Robotic Digital Reassembly

Towards physical editing of dry joined architectural aggregations

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Abstract

The accelerating changes in how people use and occupy buildings, coupled with humanity's growing consciousness towards the climate impact of construction, impose reconsideration of existing patterns in the built environment. Most buildings today are planned to resemble a fixed shape, binding their material into a static assemblage. In contrast, computerization in many fields of everyday life shifts our imagination to an editable world. While the digital world is constantly evolving and changes can be instantly programmed, changes in the physical world require immense labor, manpower, and machinery. However, the fast technological advances in digital design and fabrication are challenging the economies of static composition of buildings. Digital design tools offer access to the broad space of design alternatives on all scales, from building topologies to the single building element. By changing a few parameters, designers can reconfigure a design almost automatically. At the same time, architectural research on Digital Materials, Discrete Design, and robotic construction holds the potential to transport these digital qualities into the physical world. As a result, buildings can be thought of as material resources, can be reassembled, and their building elements might flow back into the industry for future building, contributing to the built environment's shift towards circular economy. Combining digital design tools, detachable building elements, and robotic skills is worth exploring to understand their potential and qualities for an editable built environment.

This thesis presents a combinatorial modeling framework for robotic assembly and reassembly of buildings. The applicability of the framework is demonstrated in four case studies employing strategies of robotic programming linked with digital design tools for dry-fitted and interlocking building elements. The use of tactile robotic skills is discussed in a comprehensive case study, utilizing machine learning for the design and robotic control of an interlocking assembly. The robot-oriented design focuses on building elements with quantities, geometries, and connections suitable for handling by a robot.

This shift, in turn, enables architects not only to produce changeable structures but also to gain control and thoroughly explore the design space resulting from elements that can be reassembled. In Robotic Digital Reassembly, materialization and production of architecture are not a one-off process. They rather become a series of instances shifting and adapting into an ever-unfolding future.

Keywords: *Reassembly, Robot Oriented Design, Discrete Design, Robotic Fabrication, Design for Disassembly, Dry Joined Blocks, Interlocking*

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1. Introduction

In 2020 (± 6 years), the estimated anthropogenic masses moved by the global civilization exceed all living biomass on Earth (Elhacham et al., 2020). The flow of materials has significantly sped up since the turn of the 21st century (Krausmann et al., 2018). Mankind never moved so much matter in such a short time, especially in construction, to fulfil their fast-changing demands (Smil, 2013). Yet, the construction industry typically creates more static buildings in a monolithic fashion, emphasizing their fast erection instead of focusing on the adaptability of the resulting structures (Crowther, 2016). Unlike other mass products like computers or cars, buildings are not designed to be changed or remodeled (Sobek, 2010). While some of the reasons are not within the architecture domain, there is also a lack of design tools and concepts to stimulate the reuse and recycling of building products.

Too often, the building life cycle does not fit the architectural ambitions of long-lasting buildings – neglecting the fact that designs are predictions about how a building may perform (G. B. Guy, 2015). In his book 'How Buildings Learn', Stewart Brand (1997) reveals how buildings change during their lifetime. Their organic reality requires buildings to go through adjustments or redesign to avoid obsolesces. Buildings can face obsolescence for various reasons, including economic, financial, market, functional, use, and utility (Pourebrahimi et al., 2020). In the 20th century, obsolescence became a force shaping the built environment with sustainable, expendable and flexible designs (Abramson, 2016). Various architects tried to address the idea that buildings were already destined to fail as soon as they were completed. Growing and expandable megastructures were investigated, for example, by Archigram, Cedric Price, and Kisho Kurokawa, challenging the permanent nature of buildings in projects like the Walking City, the Fun Palace, and the Capsule Tower.

Even today, most buildings are designed as static constructs, although almost all undergo some transformation (Kendall, 1999). These buildings are planned to resemble a fixed shape, binding their material into static assemblages (Bridger et al., 2010). The technical life cycle of these materials commonly exceeds the use life cycles of buildings; the material compounds are often decomposed into waste (El. Durmisevic, 2006, p. 9). All the energy that went into the manufacturing of these elements is lost. One way to overcome these problems is to embed flexibility and reusability into future buildings so that they can adapt to a fast-changing society, for which variable and mobile systems are essential (Knaack et al., 2012, p. 124).

In contrast, the computerization in many fields of everyday life shifts our imagination to an editable world. The concept of ubiquitous computing makes reprogrammable surfaces appear everywhere, including surfaces on refrigerators and even architectural surfaces like walls, ceilings or floors (Hess et al., 2002). Websites are designed for views from various devices, and their content is highly individualized. The underlying bits of information are only frozen into one instance at the time of your visit. Changes in the digital world are only a mouse click away, while such changes in the physical world require immense work and machinery. Modern societies have seen the pixels on our screen disappear and have experienced the scattering of information by individualized news feeds. These ideas started to merge into architectural practice, shifting the design of places towards interaction scenarios (McCullough, 2004). All these effects can be collected under the emergence of finer granularity.

What can be observed is a shift towards element-based approaches questioning the preassigned properties of building elements. And it might be that Moore's Law applies to architectural elements, as described by Jim Keller, a microprocessor engineer who worked at AMD, Apple, Tesla, and Intel, in an interview in 2020.

> "Imagine you're constructing buildings out of bricks, and every year or every two years the bricks are half the size. If you kept building with the bricks the same way you know and with so many bricks per person per day, the amount of time to build a building would go up exponentially. But if you said I know that's coming, so now I'm going to design equipment that moves bricks faster and uses them better because maybe you're getting something out of the smaller bricks; more strength; inner walls; more material efficiency out of that so once you have a roadmap."
>
> (J. Keller & Fridmann, 2020)

The degree to which material scientists are developing techniques to alter matter on the material scale raises the belief that building blocks might shrink (Fleck et al., 2010). At the same time, researchers have developed methods to assemble thousands of small scale building blocks within hours (J. Hiller et al., 2020). But how to design those architectural structures with micro blocks? Do these bricks still look and behave like conventional bricks, rectangular and fixated with mortar?

Digital design tools offer access to the broad space of design alternatives on all scales, from building topologies to the single building element. By changing a few parameters, designers can reconfigure a design almost automatically and similar to the pixels on a computer screen. Simultaneously, architectural research on robotics holds the potential to transfer these digital qualities into the physical. Combining digital design tools, detachable elements, and construction robotics might enable a more flexible built environment worth exploring to understand its qualities. Finally, the bricks, as described by Keller, might not be intended to build more efficiently or stronger but more adaptable. It depends on how the bricks connect and relate to each other.

In the long history of architecture, the part-to-whole relationship primarily focused on assembling elements into fixed and lasting buildings. In the last century, architecture had to deal with industrialization and standardization, exploring modular approaches towards using serial-fabricated elements and their joining. Buildings like the Sainsbury Centre by Norman Foster or the Lloyd's building by Richard Rogers are examples of High Tech Architecture dealing with industrial technologies (Davies, 1988). Interestingly, these instances celebrate the appearance of elements that can easily be exchanged and maintained (Figure 1-1). Their big open spaces are designed to offer great flexibility to their users, while the architectural elements, like staircases, seem to be plugged in place, waiting to be reconfigured. Today, it is known that reconfigurations of those buildings only happened on the level of interior walls. Yet, one can read their visual remanence of an architectural desire for flexibility.

Figure 1-1 Two examples of High-Tech Architecture: The Sainsbury Centre (left) (Foster + Partners, 1967) and The Lloyd's building by Richard Rogers and Partners (right) (Steve Cadman, 2007)

These buildings might reflect research on automation and modularity treated as open systems just a few decades before. Konrad Wachsmann's studies on the universal joint and modular building system highlight the possibility of assembling buildings from parts without irreversible fixation (Jerez, 2018). Under his supervision, one of the earliest attempts of automated assembly was constructed; the Location Orientation Manipulator (LOM) developed between 1969 and 1971 (Figure 1-2). The device could record an assembly's motions and repeat them to close the gap in totally industrialized and automated building systems (T. Bock & Lauer, 2010).

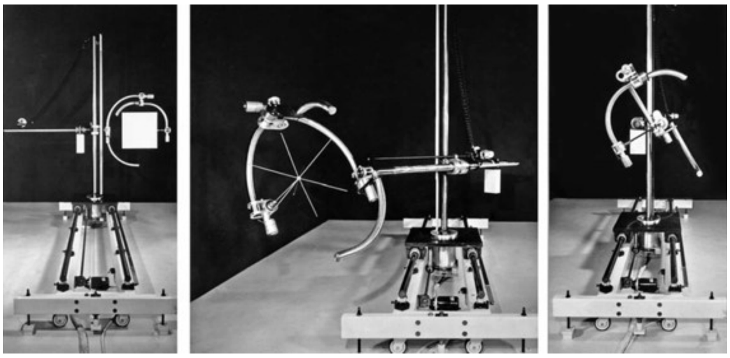


Figure 1-2 The Location Orientation Manipulator (LOM) by Konrad Wachsmann. Photos: Archiv der Akademie der Künste, Berlin

The constant adaptability and replanning of buildings was the subject of many architectural studies and projects. At the Massachusetts Institute of Technology (MIT), the Architecture Machine Group researched integrating technologies like machine learning and robotics into architectural production as early as in the 1970s, facilitating experiments for changing structures (Negroponte, 1975). At an architectural scale, architects like Cedric Price started to embrace concepts about how those technologies can be implemented into built projects to foster adaptability, as pointed out by Tanja Herdt (2017). Price's interest in planned obsolescence was highlighted in projects like the Fun Palace (Figure 1-3) or the BMI headquarter (Steenson, 2014)

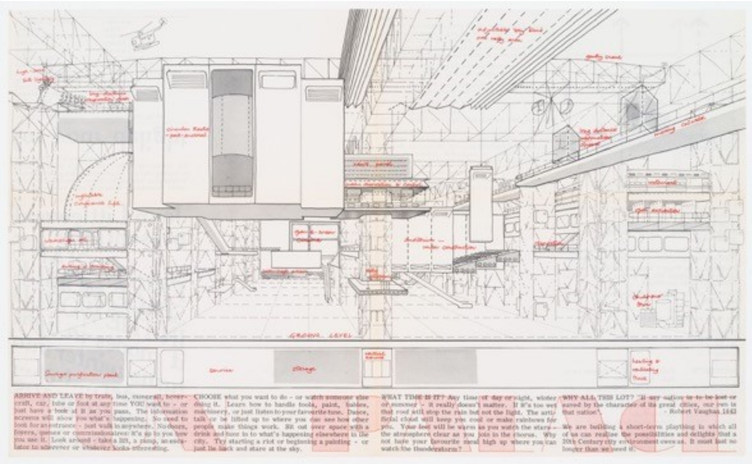


Figure 1-3 Conceptual drawing for the Fun Palace by Cedric Price (Price & Littlewood, 1964)

The dissertation seeks to identify available technologies and suggest ways of integrating them into a coherent design protocol for a more adaptable future. Under these premises, the design must be conceptualized, addressing two requirements: elements designed to be manipulated automatically and elements designed for reassembly. Robots could carry out the automation of assembly and disassembly. Considering the assembly of elements as a process carried out by robots requires a deep understanding of the skills and limitations of these machines. Robot-oriented design puts focus on discrete elements that a robot can handle. Therefore, element geometries and joints must be appropriated to robot skills. For the reassembly of building elements, designers need to negotiate the joining of the elements while ensuring their disassembly without destruction. The resolution of these elements can be set adaptively, allowing the designer to scale the elements appropriately to a specific situation. The designer accesses granular control on the level of detail of the actual distribution of the elements in an assembly. Instead of defining materials like walls, columns, or slabs, the granular distribution of elements focuses on their discrete qualities without assigning their structural position in the building. Finally, an understanding of the built reality of such assemblies must be acquired and structured for machine understanding – an as-built digital model.

1.1. Context

This dissertation's context is framed by research on robots for architecture and their integration into computational design workflows. Tremendous research has been carried out in this area over the last decade (e.g., Gramazio et al., 2014b; *Projects | Institute for Computational Design and Construction | University of Stuttgart*, n.d.). The impact of robots and automation on architecture is widely accepted in academia, and different concepts of their integration into architectural production started emerging. Many projects involving robotics revolve around material processes or explore the precision of robotics under terms like robotic fabrication (J Willmann et al., 2018) or digital craft (Fernando, 2019). These technologies also impact the architectural design tools by integrating their constraints and possibilities into the early design phases.

Many of the so-called digital fabrication techniques translate a digital signal from a digital model into an analog process—producing analog artefacts. Although these approaches use computational processes, their underlying premises are still to produce analog artefacts. The act of computing, the processing of information, is done analog (continuous) as opposed to digitally (discrete). Analog computation relies on continuous representations of information. It has been argued that many of today's "digital" fabrication techniques are still analog due to distortions and noise causing the propagation of errors as the system scales and parts sizes increase (N. Gershenfeld, 2005). If the material deposition by a robot, although the instructions are represented digitally, is continuous, then it is considered an analog process. It relies on external information, like sensors, to prevent the accumulation of tolerances. These techniques lack error-correcting thresholds, common in digital systems.

Digital systems instead rely on thresholds, discretizing the information. The discretization enables error correction and compression. Digital systems can transmit information and be reprogrammed without the loss of information. A manually fabricated calculator (Figure 1-4) performs more digitally than an algorithmically optimized and robotic 3D printed but static structure. Although the 3D printed structure is digitally designed, its manufacturing ultimately relies on analog processes (N. Gershenfeld, 2015). The calculator will always give you the exact same result for each numerical manipulation.

The reason for that is that the machine is divided into a non-programmable and a programmable part. The programmable part comprises gears and cogwheels that can be changed to perform different calculations that users set via a dial plate. A later example of programmable machines is Leibniz's calculating machine (1672/73), the well-known Jacquard loom (1804), programmed by punched cards. Blaise and Leibniz calculation machines were based on the decimal system and used mechanical systems (hardware) to perform calculations. Today, these mechanical devices got de-materialized into computer chips that can change their states and thus the information they carry.

