	Fraction (%)
Pose search	66.2	7.0	24.4
Object detection	17.0	4.4	6.3
Manipulation	166.7	17.2	61.5
Other tasks	21.1	4.1	8.8

6.5 Conclusions and Future Work

This chapter reviewed the implementation of the autonomous stone stacking workflow. In this section, we first review the developed workflow based on the Figure 8 in Chapter 3, and then we summarize contributions, limitations and future work of this chapter. As an overall summary, the project achieved adaptive fabrication seamlessly by the tight-integration of design and fabrication processes. The pose searching algorithm was integrated in the autonomous robotic system of which performance was evaluated by the experimental setup constructing vertical balancing towers with the six pre-scanned stones. The system consists of a closed-loop of object detection, target pose search, physical manipulation, and evaluation. In the system, material-aware design was implemented by the offline scanning and modeling of stones for physics simulation. Material-aware processing was performed by placing manipulation that embodies measurement and adjustment during fabrication.

6.5.1 Review of the Workflow

Figure 47 summarizes the workflow of the developed system based on the general adaptive workflow. As Figure 44 depicts, each stone was digitally scanned and modeled, that are

Figure 46: *The cost of the selected target pose of an individual stone for all eleven runs at each level of the stack. A higher cost indicates a less preferable target pose.'+' denotes a successful stacking; failed attempts are represented with a '×'.*

typical tasks in preparation process of adaptive fabrication. The feedback arrow from design to preparation represents the number of trials and errors of the stone modeling process including the alignment process discussed in Figure 41. In a broader sense, preparation includes the development of the proposed algorithm as well as parameter-tuning in the physics simulator.

As mentioned above, the design and fabrication processes are seamless that they behave as an integrated process. Since the experiment focused on a vertical stack, the target design was fixed with a vertical line; however, the system can take various curves as target design. A target design is updated every after placement of a stone, depicted by the feedback from fabrication to design. Measurement and adjustment during fabrication is also implemented within the fabrication process. When stone-picking is failed, it can be recovered by picking the same stone again or other stones. Similarly, placement can be recovered by another trial of the same stone or other stones. In this case, re-planning of the target is performed at the same time.

Unlike the workflows from previous chapters, the evaluation and assembly processes are grayed out as these processes were integrated within the placing process. Also the construction of vertical towers is a toy-problem for experiments rather than construction of architectural elements such as masonry walls or columns with multiple thrust lines. These processes would be critical when we aim for constructing those architectural elements for

validating the workflow.

Figure 47: *The workflow of the case study based on the general workflow from Figure 8. Notable actions are directly depicted in the diagram and other corresponding actions are listed below. MAD stands for material-aware design and MAP is material-aware processing, that are tagged on the upper-left of relevant actions. Arrows that happened only few times are grayed-out.*

6.5.2 Limitations and Future Work

The workflow was developed for an experimental setup with constraints and assumptions. At this moment, the system only takes six stones and the number cannot be easily scaled due to the computational cost of the pose searching algorithm. Also, the evaluation of the system was also conducted in a laboratory setup (e.g., a fixed platform in a controlled environment, flat surface, pre-scanned objects). After all, the system demonstrated the autonomous capability of stacking tasks in with strong constraints. In this way, this project rather contributed to a preliminary setup for detecting irregularly shaped objects and also validating the proposed pose searching algorithm rather than validating the feasibility of the system for real architectural practices.

As a next step to improve the stability of the planned stack in this setup, the pose searching could consider the future cost by simulating several steps ahead. Each object property can be analyzed e.g., irregularity metrics for 3D shapes can be investigated for a rough assumption of an object and pose [33]. Aiming at more practical situations, we want to focus on construction with unseen objects. This involves the segmentation of unknown objects in a scene and their handling with incomplete information. Furthermore, we aim at creating more complex target shapes, such as arches or walls. These shapes can create structures where each object is contacting with more than two individual objects. In such a situation, not just a vertical or single thrust line, but a more complex thrust line network needs to be analyzed. A more complex thrust line network needs to be analyzed.