Figure 1-4 The Pascaline is the arithmetic machine invented by Blaise Pascal in 1652 and often credited as the first calculating machine (Rama, 2016)

The emergence of these tools and their usage for design might deliver qualities that can be transferred into the physical world. Mario Carpo described the effects of digital design strategies, one of them the "Wikipedia Style", as follows (DIGITAL SUBLIME Excerpts from a lecture prepared for the conference "Architecture and the Digital Sublime," 15-16 January 2013, TU Berlin.):

"The object of design is forever drifting, permanently open to interactive editing and participatory versioning; hence objects are never finished and can never be entirely reliable or fully functioning; yet they are usable most of the time."

In most computer-aided design environments, the editability of a design is fairly easy. What is more challenging is the physical editing of a design. Editing processes can involve correction, condensation, organization, and other modifications performed with the intention of improvement. These are often associated with digital media and tools (Carpo, 2013a). To transfer these qualities into physical objects requires a rethinking of assembly techniques. Recalling the lossless editing of discrete digital data, error correction needs to be implemented into the physical matter. Two emerging technologies hold great promise for the idea of a physically editable built environment: Discrete Design and Robots in Architecture.

What constitutes Discrete Design? The last decades in research on digital design delivered great progress in the field of architecture. Mario Carpo recognized two digital turns in the past, focusing on exploring the emerging tools for architectural research (Carpo, 2013c), ranging from the first usage of animation software to parametric and generative design tools. Impressive progress has been made in the field of architectural design – the most recent change in the computer-aided investigation was entitled "Discrete". In Discrete Design, the digital logic enters the physical world. Researchers and architects have started developing ideas about how to build structures that inherit digital properties (Retsin, 2019b). These ideas revolve around digital design tools and assembly concepts for discrete elements. Researchers conceptualize part-to-whole relationships under the computational paradigm using terms like the Discrete (Retsin, 2019b), Digital Materials (N. Gershenfeld et al., 2015), Programmable Matter (Tibbits, 2010), or Granular Assemblies (Sanchez, 2019) (Figure 1-5). The concepts have in common a strong integration of automated assembly processes with self-calibrating connections that can easily be detached and reconfigured – thereby breaking the long-standing paradigm of analog materials. Researchers are emphasizing the correlation between the design of building elements and robot-operated assembly. In those instances, the building elements rely on serial prefabrication.

Figure 1-5 The project Semblr from Bartlett M.Arch Unit 19 (left), Logic Matter by Skylar Tibbits from MIT (center), and BILL-E robotic platform by Benjamin Jenett and Kenneth Cheung from MIT Center for Bits and Atoms and NASA Ames Research Center (right) exemplify different research tracks under the computational paradigm for building elements.

In architecture, attempts were made to adapt these concepts under the umbrella of Discrete Design. Architects like Gilles Retsin (Retsin, 2019b) and Jose Sanchez (Sanchez, 2019) are at the forefront, pushing the formalization of the Discrete, reflected by architectural designs that emphasize the parts over the whole with an often unfished or reconfigurable look (Carpo, 2019). Conventional assignments of elements as floor, ceiling, or column are neglected. The distribution of elements allows parts to find their position in the architectural assemblage based on constraints rather than predefined assignments. For explorations of this novel aesthetics, the current design tools have to be adapted accordingly; designers create their tools for discrete design.

To date, digital design environments are predominantly based on the modelling with surfaces or represented as solids, represented by their out boundary (BRep - Boundary Representation). Design environments mainly focus on static representations of the elements without information about the available elements. Digital design tools might check for collisions between parts, but their connectivity and physical behavior towards each other have not been addressed. This problem is particularly true for discrete elements in a different granularity than preassigned building elements like columns and slabs. Architects can move a column and see its effect on the overall system, but if the focus is put on elements that do not have these predefined assignments, their distribution needs other guidance. Panajotis Michalatos (2016) elaborated on architects' access to software tools that would allow designers to work on the scale of material design of 100:1 or even 1000:1. He notes that these tools will not only deal with geometry but might also change our ideas of authorship, similar to software development projects in which hundreds of people work simultaneously. Although lately, design environments are oriented towards discrete parts, embedding their robotic assembly has not been addressed.

1.2. Problem statement

Robots replacing human workers has received significant attention due to the fear of technological unemployment (Brynjolfsson & McAfee, 2014). Usually, when talking about robots, their manufacturers highlight that these machines can work 24/7. They do not get tired, do not need a vacation, nor will they complain about the same task every day as they do not know boredom. Thus, robots deliver high precision and endurance to carry out millions of actions with the same accuracy without the need for a break. No wonder that global industry sales of robots have increased over the last years (Heer, 2018).

Research in robotics has seen a flourishment in architecture, and the expansion of robotic skills for architectural production enjoys broad investigation. In architectural research, robots are widely accepted as tools to merge digital design and fabrication. Research institutes like the ICD Stuttgart or Gramazio and Kohler Research institute at the ETH Zurich have delivered great examples and studies exploring this emerging technology for architecture (Figure 1-6). With their research, Gramazio and Kohler have shown how robots can contribute to a shift in architecture production. The concept of Digital Materiality developed at their chair highlights the emergence of expanding complexities and concepts by linking material and robotics (Gramazio & Kohler, 2012). Famous examples include bricklaying robots, timber assemblies, and spatial metal structures. Simultaneously, there has been an emphasis on developing material systems and implementations of cyber-physical systems in architectural fabrication (Menges, 2015b), including methods and technologies developed to address uncertainties of materials or environments during the automated execution of robotic processes (H van Hoof, 2016). Cyber-physical systems bring together the discrete and powerful logic of computing to monitor and control physical and engineered systems' continuous dynamics. These systems have to align the precision of computing with the uncertainty and noise in the physical context; they must be synchronized across time and space. Finally, the imprecisions of machines and components in both the cyber and physical have to be tolerated or contained (Baras, 2018). Construction processes adapting to real-world deviations and the production of elements on time have been investigated as Adaptive Part Variation (Vasey et al., 2014).

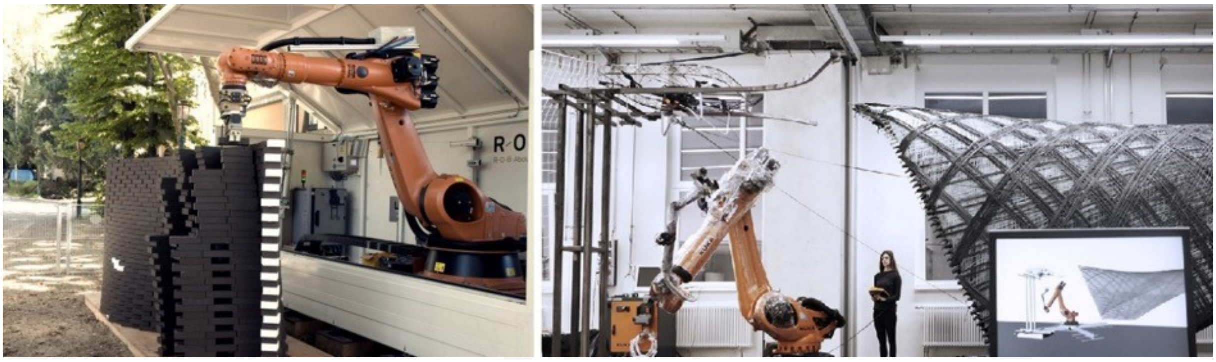


Figure 1-6 ROB Unit: the assembly of bricks (left) (Gramazio Kohler Research, 2017) and fiber winding process for the ICD/ITKE Research Pavilion 2016-17 (ICD/ITKE University Stuttgart, 2017)

Research on robotics in architecture in the last decade has shown remarkable results; however, almost all of it focused on creating fixed and non-decomposable structures. Material systems were explored, highlighting the robotic process's precision and endurance but still organized in a linear fashion. And although these investigations have led to tremendous advancements in informing fabrication, the final objects reveal a static instance of the computational design frozen into a physical object. The extension of digital editing of physical elements similar to those in the computer is still a territory for exploration. Inconsistently, researchers in robotics in architecture focused on mimicking and perfecting the resemblance of freeform shapes through an approach labeled as digital crafts.

We might miss the point of embedding a stronger linkage between digital design tools and the physical construction procedures. The automation of complex assembly tasks through a robot is still an open research topic in architecture and roboticists. Especially, if the robotic process has to be applied in both directions, for assembly and the disassembly, such constraints impact the design of elements for robotic assembly. It requires roboticists and architects to mutually and appropriately understand the capabilities of robots and design with the process of assembly and disassembly in mind.

Robots' use for assembly tasks often focuses on gluing techniques or, later, manual fixation through human workers. However, these approaches are insufficient and cannot be applied to the assembly of prefabricated parts at large – if such parts should easily find a second life. Robot technologies have not offered advancements towards decomposing or reassembling in recent decades (Melenbrink et al., 2020).

Design environments for discrete elements and feedback loops between the planning model and fabrication mechanisms are only being researched today. On the one hand, investigators and researchers describe the ability to eliminate tolerances and react to deviations; on the other, they set out to link material properties with digital processes (Sonntag et al., 2019).

Neither type of research, of course, proceeds independently of the other. Across this line of robotic research within the field of architecture production, central strands have emerged. The robotics agency did not genuinely challenge the widely accepted digitalization of architectural production because of these processes' limitations in one direction. This problem holds true for the design environments being used and most robotic processes focusing on the achievement of one ideal rather than the emergence of genuinely digital spaces.

Significant research has been conducted in building artefacts utilizing robots, saving material, or building more robust but still static – missing the point to find answers for tomorrow's problems. Precision and automation were problems of modern times when industrialization was focusing on constantly delivering the same quality of products. Today, information societies are facing the problem of fast changes and constant redistributions of data, knowledge, and technologies. Yet, the built environment still remains static and does not reflect on the accelerated technological developments it is exposed to (Feather & Feather, 2013). It does not reflect our digital age of bits and bytes that are all but static.

However, while many previous studies can rely on the known linear approach to produce their artefact, this study seeks to develop architectural solutions to create a circular flow of both matter and information.

From the previous discussion, five fundamental problems can be distilled.

- Architectural design: Current tools focus on static assemblies of elements.
- Architectural design: Disassembly and reassembly are not part of conventional architectural design processes.
- Robotic assembly: Current processes mimic existing construction principles and mostly rely on adhesives or irreversible connectors for fixation.
- Robotic assembly: Robots are currently not capable of assembling and disassembling discrete elements.
- Case studies: Demonstrations are missing that highlight the significance of automatic reassembly in architecture.

The collection of these key problems highlights their strong interdependencies. The design of elements correlates with robot capabilities, while the design interface depends on constraints both from the robot and the discrete elements. There have been tremendous technological advancements both in material sciences and automated assembly techniques that enable building editable physical structures. However, the design and integration of these techniques and technologies are still separated and have not been integrated into architectural production processes.

1.3. Research Questions

The thesis explores the relationship between three components: design system, building elements, and robotic skills. Therefore, it is necessary to systematically integrate the topics of design environment, robot-oriented building elements, and robotic skills into an overall framework. The intersecting sub-fields need to be investigated to complement each other.

Within the context of robotic research in architecture, the existing body of work has proven demonstrators and prototypes as excellent vehicles for such investigations.

To address the problems, this thesis seeks to answer three main questions.

- What is the role of the design environment for physically editable structures that are reassembled by robots?
- What constitutes building elements that can be dry-fitted and reassembled into various positions within a built structure?
- How is the design of building elements for reversible assembly integrated with regards to robotic skills?

To tackle these problems and find answers to these questions, this research aims to produce robotic assembled structures with dry-fitted elements. The ultimate goal is to develop insights and tools for integrating robotic reassembly into architectural structures.

1.4. Aims

The intended outcome of this study is to get an in-depth understanding of the design of robotically editable structures. It seeks to identify factors, such as the connection details, design systems, and automation systems, that extend the transformability and reconfigurability of architectural structures. This includes research into reconfigurability on the scale of granular building elements, focusing on reversible connection details for robotic assembly. These explorations open the territory for the design of temporal building systems. Thus, the thesis investigates the relevance of robotics for designing editable structures with prefabricated elements that might find new usage once their first lifecycle ends.

The study identifies several avenues for further investigations into combinatorial studies and robot skills for construction for the related disciplines like computer science and roboticists, such as robot sensing skills for reassembly of building elements or assembly planning for a vast number of elements. Most importantly, it seeks to inform and trigger investigations by the socio-economical disciplines to explore circular business models and to foster reading our built environment as a changing fabric and material resource for future buildings.

The findings of this study suggest technologies and systems for extending the post-building phase of buildings. To not treat them as one-offs but instead as instances of constant cultural development. The presented efforts could help improving productivity and reduce material waste by envisioning truly digital process chains. Architects with substantial knowledge of design for reassembly have to consider the lifecycle of a building and create building elements that can flow back into construction following paradigms of a circular economy. The study contributes to the usage and design of prefabricated elements for reassembly by linking them to robotic assembly and disassembly. The digital design tools strengthen the control of architects over construction processes and give them access to a level of detail never seen in such granularity in the built environment. Consequently, this dissertation attempts to open up the discussion on design for reassembly.

1.5. Objectives

Research objectives addressing the purpose of the study:

1. Granular design methods for reassembly of architectural aggregations
2. Building elements with reversible connections for robotic assembly/reassembly
3. Tactile skills for robotic assembly tasks
4. Process loop linking digital design to automated reassembly
5. Case study method for technology-driven architectural research (Test and Prove Steps 1.-3.)

As such, methods and techniques are developed that allow designing for robotic reassembly with discrete elements.

1.6. Scope

The value of teaching for early research projects has been demonstrated in several research projects. Several studies at the ICD Stuttgart or Gramazio Kohler Research at the ETH Zurich have shown remarkable results in combining research and didactics. Similarly, the scope of this research is narrowed by the didactic setup at the Faculty of Architecture at TU Darmstadt. Together with the unsettled minds of young students, questions of the thesis are discussed and developed further.

The thesis pursues the approach of acquiring knowledge from testing robot capabilities on collaborative robots. These robots allow fast testing without the burden of high-security standards, which would limit the interaction with the robots. In turn, this approach also limits the scale and material choices of the demonstrations. With limited reach and strength, the robots can only cope with elements of specific dimensions and weights. Nevertheless, the insights gathered in this study could be transferred to larger robots. Thus, these investigations into geometric rules for robot-oriented design do not focus on material properties but instead on developing appropriate robotic assembly strategies.