Project Contributors and Acknowledgement

This project was the joint collaboration between robotics and architecture at ETH in Zurich, funded by NCCR dFAB. The principal investigator and my mentor, Prof. Matthias Kohler and Prof. Fabio Gramazio prepared the research setup with Prof. Roland Siegward and Prof. Marco Hutter.

Three main researchers equally contributed to this project. Fadri Furrer led the object detection pipeline and Martin Wermelinger worked on the manipulation. These two also evaluated the performance of the integrated system. I would also like to acknowledge Luca Forni and Yves Zimmermann for their excellent work on the development of the object detection pipeline with Furrer and Wermelinger. I would like to thank Kohler and Gramazio to provide the Fadri Furrer and Martin Wermelinger to form the team as well as the equal-contributions on this project from different disciplines. I also show gratitude and respects Jemin Hwangbo for his knowledge and expertise in simulation and optimization methods.

7 Conclusion

In this chapter, we first revisit the problems and challenges with standard/non-standard materials, and then review the contributions from Chapter 1. We also summarize the results of case studies by a taxonomy with adaptive fabrication approaches as in Figure 48. Second, we reflect on the overall thesis by discussing the results and the research methodology with case studies. Each case study analyzed developed systems with the general workflow for adaptive fabrication from Chapter 3. This chapter synthesizes these analysis and reflects on the general workflow from the perspective of the overall thesis. Finally, we discuss limitations of this thesis regarding selected topics such as materials, metrics of performance, and real applications, and finally close the thesis by suggesting the idea of 'computational upcycling' as an extended area of study. Note that limitations and future work of individual case studies are discussed in the end of each chapter.

7.1 Summary

As a summary, this thesis demonstrated the feasibility of the idea of upcycling non-standard materials through three case studies. We first discussed the problem of standard materials in architecture and described what non-standard materials and their challenges are. The problems of standard materials are twofold: the unrecognized richness of materials and the unresourceful use of energy and materials. The challenge of non-standard materials is design and fabrication with rich features such as geometry and material behavior. We proposed 'adaptive fabrication' as a conceptual framework and discussed material-aware design and processing as technical approaches. In chapter 3, we share the checklist and discuss the difference among digital fabrication, digital upcycling, and adaptive fabrication. Through the three case studies, the workflow of adaptive fabrication was consistently applied for each study for discussing and better understanding of the workflow. Figure 48 summarizes the results of the case studies regarding materials, construction methods, and approaches of adaptive fabrication. With the workflow, the checklist, and the summary of the case studies, this thesis provides a guideline for those who consider developing own adaptive fabrication systems for their non-standard materials.

Repeating the contributions in Chapter 1, this thesis contributed in the following items.

- Clarifies the opportunities and challenges in using non-standard materials for architectural construction. Architectural applications demonstrated the opportunities for upcycling.
- Proposes 'adaptive fabrication' as a framework for non-standard material, consisting of two concepts as follows.
  - Material-aware design for recognizing richness of complex non-standard materials.
  - Material-aware processing adds measurement and adjustment loop including humans to the conventional digital fabrication.
- Provides three case studies with different non-standard materials and construction methods.

– Human-assisted deposition of chopstick-rejects from production lines.
– Assembly of tree branches from forestry thinning.
– Placing of stone or rubble from demolition waste.

Figure 48: *A summary of three case studies. Adaptive fabrication and its technical approaches are used as a framework for this summary.*

7.2 Reflections and Discussions

In this section, we reflect on the overall thesis regarding its aim, methodologies, and contributions. For more detailed discussions about the content of each case study, see the next section as well as the conclusions of each case study.

7.2.1 The Aims and the Results

In Section 1.3, we stated the aim as *'demonstrating more scalable upcycling enabled by accessible technologies'*, and *'providing a guideline for digital upcycling with non-standard materials'*. The results from the case studies demonstrated the feasibility of constructing architectural elements by the proposed adaptive fabrication workflows. These architectural applications guided us to consider scalability and accessibility in terms of cost effectiveness. Noteworthy point is that the developed workflows in this thesis were mostly implemented with low-cost sensors and hardware, except for the stone stacking system with the industrial robotic arm. As for the autonomous placing system, the arm and gripper are not easily obtainable; however, the added sensor was a low-cost consumer camera and the developed workflow itself is not dependent on high-end devices. The built outputs also demonstrated scalability to some

extent which we discuss more details later in this chapter.

This thesis could provide a guideline for users how to select non-standard materials, construction methods, and reasonable approaches for adaptive fabrication by the checklist, the general workflows, and the case studies. Each study analyzed each developed workflow based on Figure 8, informing readers to understand how adaptive fabrication could be implemented with actual materials and what are the challenges. In this sense, the checklist, the concept of adaptive fabrication, and the summaries altogether can be considered as high-level results of this thesis.

The built architectural applications might give an impression that this thesis aims for artistic expressions. Our approach is to include non-standard materials for scalable production of architectural elements by digital technologies. Considering a modern art is not only valued by the work itself but its process of making, adaptive fabrication process can be considered as an artistic contribution, demonstrating an alternative form of material-aware production. The built results also demonstrated that irregular features of non-standard materials provide ornamental effects with some mechanical functions. As for the ornamental effects, it is highly dependent on composition with other materials. Combination with standard materials is interesting in the contrast between complex non-standard and simple standard materials. If we push this direction further, we are able to provide a tool for artists to support their expressions with minimum material processing.

7.2.2 The Contributions

This thesis showed the feasibility of upcycling with non-standard materials. Experimental upcycling projects with digital technologies exist before this thesis; however, the thesis spotlighted on non-standard materials and leveraged digital technologies to tackle on the challenges with non-standard materials. To do so, the thesis first collected various works using non-standard materials ranged in various fields. As we reviewed the precedent works, non-standard materials have been used mainly in art and architecture communities with the emphasis on their richness. Except for these communities, non-standard materials have not been discussed in a coherent and systematic manner. Instead, artists, architects, and HCI researchers individually worked on non-standard materials with their personal motivations. There was no multidisciplinary survey about non-standard materials, collecting precedent works from various domains, not to speak of general approaches to upcycle them with digital technologies. In this manner, this thesis provided a new perspective of non-standard materials instead of just categorized as the rest after standard materials.

This thesis sets the target application as architectural elements that brought some engineering challenges, namely structural and fabrication performances regarding efficiency and scalability. Comparing to other upcycling projects with exploration of decorative expressions, this thesis puts emphasis on the evaluations of structural performances; however, these structural evaluations are still limited and other metrics could have been suggested on top of structural performance. Also, architecture is not only the application but other applications in different domains can be further explored. Recently, roboticists are interested

in manipulation of irregularly shaped objects for its engineering challenges, and economists started investigating in upcycling cases in industries for sustainable development. As a prospective research directions, these domains can formulate their own idea and approaches for non-standard materials.

7.2.3 Methodology of Research Through Case Study

As a methodological reflection on this thesis, we discuss the validity of the "research through case study" method. Through case studies, we wanted to explore various types of non-standard materials, valid construction methods, and challenges for scaling non-standard materials. The three case studies are obviously not exhaustive to cover all non-standard materials as well as available construction methods; hence, questions we discuss here would be "how many case studies are sufficient?" or "how different should each case study be?" The short answer is that the thesis lacks explanations of judgment and reasoning for the selections. Materials and construction methods were empirically selected, and approaches for material-aware design and fabrication were heuristically defined. The selected three materials were also biased regarding how obtainable the material is for the author.

7.3 Lessons Learned from the Case Studies

Although we acknowledge the methodological issues of case studies, the studies brought several insights. This section first summarizes the results of the studies, and then reflects on each case study from the global perspective of this thesis.