Further, current research in the field of robotics is continuously extending robot capabilities. The thesis integrates the latest research in robotic skills from the computer sciences to benefit from this knowledge growth. While this creates a dependency, it also enables gathering thorough insight and actively participating in developing the latest robotic technologies.

1.7. Structure of the thesis

The thesis is structured into five chapters with the main body of work presented as distinct case study reports (Figure 1-7). Following this introduction, **Chapter 2** covers the state of the art in building systems, connection types, and robotics in architecture. It provides an overview of the relevant technologies and concepts. It defines the most pertinent concepts and reviews relevant previous work in robotic construction and digital design, focusing on assembly. The thesis is contextualized within the field of discrete design and robotics.

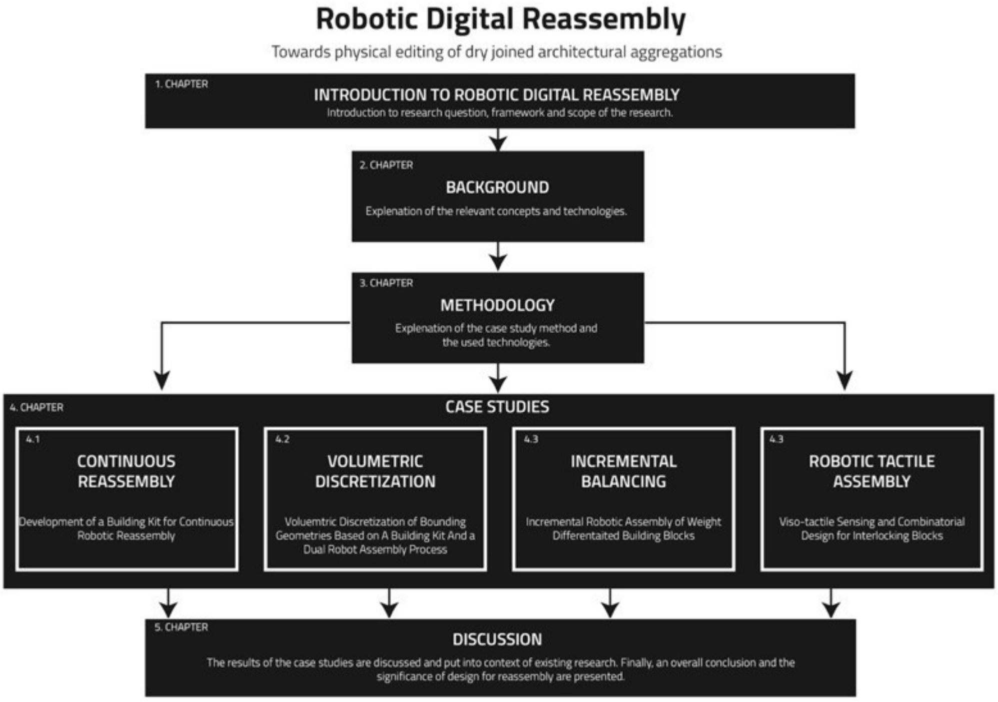


Figure 1-7 The thesis is compiled around the different case studies.

Chapter 3 presents the overall methodology of this study and the developed techniques, tools, methods, and acquired knowledge to investigate design for reassembly. It situates the technologically-driven research approach of the thesis and introduces the concept of research through design. In line with this concept, the case study research method is explained in relation to the thesis topics. Furthermore, the overall setting for the case studies is presented, and the accessible technologies are described.

Chapter 4 presents the distinct case studies separated into the topics of discrete assembly and robot skills. It illustrates the results of the case studies conducted in the academic environment of TU Darmstadt. Different prototypes are tested, and final demonstrators are documented. Each study is protocolled by introducing the case study, background, description of the methods, presentation of results, and a discussion. The four case studies (Figure 1-8) were conducted sequential: Continuous Reassembly (2018), Volumetric Discretization (2019) Incremental Balancing (2019), Tactile Robotic Assembly (2019-2021).

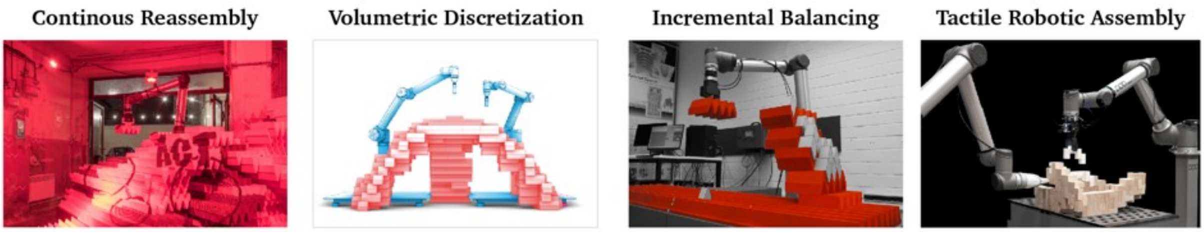


Figure 1-8 The four case studies

Finally, **Chapter 5** summarizes the main findings of the case studies and draws the overall conclusion. It retraces the critical decisions taken regarding design for reassembly and elaborates on the contributions to the field of robot-oriented design and fabrication in architecture. The limitations are revisited, and possible traits for future research are suggested. The chapter concludes the thesis with a discussion of the results, presents an outline for future research and sheds light on possible implications.

2. Background

> Digital technology has most notably revolutionized information technology and computing, but construction and fabrication are still largely continuous (analog) processes. This results in parts for products being one-off designs that cannot easily be reused; when these parts become obsolete they most likely end up in landfills.
> (N. A. Gershenfeld & Ward, 2012, p. 13)

The chapter seeks to identify why the assembly of prefabricated elements on construction sites today looks very similar to 100 years ago (Figure 2-1). It gives an overview of three main topics of this research: building systems, reversible connection, and robotic assembly processes. Previous assembly strategies are reviewed, and approaches for automated assembly with robots are introduced to give a critical overview of the current context of Design for Reassembly. In the first section, different scales and hierarchies within the building system for reassembly are lined up, moving from bigger to smaller scale building systems. While fabrication techniques in construction played a crucial role, one can also recognize emerging attempts fostered by computational tools merging into the design process. The second section elaborates on reversible connections for building elements, highlighting the limitation of most existing connections for reassembly. The third section is devoted to robotic assembly. Emerging capabilities for robots and the challenges of robot integration into the overall building system regarding the integration are discussed. Finally, an overview is presented of current robot programming tools available to architects.

Construction with prefabricated or existing elements requires systematic thinking, which is more critical than the development of a universal kit of building elements. The focus has to be put on the interaction of the components and elements in a complex situation, where the whole is more than a sum of its bits (McKean, 2006).

Figure 2-1 The assembly of prefabricated building components in 1926 compared to 2019. The Frankfurt assembly method in a project from Ernst May, photo from Das Neue Frankfurt, 1926/1927/2 (left) (Seelow, 2018) and a recent assembly of prefabricated elements in The K90 Building Project constructed by Katerra (Katerra, 2019).

2.1. Reversible Building Systems

The reversibility or reassembly of buildings can be addressed at different stages of the designing, planning, and fabricating process. Figure 2-2 categorizes the various dimensions to be considered when designing reversible buildings. The adaptability of space refers to the capacity to accommodate different use scenarios, while the latter two focus on the exchange or reconfiguration of matter. The reversible space relies on predicting future scenarios; the other two can be open to unforeseen futures. Thus, the possibility to separate elements can accommodate a spatial reconfiguration.

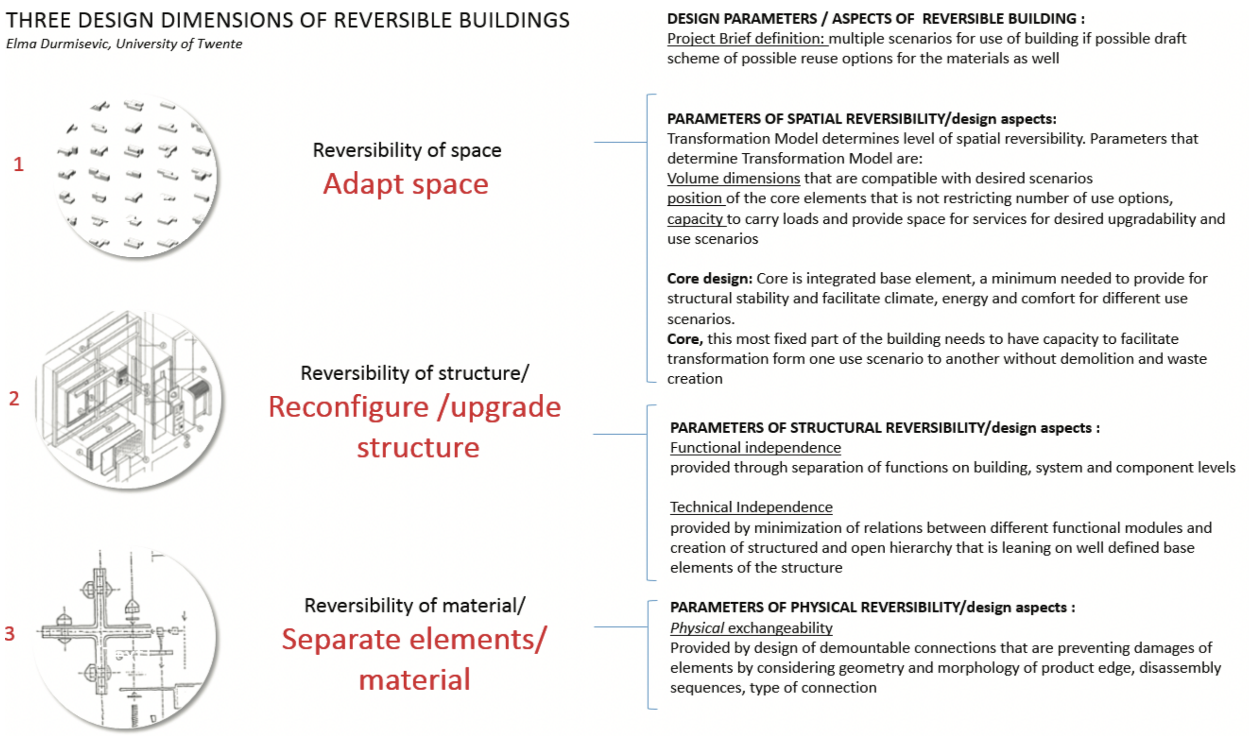


Figure 2-2 The three dimensions of reversible buildings highlighting the different aspects of space, structure, and material (Elma Durmisevic, 2019, p. 38).

The use life cycle and technical life cycle of buildings do not always correlate (El. Durmisevic, 2006). Many buildings lose their determined purpose way earlier than technical components degenerate. The frame or structure has a longer life cycle than the partitioning (Figure 2-3). This highlights that flexibility of building is required on different levels of the building system to address the varying durability of building functions.

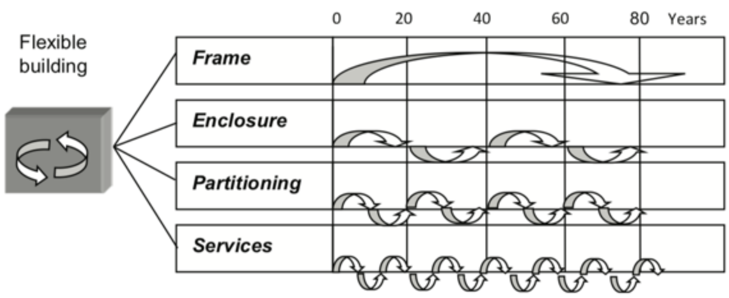


Figure 2-3 Different degrees of the durability of building functionalities (El. Durmisevic, 2006, p. 43)

In the best-case scenario, architects start by implementing reversibility right from the design stage to ensure that it becomes an inherent property of the design (Fernández, 2012). Conventionally, most building projects follow a brief focusing on one defined use case. It aligns the different life cycle phases of the building in a linear fashion, resulting in buildings that can only be demolished at the end of their service life. Instead, architects could focus on a cyclic model that promotes reuse or reconfiguration (Figure 2-4).

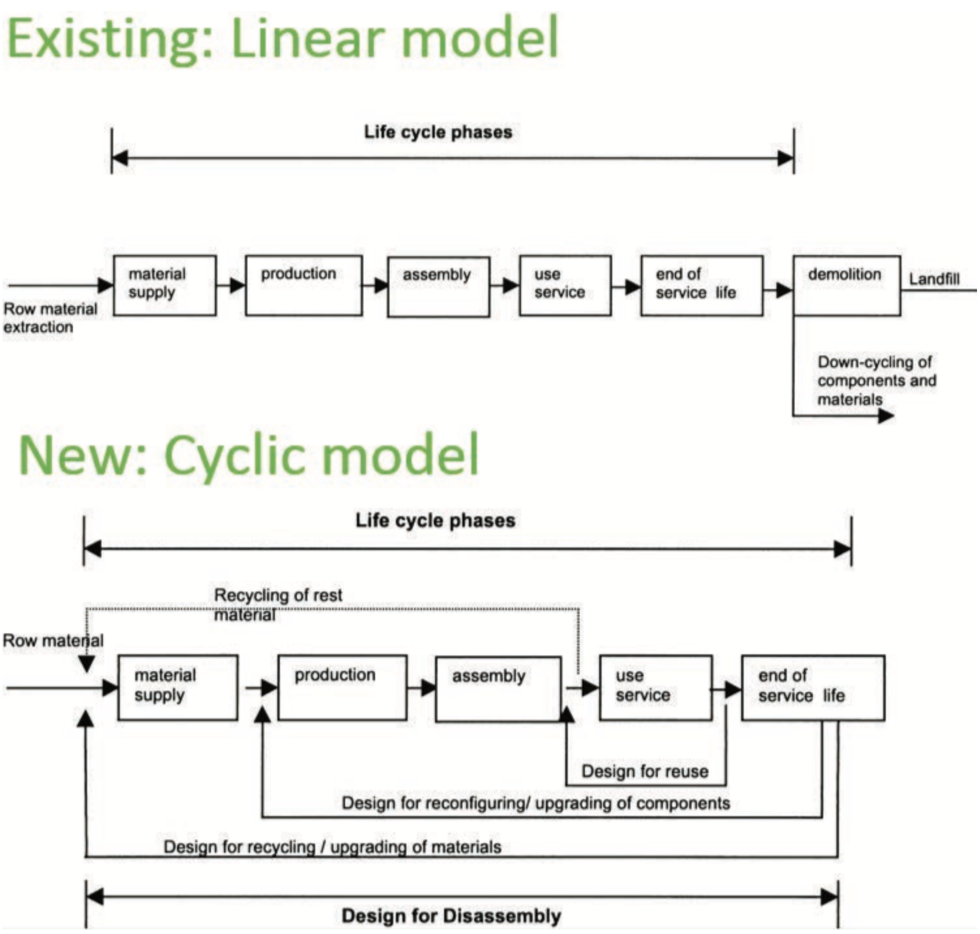


Figure 2-4 Difference life-cycle models in construction, highlighting different building approaches. The linear model is intended for one end of life scenario (top). The circular model focuses on design for multiple life and reuse options (Durmisevic 2006).

However, a cyclic model in architectural production can only be accomplished with systematic changes. These changes have to happen along different stages of architectural production. Debacker et al. (2017) named four fields to achieve such a model: change in design culture, intense collaboration within the entire value network, business creation through product service, and centralized management of building and material information. They summarized the required systemic changes in the design culture as follows.

- Design buildings to support future change and possible disassembly, instead of (merely) designing them to be constructed and create the illusion they will last forever

- Design open building systems – with the intention to exchange building components – instead of designing buildings as such
- Educate building and product designers through life-long learning in designing for the future

Based on these points, new reversible design protocols for buildings have to be implemented. Design for Disassembly (DfD) is the field interested in the reversibility and disassembly of buildings. One of the main challenges when it comes to Design for Disassembly is the role of design knowledge for such reversible buildings. The five key principles to embed DfD are listed below (Rios et al., 2015).

- Design the accessible connections and jointing methods to ease dismantling (e.g., minimizing chemical and welding connections and using bolted, screwed, and nailed connections, using a prefabricated and/or modular structure)
- Separate non-recyclable, non-reusable, and non-disposal items, such as mechanical, electrical, and plumbing (MEP) systems
- Proper documentation of materials and methods for deconstruction
- Design simple structures and forms that allow for standardized components and dimensions
- Design that reflects labor practices, productivity, and safety.

Interestingly, the benefits from automation and digitalization are only briefly mentioned in the field of Design for Disassembly (Kissi et al., 2019). Although the planning and execution of disassembly could highly benefit from such technologies, there is a lack of technical knowledge and supporting tools (Kanters, 2018). It could include digital passports for our buildings, building elements, and materials linked to a planning tool in the sense of BIM, not only intended for one-off designs but rather treating our built environment as in flux.

2.1.1. The Hierarchy in Building Systems

Many different hierarchy classifications in building systems exist (e.g., Asbjørn, 2009; El. Durmisevic, 2006, p. 143). To attain a consensus for this dissertation, the following definitions are used as illustrated in Figure 2-5. The top level of a building is the ultimate form or building level. The building can be split into its distinct parts by a geometrical system; a house can be partialized into its different rooms and areas. The sleeping room and the living room are parts of the house. The different parts can be broken down into functional components, like walls, beams, doors, etc. These components consist of elements such as bricks, wooden rots, metal sheets etc. Elements cannot be disassembled into smaller entities and can only be degenerated into their material composites. Concrete walls, on the other hand, commonly consist of cement and steel reinforcement; hence they can only be degenerated into the materials, especially when fibers are used as reinforcement. The same is true for a steel IP-beam. In contrast, a truss, as a building component, can be degenerated into the members it is composed of, like joints, chords, struts etc.

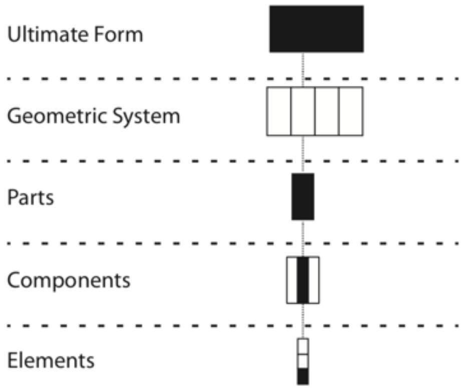


Figure 2-5: Interdependence between building modeling systems and constituents' elements; redrawn based on: (Baharlou, 2017, p. 13)

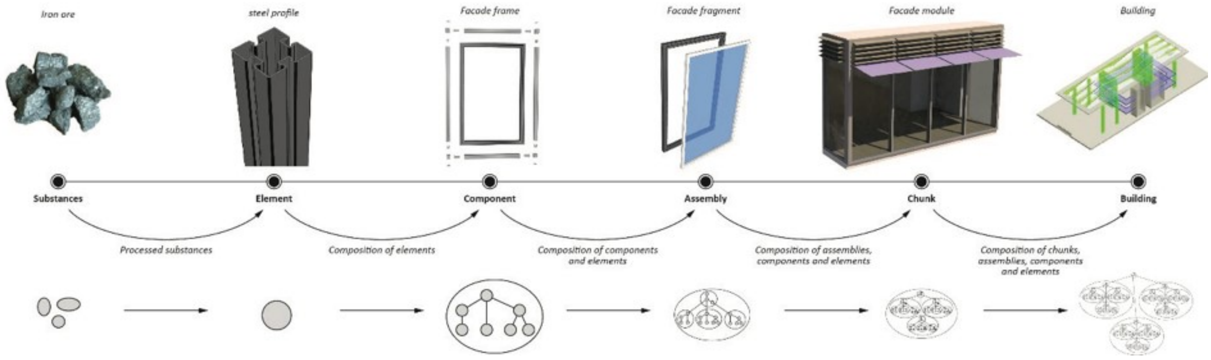


Figure 2-6 Architectural levels in a building system (Elma Durmisevic, 2019, p. 59)

Reversibility can be implemented into the various assembly levels of a building. A building is made of various chunks, assemblies, components, elements, and materials (Figure 2-6). Although approaches to reversibility are not limited to one level, it becomes clear that the composition of a building is rather complex related to dependencies between the different levels. Nevertheless, a systematic approach towards this hierarchy and these dependencies can foster the reassembly of buildings.

One approach to systematize a building is the idea of modules. The concept of modularity was established in modern architecture (Russell, 2012). It did not only serve as a unit of measure but also an organizational system with the attempt to transform construction through the use of prefabrication and on-site assembly.

> "Modularity describes specific relationships between a whole system and its particular components. A modular system consists of smaller parts (modules) that fit together within a predefined system architecture. Modules feature standardized interfaces, which facilitate their integration with the overarching system architecture. A key feature of each module is that it should encapsulate (or "black-box") its messy internal details, thus masking technical, organizational, cultural, and political conflicts to display only a consistent interface. The designers of modular systems are therefore able to swap modules in a "plug-and play" manner, which increases the system's

flexibility. Modularity, in a general sense, is therefore a means for confronting and managing complexity in a dynamic and systemic context.” (Russell, 2012)

There are many different definitions of modular in the field of architecture (Knaack et al., 2012). Modularization can be regarded as the process of subdividing a system into units (Figure 2-7). The selection of a design or construction system determines the exact implementation of the individual units. It defines the degree of adjustment necessary to fit units into the system. It can be a top-down procedure in which a given geometrical system exists which is then subdivided, or a bottom-up approach in which a set of units is composed to generate an ultimate form. Often, the term is used in regard to repetitive building units.

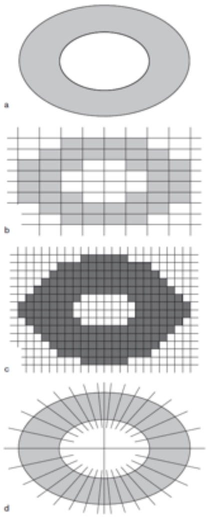


Figure 2-7 Principles of design and construction systems. Individual requirements (a), coarse grid of units in a building system broken down into parts (b), finer grid of a unit subdivided into components ((c), and individually adjusted units (d) (Knaack et al., 2012).

However, principles of modularity and regularity are often confused in literature through the notion of reuse. Lipson (2007) proposed quantitative definitions for the concepts of modularity, regularity, and hierarchy that are independent.

> “For example, opening the hood of an (old) car reveals a system composed of a single engine, a single carburettor, and a single transmission. Each of these units appears only once (i.e., is not reused anywhere else in the system), but can be considered a module because its function is localized. Its evolutionary advantage is that it can be adapted more independently, with less impact of the adaptation on the context. A carburettor may be swapped for a newer technology, without affecting the rest of the engine system. We thus have have modularity without regularity. “(Lipson, 2007).

Similarly, a jigsaw puzzle can be considered to consist of modules without any regularity, while LEGO blocks have a higher degree of modularity and regularity (Figure 2-8). Thus, modularity relates more to the openness of a system than regularity does.

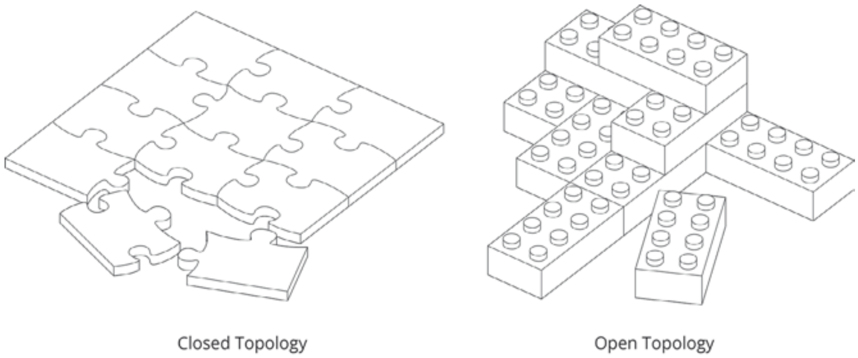
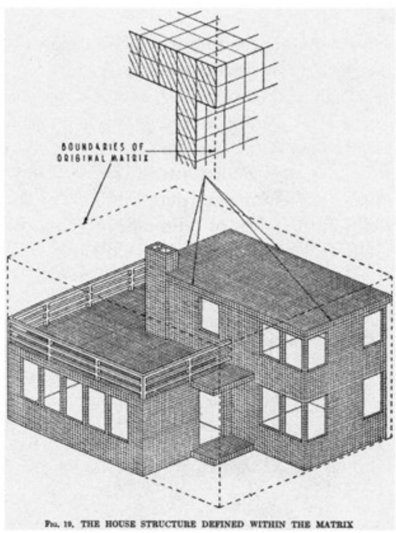


Figure 2-8 Holistic set (jigsaw puzzle) vs non-holistic set (LEGO) (Sanchez, 2019)

Architects have been striving to find universal modules for almost 100 years. One of the earliest examples for such a universal unit on a conceptual level was the four-inch cubical module by Bemis (Figure 2-9). A three-dimensional matrix is filled with cubes, generating the volumetric mass of a house. The organizational grid of four inches would guarantee sufficient flexibility while minimizing the number of different module types. It was an approach to transform the housing industry, starting at the design stages. His approach was more abstract, focusing on fundamental changes in architectural production. It was an attempt at an organizational shift that goes beyond the narrow fixation of prefabrication (Russell, 2012).



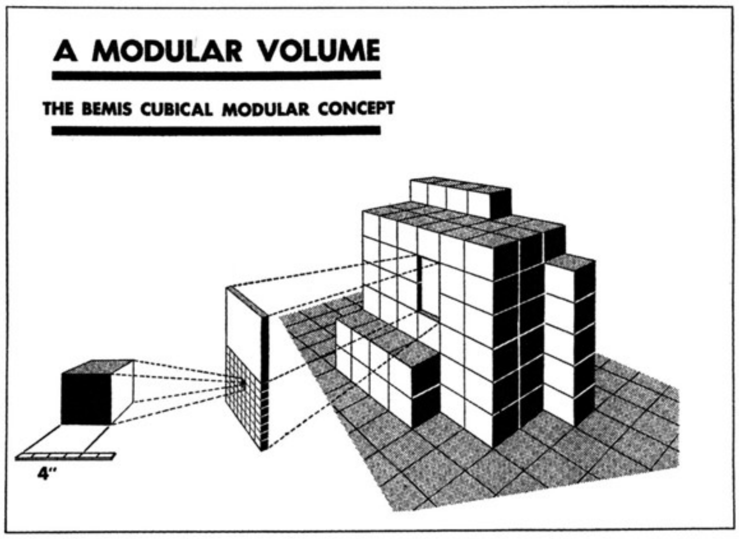


Figure 2-9 Four-inch cubical modules as a basis of structural design, in Albert Farwell Bemis, The Evolving House: Volume III: Rational Design (Bemis, 1936, pp. 66–91)

Figure 2-10 The Bemis cubical modular concept, from "A Modular Volume: The Bemis Cubical Modular Concept (US Housing and Home Finance Agency, 1953)

Nevertheless, prefabrication is an interesting approach for creating ephemeral architecture because it allows for a swift construction process on site. Prefabricated elements, often modular in design, are assembled in a controlled environment with great precision and planning. Actual time spent on site is minimized and simplified, creating a smooth transition process from one stage to another during construction (Knaack et al., 2012). The processes enabling the fast construction can be enhanced with parameters like reversibility and disassembly (Heisel et al., 2019).

Therefore, it is crucial to consider the hierarchical levels on which reassembly could be implemented in a building. This requires an understanding of the composition of the building from its overall spatial system, its constituent parts, components, and elements. The following sections illuminate approaches to disassembly and reassembly on the different levels of the building hierarchy. Architectural history offers precedents for the disassembly and reuse. It is worth putting these in context to understand the development of approaches of reversibility of the last century. The examples are organized in subsections following the hierarchical lineage from building parts down to the scale of elements.

2.1.2. Building Parts

Building parts can be considered the first level of the subdivision of a building. Based on the previous sections, parts here are understood as entire rooms or passageways. Buildings made from containers, used to quickly erect a structure, can be considered to be part-based. Container buildings like Shigeru Bans Onagawa's temporary housing container serve to help during spatial shortcomings following catastrophes (Hikone & Tokubuchi, 2014). While the shipping container is one of the most dominant examples of part-based building, another can be found in pre-fabricated capsules. Most temporary buildings made from containers and capsules were only build up once and never reassembled.