7.3.1 Reflections on Construction Methods

We set two construction methods, *material deposition* and *assembly of parts*, as valid approaches for building a structure out of non-standard materials. Table 9 summarizes the materials, construction methods, and short descriptions of adaptive fabrications for each study. Although quantifiable metrics are limited for evaluation in Figure 48 and Table 9, three case studies show suitable construction methods based on the specifications of the selected non-standard materials.

Table 9: *The scope and the results of the case studies*

	Materials		Construction Methods	Description of Adaptive Fabrication
	Size [mm]	Number		
Chopstick-rejects	10 to 200	$10^4 - 10^6$	Material deposition	On-the-fly guidance for human-assisted deposition for controlling complex accumulation
Tree branches	400 to 700	$10 - 10^2$	Assembly of parts with CNC milling	Load-bearing branch assembly through human-assisted fabrication
Stones and rubble	50 to 150	$10^2 - 10^4$	Assembly by simple placing	Turn-taking placing planning by simulation

In general, material deposition is suitable for small-sized materials with large amounts. In case of the chopstick and glue, before we selected sticks, we first explored smaller materials such as wood chips, and then empirically tested with larger and longer materials. After all, we could find the stick element that is not too small that they are accumulated efficiently, and could achieve material-driven design that was a combination of human-manipulation and the random directions of chopsticks. If the size of individual elements were larger and the available amount were smaller, assembly of parts method could have been more suitable as tree branches demonstrated. The downside of material deposition is that it requires considerable preparations, e.g., research and development in deposition mechanisms as well as material behaviors. This process involves empirical trials and errors. A learning from the chopstick and glue project is that the preparation duration can be shortened by adopting a human-assisted fabrication approaches instead of aiming for a fully automated workflow.

As for assembly of parts method, we explored with tree branches that are assembled by humans, and with stone stacking by an autonomous placing system. While most assembly of parts processes are performed by humans as tree branches, the stone stacking project deliberately focused on the autonomous placing to explore diverse methods. A learning from the case studies is that assembly of parts can achieve more precise control by modeling connections between objects. If the mechanical connection is precise enough, feed-forward assembly without adaptive fabrication works well as we experienced in the tree branches assembly. As an alternative option of the stone stacking project, it could take the material deposition method such as *Rock Printing* project [65], depositing 30-50 [mm] aggregates with threads. Similar to this approach, the chopstick case study used a metal wire system as a secondary system to hold a structure to avoid destruction at once or against strong winds.

7.3.2 Reflections on the General Workflow

At the end of each case study, we reflected the developed workflows based on the general workflow proposed in Chapter 3. In this section, we think inversely; discuss possible workflows based on the general workflow. Before discussing possible workflows, we extract common features and differences among the case studies. Figure 49 shows the workflows of each study.

The basic processes such as preparation, design and fabrication are shared. Preparation process is especially indispensable among the all studies for material-aware design, which characterizes adaptive fabrication workflow. Preparation is also challenging in a way that it tends to be tedious and time-consuming process. Human-assisted fabrication approach can accelerate the process by outsourcing the functionality of measurement and adjustment to humans. In design and fabrication processes, the cyclic measurement and adjustment during fabrication is appeared in all the case studies but with a different range of update rates. For example of the chopstick-rejects and tree branches, we let humans involved in the loop that required relatively high frequency at least 3 $[Hz]$ to be a natural human-machine interaction. On the other hand, the stone-stacking was turn-taking process that did not require as high frequency as human-in-the-loop fabrication. The assembly and evaluation processes for stone stacking was grayed out. They are seamlessly integrated within the design and fabrication processes. Also, stone-stacking was rather experimental setup for evaluation than aiming for

Figure 49: *The developed workflows for each case study from Figure 19, Figure 38, and Figure 44.*

constructing architectural elements.