Nevertheless, a few studies and built examples exist for the reassembly of entire building parts. Interestingly most of these projects can be found in the 1960s and 1970s, which might be related to a new kind of science that started to emerge: cybernetics. The term first appeared in a book written by Norbert Wiener (1948) and laid the theoretical foundation for analog computing, artificial intelligence, neuroscience, and reliable communications (Clark & Ashby, 1965). Cybernetics can be conceived as the science replacing simple cause and effect relationship in many sciences with ideas of feedback loops and self-regulating mechanisms (Tessmann, 2008). Architects found themselves confronted with new possibilities of technical systems, procedures, and processes in an advanced technoscientific world (Vrachliotis, 2012). And although the reassembly on the building part level is a logistically difficult task, giant gantries and cranes were envisioned to reproduce some of the effects of feedback loops into construction.

Some of the most prominent examples can be found in the work of Cedric Price and Archigram (Hardingham, 2016). One of these examples and role models for architecture that is flexible and can transform constantly is the Fun Palace. The design by Cedric Price was highly influenced by the ideas of cybernetics. Price was highly interested in translating these ideas into spatial organizations. Together with Gordon Pask, one of the key figures in early cybernetics, Price developed the project as an architectural system designed to be programmed (Vrachliotis, 2012). Figure 2-11 shows the cybernetic diagram by Pask next to a drawing of the Fun Place by Price. The similarities between the two are no coincidence, as Prices was very interested in the organizational qualities of the Fun Palace (Hardingham, 2016). Dotted lines indicate flowing information, which Price translated into movable cranes in the plan. The boxes filled with text describing functions were inscribed into the plan as rectangles that could be filled with furniture, indicating the programmatic assignment. The denied feedback loops in Pask's diagram would result in a constantly evolving structure. Cranes and movable platforms would make the project an ephemeral happening rather than a fixed building.

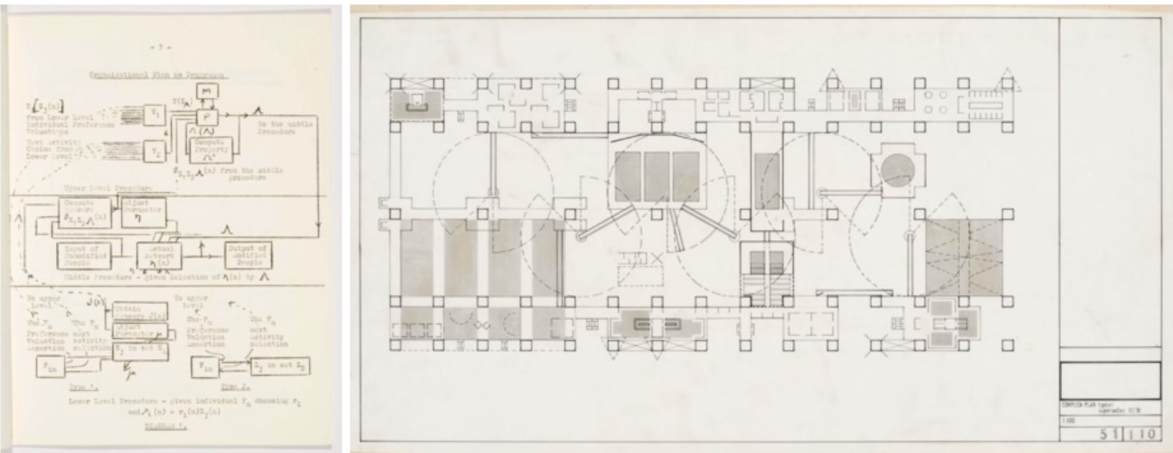


Figure 2-11 "Organizational Plan as Programme", from the minutes of the Fun Palace cybernetics committee meeting, 27th January 1965 by Cedric Price (Hardingham, 2016).

Moreover, the ephemeral qualities of the Fun Palace are also reflected in Price's considerations for its lifespan as a building. He wanted the building to be torn down after five years; later, he would have agreed to ten years. The demolition of the building might have been a spectacle as simulated in a model for the project (Figure 2-12). Only few architects consider the end-of-life time of their buildings. Prize, however, understood himself as an anti-architect and the Fun Palace as an anti-building (Wigley, 2017). This might point to the idea of buildings to be conceived as something that does not come with a limited lifespan or that the end of life falls into another domain, not the architect's.

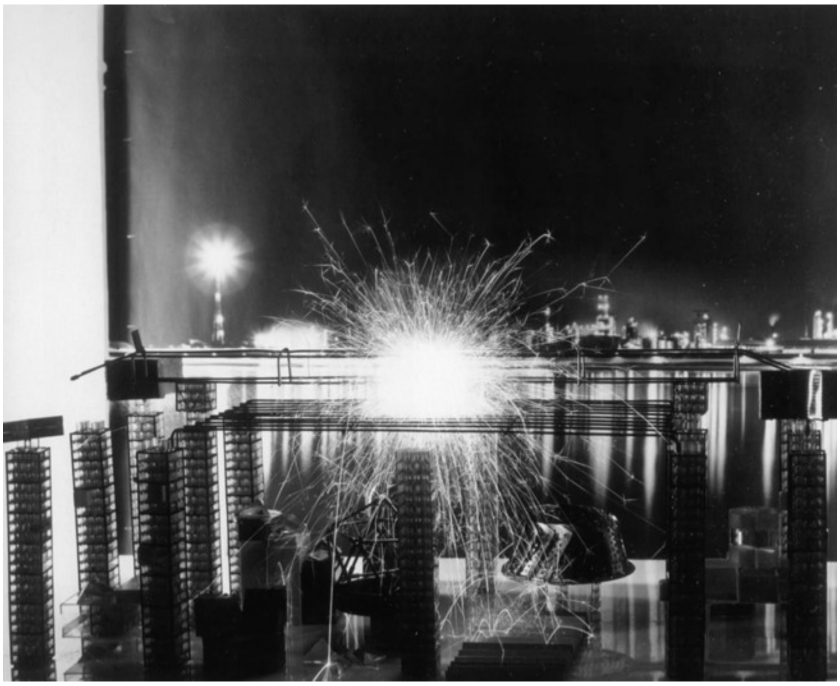


Figure 2-12 The Fun Palace model with an explosion simulating the later loud destruction of the building. Photo: Cedric Price fonds (*Cedric Price Fonds*, n.d.)

However, attempts also existed to embed ideas of reconfiguration of buildings. The Plugin City by Archigram is such an example. The design consists of a scaffolding in which containers were to grow by themselves; by means of mobile cranes, the construction would constantly be in motion. It was based on prefabricated dwellings – capsules – that could vary in size and were to be customized by the occupants. The design was an attempt to show that prefabrication does not have to be boring. By exchanging capsules over time, the overall complex would be sprinkled with varying capsule designs (Cook & Crompton, 2020). Beyond these ideas, the Plugin City is a speculation of the flow of goods and logistics with a futuristic city, reassembled in their drawing with heavy-duty railways, shop supply tubes, and local feeder roads (Figure 2-13).

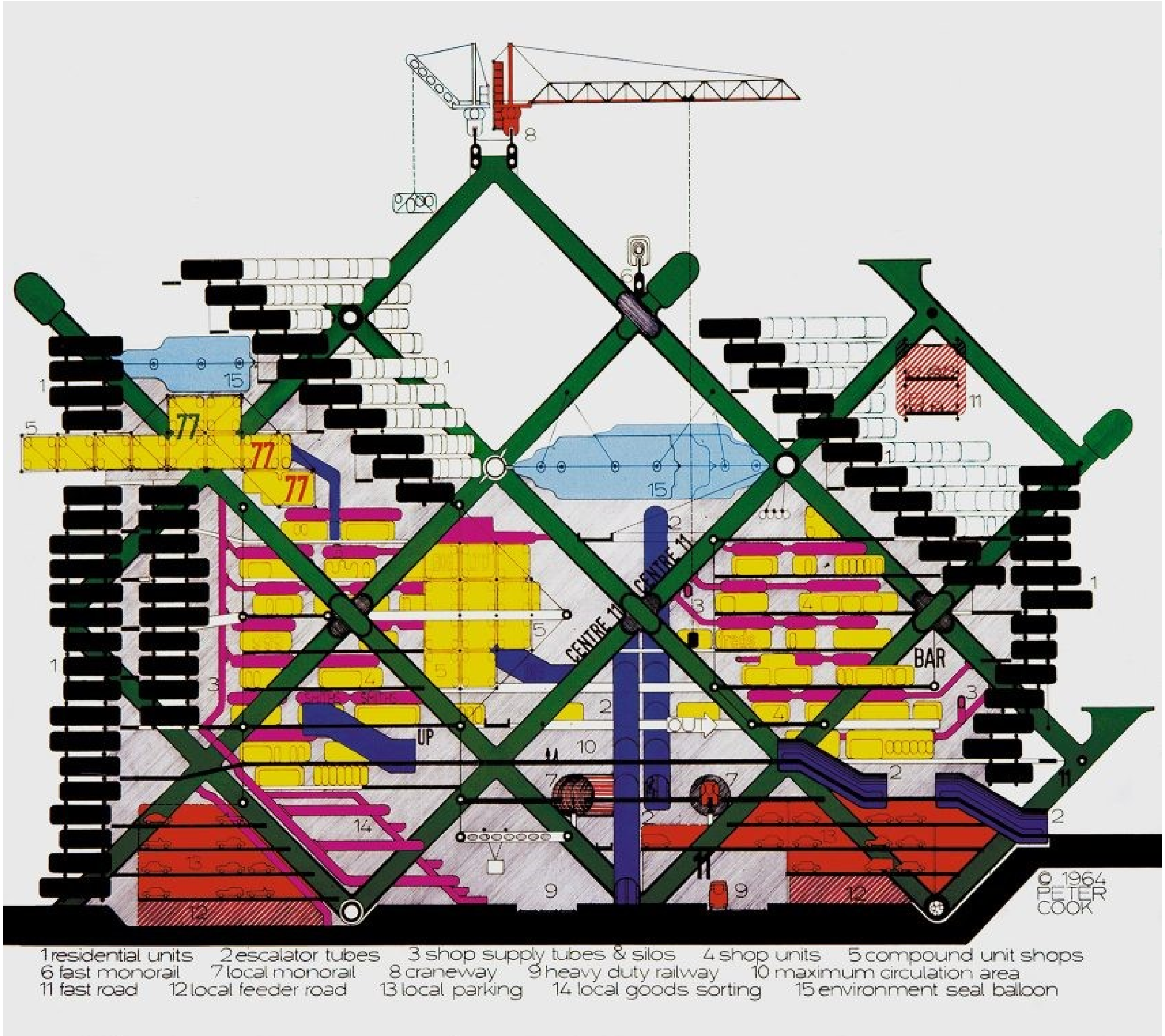


Figure 2-13 Typical section of the Plug-In City by Warren Chalk, Peter Cook, and Dennis Crompton, 1964 (Sadler, 2005)

Archigram were not the only architects working on ideas of reconfigurable buildings. In a competition entry for the University Bremen, Lyubo-Mir Szabo, Wolfgang Rathke, and Heinz Behrendt proposed a gigantic gantry as part of the university complex (Figure 2-14). Inspired by ideas of cybernetics, the campus building would be in constant flux depending on class demands (Hnilica, 2014).

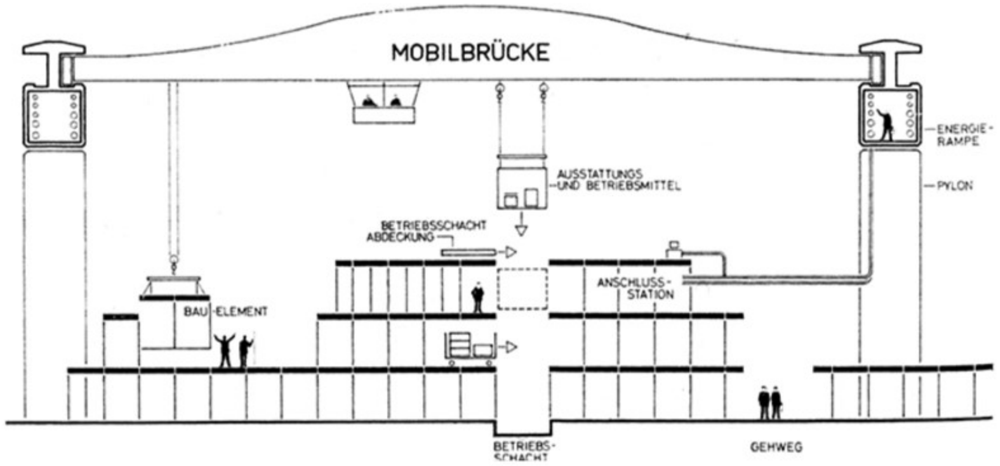


Figure 2-14 Competition entry for the University Bremen by Lyubo-Mir Szabo, Wolfgang Rathke, and Heinz Behrendt ("Ergebnis Des Ideenwettbewerbs Universität Bremen," 1967).

However, the competition was not won, and the design remained in its conceptual phase. Most likely due to similar scepticisms that caused the Fun Palace to be withheld as the following quote points to.

> "The technical complexity of the projects like Fun Palace or Potteries Thinkbelt seemed too far-fetched to a public and a government unfamiliar with computers and advanced technology." (Mathews, 2006)

One of the few build projects that would have had some of the qualities described in these projects was the Nakagin Capsule Tower from 1972 by Kisho Kurokawa & Associates. It was designed with replaceable prefabricated capsules for living. The recyclable and moveable pods were inspired by the developments of space shuttles as enclosed environments (GARDNER, 2020). The replacement of the capsules could have been done in less than four months per tower, according to the architect. While technically possible, there were problems of ownership, as each capsule was owned by its resident, and with inheritance, the ownership would get even more complicated. The idea of replacing the capsules every 25 years was never pursued (Kurokawa, 2007). The replacement of the capsules would have been prohibitively expensive, and because of the lack of maintenance, the building is facing its lifecycle end. Today, the priority has been given to developing its site, which is considered prime real estate within the city of Tokyo (Ouroussoff, 2009).

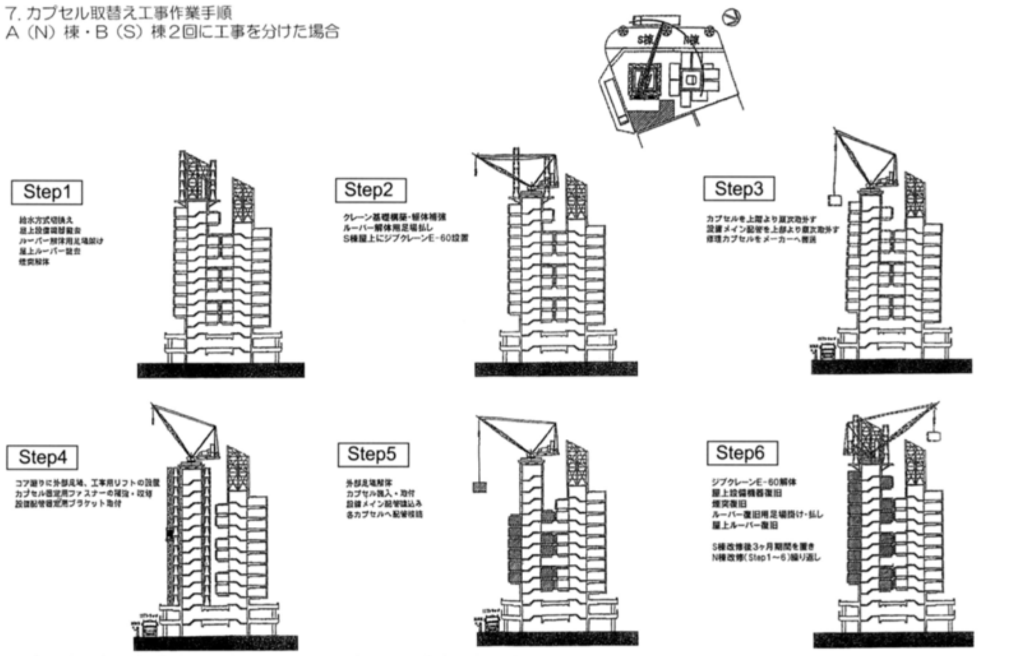


Figure 2-15 The planned procedure for capsule replacement: 1 demolish rooftop equipment, demolish stack; 2 assemble crane foundation and support, set crane on tower roof; 3 remove capsules from central services in order of precedence; 4 assemble scaffolding around core, renew fasteners for capsules; 5 disassemble scaffolding, install new capsules and connect to central services; 6 disassemble crane, rebuild rooftop equipment (drawing by Kisho Kurokawa Architect & Associates).

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Building flexibility during occupation can enable the adaptation of necessary changes. One example of the vertical expansion of a building was implemented in a tower in Chicago. The 33-story first phase was completed in 1997, and ten years later, 24 stories were added on top. The building stayed in full use during the extension (Japsen, 2006). The approach of extending the city vertically has been further conceptualized utilizing construction automation and robotics (Hu et al., 2018). Again, gigantic gantry cranes became inherent parts of these buildings to enable dynamic changes or extensions (Figure 2-16). Following the open building concepts, the entire site becomes an on-site assembly environment.

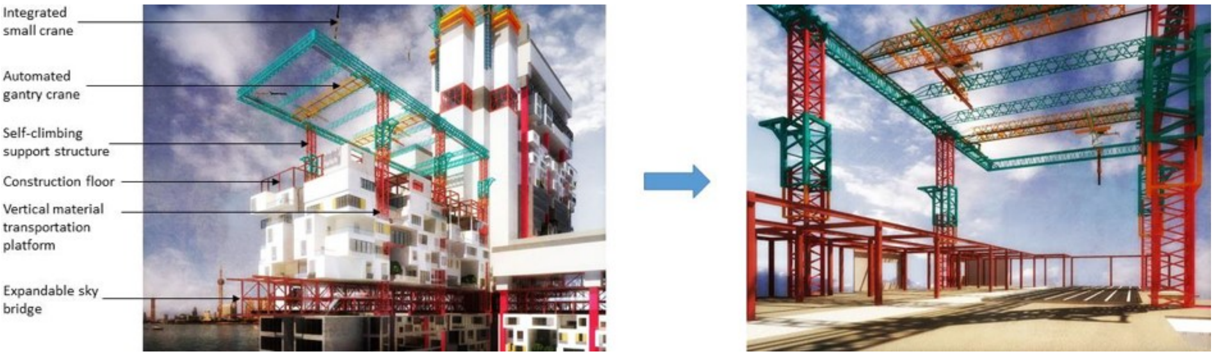


Figure 2-16 The on-site construction factory consisting of a self-climbing crane and special crane application for the vertical city expansion (Hu et al., 2018)

However, prefabricated pods today are still assembled with cranes and human workers. Automation and advanced technologies have not been implemented on-site for assembly tasks. Even in technologically advanced projects like The NEST, the construction follows traditional procedures (Richner et al., 2017). This makes the assembly a labor-intensive task, as Figure 2-17 shows. Seven people have to work on-site to place the pre-fabricated pods at their defined position.

Figure 2-17 Stills from the video ‘The NEST unit „Urban Mining & Recycling” is taking shape. The color overlay highlights human workers during the assembly (*The NEST Unit „Urban Mining & Recycling” Is Taking Shape*, 2017).

Attempts to reassemble buildings parts can be found in the history of architecture both as concepts and as built projects predominantly during the 1960s and 1970s. These modular buildings were designed to offer the possibility to change parts of the overall building structures. Here building parts were designed as capsules or containers separated from the structural frame. The functorial units enabled buildings as an open system. As we have seen on the conceptual level, these buildings incorporated machinery like cranes or portals. However, most of the concepts with an integrated machine were never realized. The closest project to the integration is the Nakagin Capsule Tower which used the circulation cores as the base for cranes. And although most of these architects were familiar with the development of technologies that could foster such projects, they remained on a conceptual level due to technical and financial challenges.

2.1.3. Building Components

Building components are the next smaller level in the hierarchy in the building system. They are charged with functionalities like load-bearing in columns or spanning in beams. Components are often referred to as architectural elements, though elements are defined as entities that cannot be further subdivided, which components can. A beam can be subdivided into its members and a column into capital, shaft, and plinth. Components come with designated functions.

One first example of a prefabricated building that was reassembled was the Crystal Palace in London. For Konrad Wachsmann (1961, p. 14), one of the leading figures in modular building systems at the time, the Crystal Palace was the visual becoming of the Turning Point of Building due to its approach to prefabrication. Designed for the Great Exhibition of 1851 in London, it was assembled from iron cast columns and large glass panels. The glass panels were made from panes, the largest available at the time measuring 25 cm wide by 120 cm long, which determined the overall units for the modular construction. First built in London's Hyde Park, it was disassembled after the six months exhibition. After that, it was redesigned to be relocated in1854 to Sydenham Hill Park, 15 km away. The new building incorporated most of the construction parts of the Hyde Park building (Figure 2-18). This relocation included most of the 1,000 iron columns comprising 4,000 tons of iron (Wikipedia, 2021). Although the distance between the two locations was relatively small, the weight of the iron columns and the fragile glass panes made it a logistically challenging endeavor. The Crystal Palace was a strictly rasterized and modularized building. Its serialized and typified building kit allowed it to become one of the first buildings as a possible open system, highly expandable (T. Peters, 1996).

Figure 2-18 Reassembly of the Crystal Palace in Sydenham Hill Park in 1854, photo by Philip Henry Delamotte.

The industrialization of construction increased efforts to rationalize architecture and building processes. Especially during Modernism, the degree to which industrial principles such as rationalization, systematization, standardization, prefabrication, and serial production processes were integrated into architectural production increased drastically (Seelow, 2018). During the 1930s, Walter Gropius put a lot of effort into transferring these principles into the production of prefabricated houses. The houses he designed and engineered for Hirsch Kupfer- und Messingwerke HKM were assembled from prefabricated copper-clad wall components (Figure 2-19). Gropius developed novel fabrication techniques that would allow stacking of the panels and making them lighter. The weight reduction and his efforts in improving the logistics allowed these houses to be assembled with high efficiency and in a shorter time compared to conventional houses (von Borries & Fischer, 2009, p. 107).

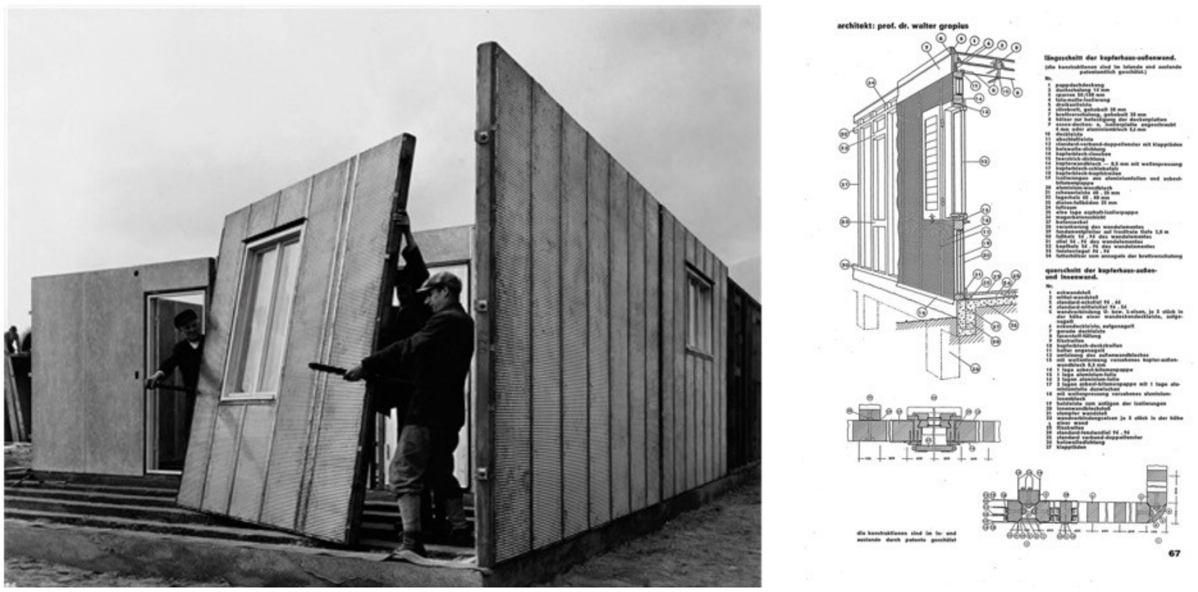


Figure 2-19 Assembly process and façade construction detail of the Förster-Krafft-System House exhibited at 'The Growing House' exhibition in Berlin (1931–1932) (Wagner et al., 2015)

Besides Gropius' obsession with the industrial and serial fabricated house, the notion of the building kit drew more and more of his attention. The idea behind the building kit was the flexible assembly and configuration of elements into an individual whole. The dwelling was supposed to become an industrially manufactured product, which would be assembled from a highly flexible construction kit of components - the "individual house off the shelf" (Gropius, 1927).

Flexible housing was coupled with a simple design system and a simple cost calculation for potential homeowners. The building system for the company Christoph & Unmack was based on wall components and defined the possible design system as a grid of 1.05 m. Besides the simplicity of the design tool, the advertisements also stressed that these houses could be changed or extended (Figure 2-20).

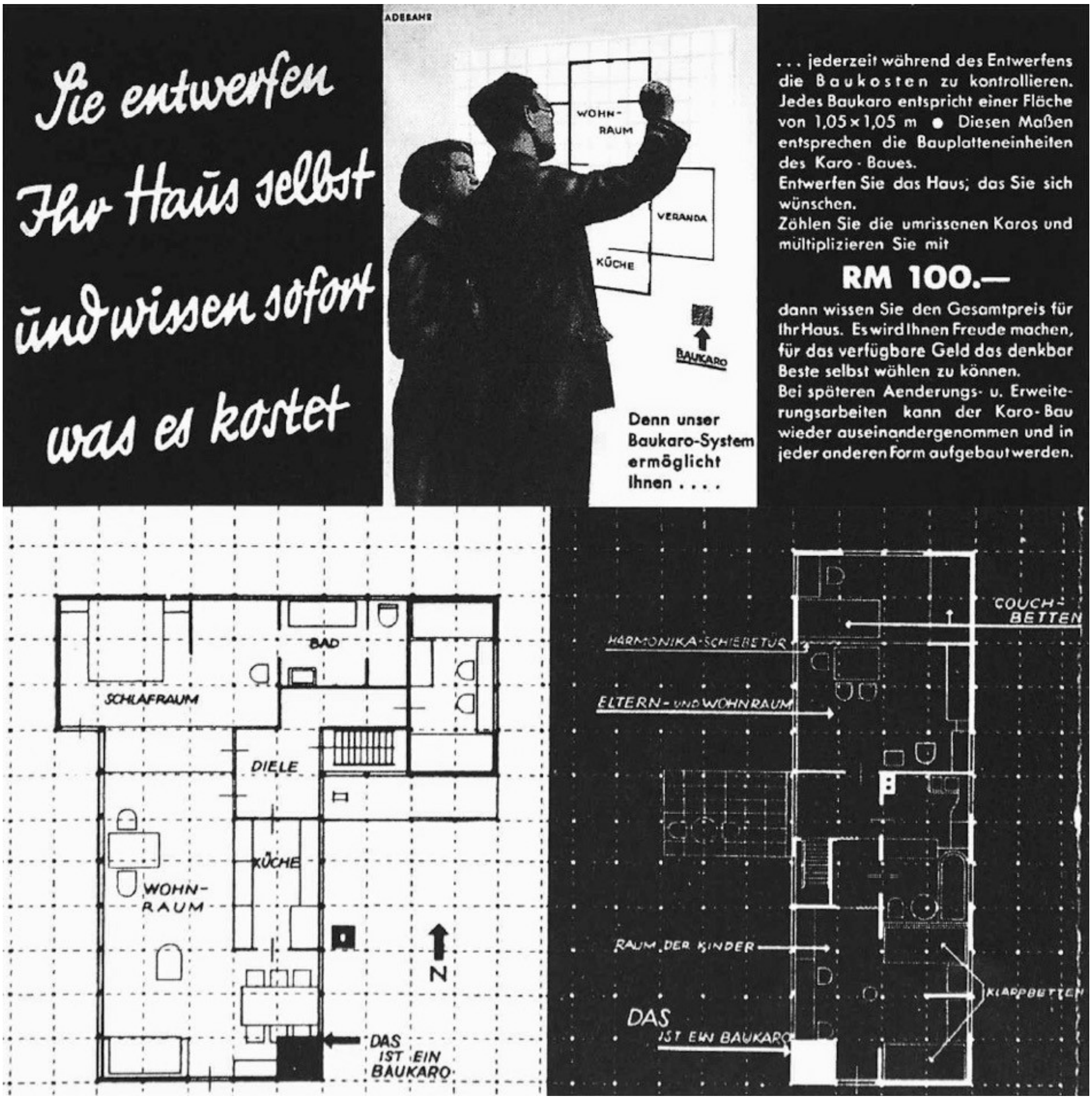


Figure 2-20 Hans Scharoun's «Liegnitzhaus» Gartenbau-Ausstellung 1927 Christoph & Unmack

A similar approach to a building made from industrial prefabricated parts is the Maison Tropicale by Jean Prouvé from 1954. It is a modular building entirely made from prefabricated components that can easily be dismantled and reassembled elsewhere (Figure 2-21). The kit consists of a frame structure of transverse and longitudinal braces holding the panels for floor, wall, and ceiling cladding. All structural elements were mainly made of steel or aluminum. The floor area of the hall-like space could be divided as needed. A gallery wraps around the entire house. The Maison Tropicale could be packed into standard shipping containers and transported by truck, train, ship, and airplane. It fits into six containers, and it took only four men about seven to ten days to assemble and disassemble it.