As the stone stacking workflow integrated the assembly and evaluation processes within the design and fabrication loop, preparation can be integrated by developing tools for material collection and preparation. Material collection process can leverage the idea of human-in-the-loop as we explored in the tree branch preliminary study. Similarly, humans can focus on hard tasks for machines such as placing and other dexterous manipulations. In this way, the action of stone stacking could be performed by humans as the chopstick project, which accelerates the preparation and probably the fabrication processes. Parallelism of fabrication process is another direction for the accelerated process. The autonomous placing was slow due to the inflexibility of hardware and software; however the speed can be covered by scalable multiple arms. For example, CNC milling from chapter 5 and stone stacking from chapter 6 could be performed by multiple machines. Also, parallel processes need to communicate each other for collaborative fabrication, which is an interesting research topic.

As a summary of reflections on the workflows, we conclude that human involvement is inevitable for design and fabrication with non-standard materials at this moment. Humans are performative in their measurement and adjustment loop, especially with tasks requiring

complex manipulations. Their mobile flexibility was leveraged in the chopstick project as well. Considering the complexity of material setup, processing, and assembly processes, current hardware is not generalized enough; therefore, full autonomous approach requires tremendous effort in preparation phase compared to human-assisted approach. The discussed workflows are all scalable by parallelism, which can be suitable for adaptive fabrication framework in a way that a target design is re-planned based on the multiple fabrication results.

7.4 Limitations and Future Work

In this section, we discuss the limitations in individual topics, namely materials, metrics for evaluation, and real applications. Finally, we close the thesis by suggesting the idea of 'computational upcycling' for future work.

7.4.1 Materials

This thesis limited the scope of materials in sorted mono-materials. The case studies did not explore metal and synthetic materials. As future work, various materials and connections between them can be further explored. Also, collecting, separating, and sorting are closely related to this thesis; however, they are not included intentionally due to they are complicated processes, and tremendous engineering efforts are necessary for integrating such systems. Although autonomous material collection is time and effort consuming, human-assisted collection could make implementation and integration easier. As we demonstrated in BranchConnect, the collection part can be gamified, or users can be motivated by receiving economic rewards. Another approach is to implement an autonomous sorting system as the ZenRobotics Recycler system [60].

Another future work regarding materials is measuring the degree of irregularity of materials. Non-standard materials are not counted as standard for various reasons. A dominant aspect is the irregularity of materials. Irregularity could be caused by input material's geometry and mechanical specifications or as a result of a selected production process, such as human errors and uncertain material behavior during the tooling process. For example, stone shapes can be represented by star-shapes generated by spherical harmonics [33]. By the spherical harmonic analysis, we can quantify the irregularity of a stone shape as well as generate random shapes taking irregularity as an input. Not only measuring the geometric irregularity, but some information of inner structures can also be obtained by non-destructive testing such as X-ray or applying active acoustics and vibrations.

7.4.2 Metrics of Performances

This thesis empirically extracted a guideline for digital fabrication with non-standard materials, but the guideline is not quantitatively validated yet. Various criteria for further evaluation can be suggested; richness and irregularity of materials, degree of conservation of original features, how much a developed system controls or adapts to a material, waste/resource ratio

of materials, feasibility and scalability, and so forth.

Metrics that can quantify the performance of each case study are essential for meaningful discussions. Although metrics could be various, and some of them can not be measured directly, major categories of performance metrics are output application, construction/fabrication method, and upcycling. The performance of built outputs and its measurement is relatively straightforward as we have measured the structural performances of the selected materials as well as the structural performances of the outputs by physical tests. On top of the mechanical specifications, the performance metrics can include durability with weathering, aging, and fire-resistance, depending on intended applications.

Construction/fabrication performance can be measured by duration of construction, cost, total efforts, and energy (if possible to measure it). As a performance of the fabrication method, we could have measured geometric coincidence comparing the target design and the fabricated physical output. Metrics can be shape-descriptors used for 6D pose estimation [101].