Figure 2-21 Maison Tropicale, Jean Prouvé, was first built in Congo around 1954, dismantled some 50 years later, and reassembled in New York (D.J. Huppatz, 2007).

Prefabricated housing systems were implemented in the US as early as 1940. An extensive study that surveyed house construction companies dealing with prefabricated components showed that the focus of the construction system was mostly put on building fast and affordable houses. Although their modular systems with demountable joints would benefit adapting houses in the future, only 22 out of 52 companies would emphasize this possibility. And only very few mentioned the capability of moving partition walls (Kelly, 1951, p. 285). Hence, the focus of most systems utilized during these times was put on the easy and fast assembly rather than adaptation or reassembly. The component-based construction system reviewed here started to occur during the ages of industrialization. They were based on an optimization towards standardization, while adaptations and changes of the houses only played a minor role (Henry R. Luce, 1947). Instead, these systems achieved answering the acute shortage of affordable housing by mechanization, industrialization, and rationalization. The idea of the flexible construction kit that would offer more potential for customization never flourished in architecture and was, if implemented at all, only limited to individual projects (Seelow, 2018).

2.1.4. Building Elements

The minor units in construction are building elements. While components can be made from elements, the latter cannot be further divided. A brick wall as a building component is made from bricks as elements. However, bricks bound with mortar form a unit that would be unsuitable for easy disassembly.

Temporary buildings made from rented materials face several challenges. The shipping container – often associated with temporary building – was used for the Nomad Museum by Shigeru Ban. The temporary building was erected for only one year and traveled to four different locations. While, in many cases, the containers are used as modular building parts that can be occupied, Ban uses them as building elements to create walls by stacking them. And although shipping containers are made for reassembly with machinery, they are impractical in many locations due to the heavy weight of the crane. Many of the used components and materials like the shipping containers and the paper tubes were cheaper to be bought new for the sites. The building was intended for disassembly and reassembly at different locations, yet the site-specific adaptation caused several problems and delays in the construction process (Zheng, 2016).

Figure 2-22 The Nomad Museum at its different locations: New York in 2005 (top left), Santa Monica in 2006 (top right), Tokyo in 2007 (bottom left), and Mexico City in 2008 (bottom right). (Zheng, 2016)

There are also buildings that were reassembled, although they were never designed with this intent. In 1971, the London Bridge was reassembled and opened for crossing in Lake Havasu, Arizona, USA. After 136 years of spanning the Thames in London, the bridge's entire structure was purchased in 1968. The dry-fitted granite stones were carefully dismantled, numbered, and packed to be shipped to Arizona (Elborough, 2013). The 33,000-ton stone bridge was reassembled with a hollow core of steel-reinforced concrete in three years. While this was an impressive endeavor and marketing move to put Lake Havasu City onto the map, it is also absurd when it comes to the mass that was moved in this case. However, it also represents the symbolic charging a building can transport, in this case, the shift of power from the old British Empire to the United States of America.

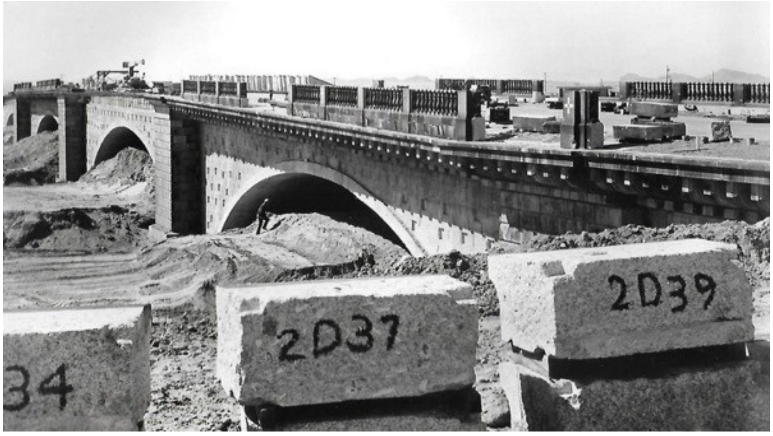


Figure 2-23 The reassembly of the London Bridge in Lake Havasu City (Elborough, 2013)

One early example of an element-based building system was the Metacity Wulfen. The experimental project was designed from prefabricated elements to provide flexible housing. The overall complex consisted of stacked housing units to create extra spaces for balconies. The system was designed in such a way that all elements and components could be exchanged or replaced. To ensure a high degree of variability in use, the finishing system was separated from the structural system. Movable partition walls, changeable facades, and the ability to retrofit sanitary and electrical installations employing detachable floor slabs above the hollow core ceiling (Prochiner, 2006, p. 133). The dotted facade of the complex highlights how all connections between facade elements were integrated (Figure 2-24). Even though an early example for such systemic and flexible approaches, it posed many problems regarding insulation. Problems with the building physics of the construction and connection details in the facade and a lack of knowledge of how to exchange building elements rendered it uneconomical to maintain the building. Although the demonstration building for this new construction method could easily be demounted into the components, it was utterly demolished only 13 years after it was finished. Even though just fixated by screws and bolts, all building elements became demolition waste.

Figure 2-24 The Metacity Wulfen (Germany, 1975)

Figure 2-25 The Metacity Wulfen built in 1974 and demolished in 1987. Photos: Wolfgang Krüger

More recent examples of a construction system based on elements can be found in Japan. SUS developed the ecology and economy modular system Ecoms, an industrial lightweight system made from aluminum elements. The modular panels can be assembled into walls and are easily disassembled. The Ecoms House by Riken Yamamoto & Field Shop was constructed as a prototype in Tosu-City, Japan, in 2006. The modules are designed to be interchanged or completely disassembled. However, their assembly still relies on manual labor, and their connection is based on bolts and screws.

Figure 2-26 Ecoms system by SUS from Japan (*Ecoms | SUS Corporation*, n.d.), photo: © Shinkenchiku-sha

The presented physical building elements have the embedded possibility to be disassembled and reconfigured. However, in most cases, not only the disassembly seems to be a burden but also the creation of new designs. While there have been attempts to simplify the design process, the connection between building elements and a design tool have not yet been put to focus.

2.1.5. Computational Building Systems

In the last decades, computational design tools enriched the design reportion and enabled explorations of possible variations (Nguyen et al., 2016). The computational turn in architecture gave birth to computational techniques that would quickly adapt a design to new parameters (Carpo, 2013c). The Embryological House by Greg Lynn is a role model for this kind of design system. The extra task of designing several instances of a house with varying parameters almost comes without additional effort (Figure 2-27). These early examples of computer-generated forms were generated borrowing software tools from the movie industry, such as Autodesk's Maya or 3D Studio Max. The materialization of these forms became a challenging task.

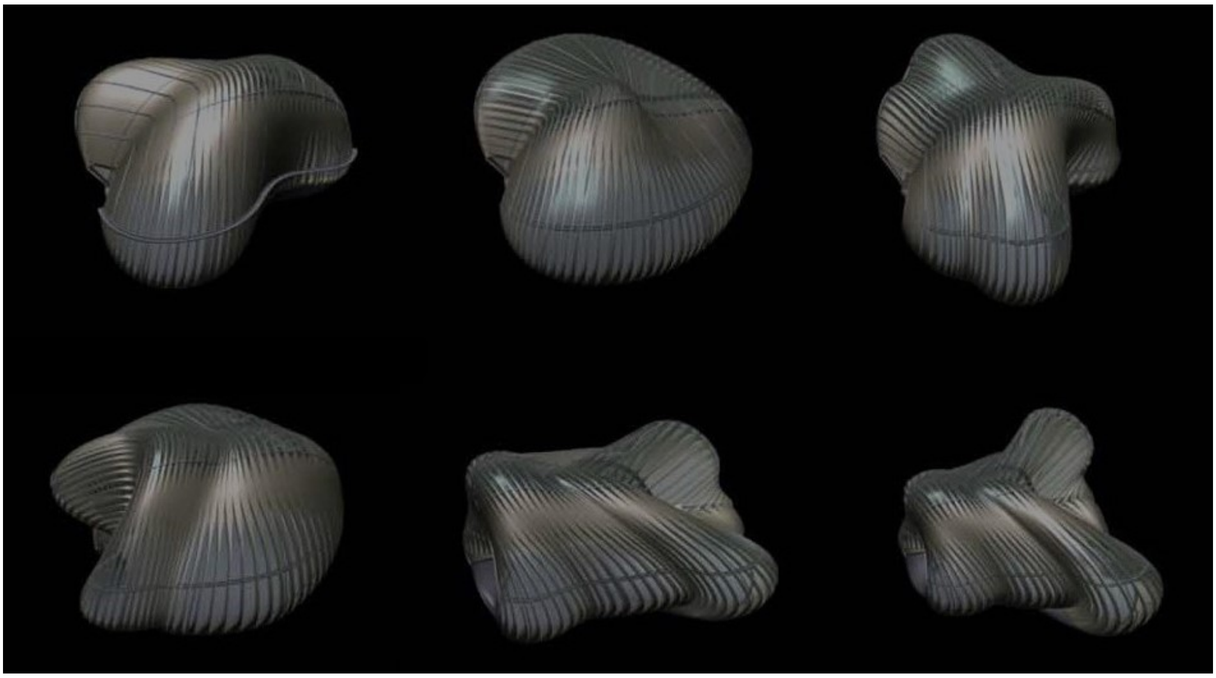


Figure 2-27 Six variations of the Embryological house from 1999 (“Greg Lynn Form,” 2008)

In the last decades, the discrete nature of architecture was only addressed as a secondary step after a complex design was generated. The Innsbruck train station by Zaha Hadid serves as an exemplar of these often continuous and curvy buildings (Figure 2-28). Researchers and software developers put considerable efforts into translating the complex, curvy geometries designed by architects like Gehry + Partners, Foster and Partners, M Fuksas D, NOX Arch, ONL, EMBT, Greg Lynn Form, and Zaha Hadid (to name just a few) into buildable elements. The Smart Geometry Initiative and the resulting Generative Component Software were all about tessellation, subdividing, and post rationalization (e.g., Martin et al., 2006; Piacentino, 2013). The fabrication techniques, in many cases, relied on computer-controlled manufacturing via CNC machines and was only implemented afterward (Ruffo Dominguez Calderon & Hirschberg, 2011). The underlying approach in many of these cases is based on a module. However, it creates many one-offs, yielding customized elements similar to the zig-zag puzzle (see Figure 2-8), where every element has only one predefined place.

Figure 2-28 The roof construction clad in glass panels (copyright Arch Photos)

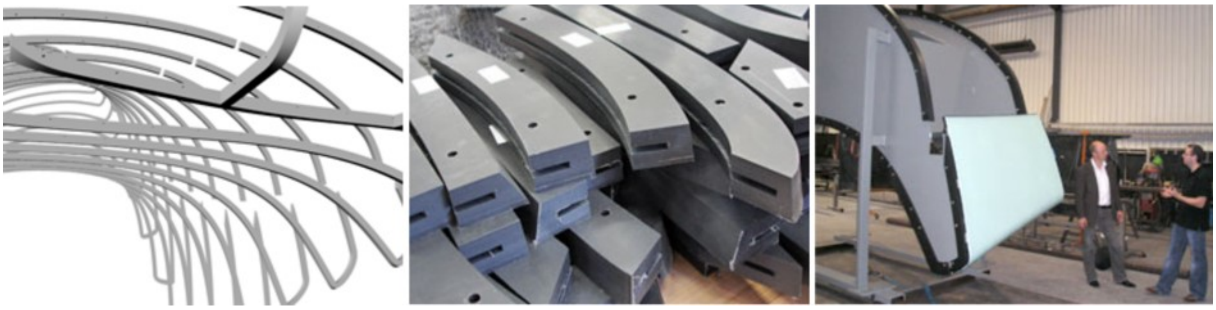


Figure 2-29 PE profiles for the roof construction of four train stations in their differentiated position in the digital model (left), the piled-up stack of profiles (middle), and a mockup of a section of profiles with one curved glass panel (right) (drawing and photos by designtoproduction)

Today, designers such as Gilles Retsin and Jose Sanchez seek ways to overcome the idea of discretization as the secondary step. They are exploring approaches in which sets of discrete elements are the starting point of their design. The combinatorics of the elements are algorithmically implemented, enabling the exploration of a vast number of possible arrangements. In architecture, this idea has been coined with various names like Discrete Design, Programmable Matter, Granular Design, and Digital Materials. These concepts foster the formalization of open-ended building systems in which serial elements can be arranged in almost infinite ways (Figure 2-30). This approach differs from the modular design approach in Modern Architecture.