The upcycling performance can be measured by evaluating the process of upcycling and the increased value of the input material after the process. Once the target design is defined, we follow the principle of conservation of input materials introduced in Section 1.5. The performance of conservation can be evaluated by measuring the degree of modification on the material, the amount of newly added materials, and the energy spent on these manipulations. As for the actions of upcycling, we explored construction methods in this thesis. The increased value may not be measured directly but partially inferred by the performance of the output and other external factors such as the needs of users. The challenge of measuring the increased value is the dependency on target design; namely, a single non-standard material is typically less valued, but an assembly of them as a whole, such as a furniture, increases the value of the material.

7.4.3 Towards Real Applications

Non-standard materials are currently not promoted for construction and architectural applications [1]. There are mainly three reasons for this situation: challenges in design and fabrication, legal systems, and not many needs in the market. The irregular shapes and properties of non-standard materials make design and structural calculation technically or physically challenging. Even we, fortunately, manage to clear the technical challenge, it would take some time for building laws catching up the new proposed use of non-standard materials. In other words, it takes some time and effort for non-standard to be standard; years of evaluation of durability, creeping effect, and whether it is resistant to the weather, fire, and insect proofs or not. Standard materials are proven for quality and performance; hence, they are considered to lower the risk for insurance and bank loans. Due to above-mentioned reasons, non-standard materials cost more, and could be less performative than standard mass-produced materials.

One application scenario is a large scale critical regionalism architecture designed by enthu-

siastic architects. In this case, non-standard materials are used for articulating social and environmental issues. It is possible to clear the above-mentioned legal and cost issues by collaborating with enthusiastic structural engineers and clients. As we demonstrated with the large pavilion with millions of chopsticks, safety structure can be used alongside of the structure by non-standard materials. This scenario is the case of non-standard materials in the domain of standard materials; however, it is not realistic to compete with standard materials that is not the aim of this thesis.

Another scenario is to develop generalized adaptive fabrication processes which can take any kind of non-standard materials in a scalable way. One direction is to develop a system with more generalized hardware such as a manipulator with high degree of freedom. Robotics have researched in this direction by developing manipulator that can handle complicated dexterous task as human arm and hand. Once we develop a sufficient level of generalized system, the system can be centralized and parallel production lines can be organized.

If we accept that the use of upcycled materials probably does not scale immediately, we can discuss more minor scenarios, for example a personal use case by DIY hobbyists. Upcycling materials they find by themselves stimulate strong ownership of the found materials. If we provide a design tool and fabrication service for them, it could be scaled to many individuals. Design tools can consider safety factors and suggest more materials than actually necessary amount, or connectors can be structurally performative, but members in-between connectors can be non-standard materials.

7.4.4 Towards Computational Upcycling by Adaptive Fabrication

Throughout this thesis, what we tried to achieve is to design and fabricate with minimum processing of the input materials, namely the law of conservation of materials. Here we coin the term "*Computational Upcycling*", collecting technical approaches of design and fabrication with the minimum, or even zero fabrication. The most successful case is not to change the material at all, as the placement of stones. Such use of materials is not limited in placing but a design interface that suggests creative re-purpose of input material can also minimize the modification on the material. In this way, an extreme form of computational upcycling is replace design and fabrication to selection and assignment.

Suppose we successfully define a target design with multiple elements and have multiple available materials, we can formulate upcycling of non-standard materials as an assignment problem of the materials to the target's elements. The assignment problem needs to calculate combinatorial optimization. This calculation could be computationally costly as we need to compute all the costs of the available materials with the target's elements. It is an open-ended question how to reduce the computation cost. If the process allows minimum fabrication, and then optimization in continuous fabrication space needs to be considered, resulting in high computation cost. If we accept the modification of the target design, the problem we need to solve is even more challenging.

In the case of a large number of available materials and target elements, we can reduce the

computation cost by filtering out apparent non-suitable materials for the target design. For filtering, we can put labels and categories on materials offline. These categories can be inferred by data-driven approaches. Combining classification and combinatorial optimization, we will be able to 'select and assign' (design and fabricate) various materials in the future.

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