> "While the modular project seeks to establish a framework for unity, the discrete paradigm seeks to establish a framework for diversity. [...] Discreteness is not a property of space as modularity is but a property of compatibility; e.g., a property of links. The construction of a discrete framework aims to reconsider parts and their relation with a totality, placing at the foreground the autonomy of units over superimposed structures such as a modular grid." (Sanchez, 2019)

Figure 2-30 Bloom is an open-ended building system made out of identical elements. Crowds can constantly rearrange and dispatch the elements into different formations (Sanchez, 2019)

Discrete projects are defined by autonomous units that can be arranged into a multiplicity of configurations (Sanchez, 2019). Contrary to predefined components, the elements can take on different functionalities (Figure 2-31). The building elements are tied with the digital logic of the computer, offering a new type of open system architecture. Through the power of computation, designing shifts from being a restricted task towards a liberation from the superposition of functionalities and grids. Beyond the design of one fixed place for an element, discrete designs offer various design solutions through a predefined set of rules integrated directly into the elements.

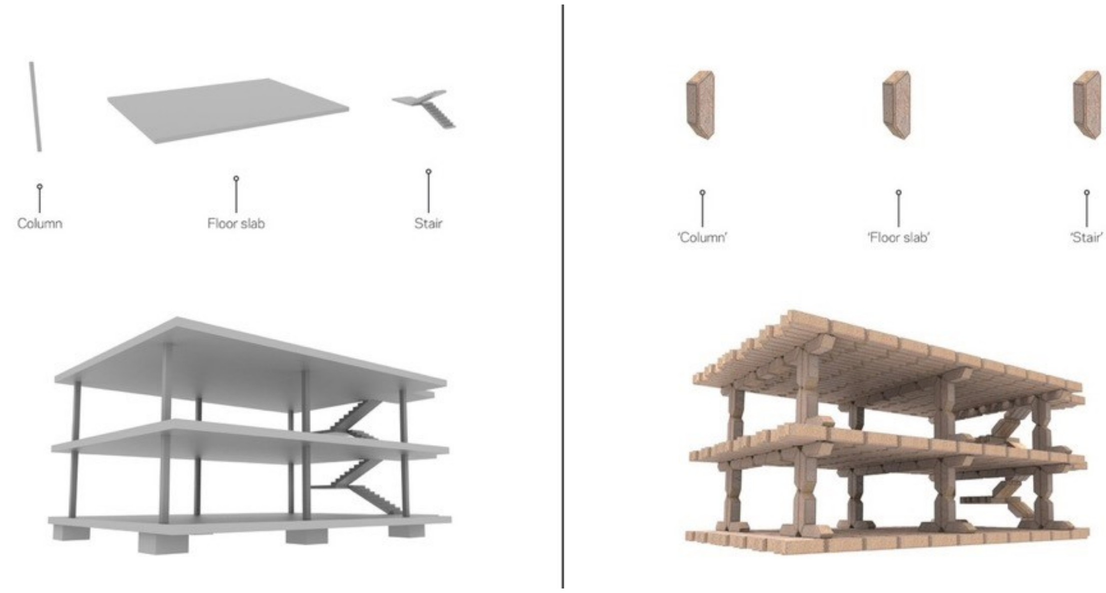


Figure 2-31 The Maison Domino with its distinct components (left) and rebuilt with discrete elements that do not have a preassigned functionality (right). Image: Ivo Tedbury, Semblr, Unit 19/DCL, 2017 (Claypool, 2019)

The element-based construction approach can offer more flexibility due to the smaller sizes of the building units. Here, elements are defined as the smallest units accessible for the design and construction process. As shown in Figure 2-32, smaller elements trace the underlying design intent, a curve, in greater detail. Bricks, for instance, have presented their flexibility in construction. However, their fixation through adhesives like mortar makes them unsuitable for future reprogramming.

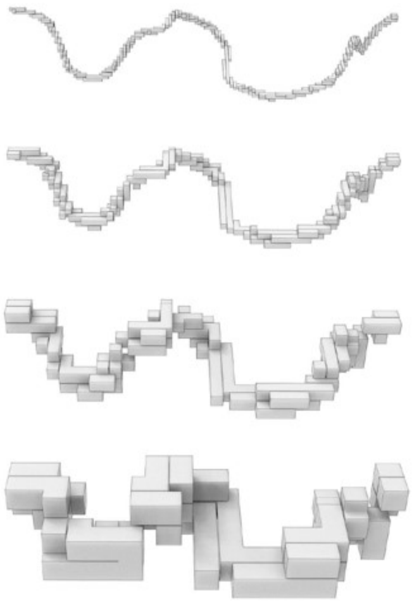


Figure 2-32 Greg Lynn's curve discretized with various cubic elements (Retsin, 2016)

The element-based approach of discrete design enables the assembly of different structures with the existing stock. One of the early examples of these approaches can be found in the Tallinn Pavilion by Gilles Retsin. The pavilion is constructed from a set of four different types of elements that are just fit enough to perform in the possible positions in an assembly, as shown in Figure 2-33. With predefined connections similar to LEGO bricks, the building elements share connection interfaces, allowing the elements to be reprogrammed into other structures.

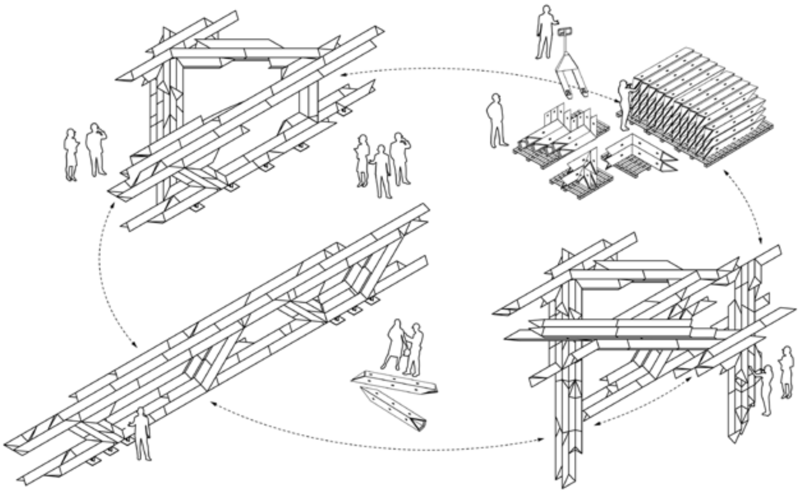


Figure 2-33 Different formations of the building elements designed for the Tallinn Pavilion (Retsin, 2019a)

Figure 2-34 Architect Gilles Retsin (left) with his team member Kevin Saey (right) manually assembling the prefabricated elements of the Tallinn Architecture Biennale Pavilion (Tedbury, 2017a)

Due to the discrete nature of the connections, the assembly logic can be combined with concepts of digital information processing. One example is the project Logic Matter that embeds computation and programmability within a physical building block (Tibbits, 2010). The material becomes a digital medium, aiding the assembly with discrete and logical connections. The whole assembly in the project Logic Matter is inscribed through a sequence of block connections, defined in a logic-driven sequence of 0's and l's. The binary system logic merges digital qualities like error correction and the reduction of redundancies. Linked with software tools to generate the assembly sequence, the stored information in the computer and the assembly truly match.

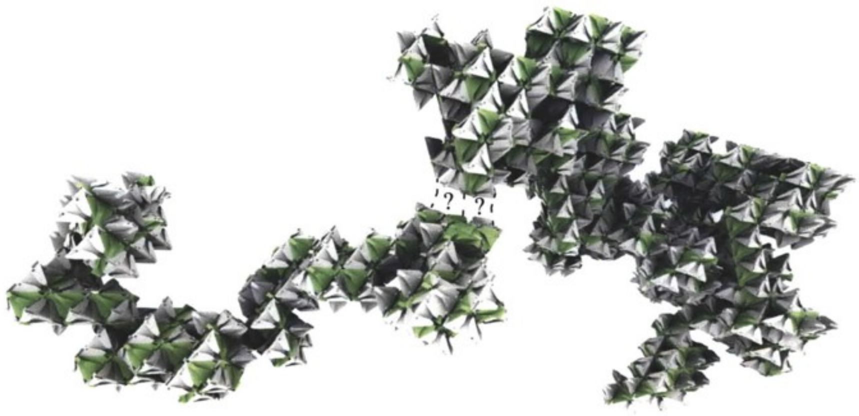


Figure 2-35 Failure and Disassembly Example. A complex structure with a single point of failure can be reassembled accurately by reading the adjacent unit's stored information (Tibbits, 2010, p. 72)

The material aggregation stores the assembly information similar to the digital model stored inside the computer, merging digital qualities into the physical and vice versa. For structures made under these premises, the actual built state and the idealized structures match. Usually, the acquisition of the as-built state of a structure requires capturing devices like 3D scanners and remodeling the data into a semantic model (Becker et al., 2019). Following the concept of Programmable Matter, this acquisition and transfer can be simplified. Making future conversions of such structures more attainable due to the digital structure.

Not all design environments commonly used by architects offer the possibility to implement such ideas. Digital design models that are capable of easily altering huge amounts of elements following defined connection rules need certain properties. One prominent tool for designing various instances in a parametric fashion are generative design tools. They offer designers to implement rules and parameters in the form of algorithms that can be modified by the designer (Figure 2-36). Those algorithms can help to improve the design process and the creation of variations (Monedero, 2000). One of the most common generative design tools in architectural design is Grasshopper, a graphical programming language for Rhino. It enables designers to set up parametric models in which numerical and geometrical relations are algorithmically inscribed. Thereby, designers are not limited to design one instance but rather define dependencies and relationships between various objects. Once such an algorithm is set up, it can generate variations within the specified constraints of the algorithm.

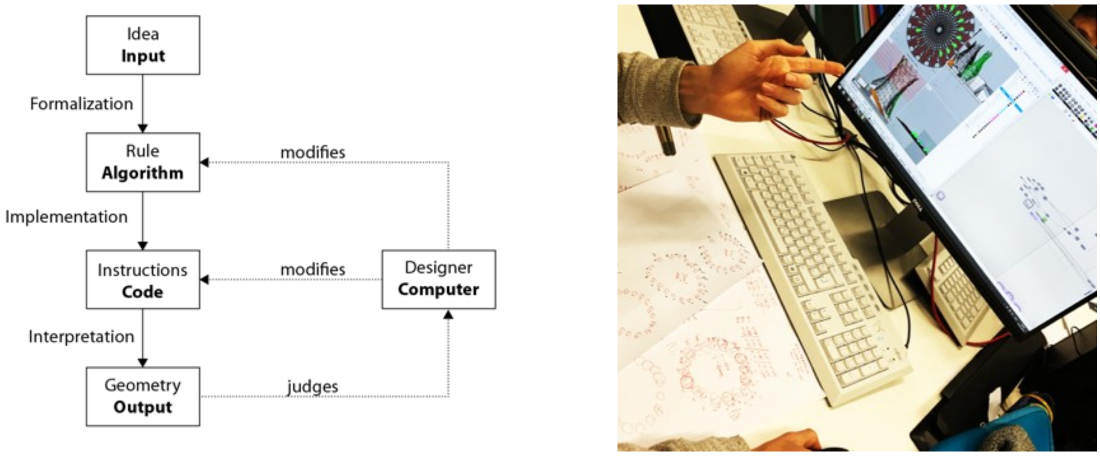


Figure 2-36 Scheme of generative design as an iterative process; redrawn based on (Groß et al., 2018)(left). A student in front of Rhino 3D and an open Grasshopper script fed with parameters from his notes (right).

The rules and parameters for a design might also change, which would call for the implementation of a new algorithm. This circumstance needs to be fulfilled by a design environment. Grasshopper can be understood as a live programming language as it allows designers to alter the algorithm while immediately seeing the changes (Victor, 2012). They are working without the burden of compiling it before seeing the results of changes inside the algorithm. Thereby, it is not only possible to change geometries with the design environment but also the rules and dependencies. The most convincing argument for this type of programming is how it accelerates the possibility of seeing the results almost instantaneously.

In recent years the element-based algorithms and tools are enjoying growing interest in architecture. Table 1 shows current algorithmic implementations of these approaches for Grasshopper. Although Rhino 3D is designated as a surface modelling tool, these plugins allow element-oriented design features. These tools can be fed with various forms and types of objects to achieve a wide variety of geometrical differentiation.

Table 1 Discrete design plugins for Rhino/Grasshopper

Logo	Name	Developer	Algorithm	Link	Publishing Date
	MONOCEROS	Ján Pernecký and Ján Tóth	Wave Function Collapse	https://www.food4rhino.com/app/monoceros https://github.com/subdgtl/Monoceros#1-authors	2021-1-31
	WASP	Andrea Rossi	Rule based aggregations proximity based	https://www.food4rhino.com/app/wasp https://github.com/ar0551/Wasp/	2020-03-06
	WASP++	Blake Hagemann	Recursive structures of aggregation	https://www.food4rhino.com/app/kukaprc-parametric-robot-control-grasshopper	2020-05-08
	Fox	Petras Vestartas	Series of algorithms for Graphs, Aggregations, Iso-surfaces.	https://www.food4rhino.com/app/fox	2017-05-05
	Instance Manager	Amin Bahrami	Manages Object Instances	https://www.food4rhino.com/app/instance-manager	2019-07-14

The combination of physical elements and the design environment contribute to the final building. This systematic linkage between the two comes with further challenges during its materialization. The reversibility of connections of building parts, components, or elements is another challenge for the approach of reassembly.

On all levels of the building system hierarchy, we have seen attempts for designs that hold the potential for reassembly. While the physical units are important, it became obvious that it is also a matter of the design system, may it be on paper, algorithmically defined or just digitally represented. BIM might help to overcome many problems in the circle of assembly, disassembly and reassembly. However, the design complexity of working with existing elements is often not addressed in today's BIM environments. Discrete Design and element passports linked to BIM models could make these things easier. However, designers still are not incentivized to reuse elements and thus opt for designing and manufacturing buildings made from new elements (De Wolf et al., 2020). As traced in this section, in recent years, the units of assembly shrunk, providing more flexibility for designers. Design tools that manage the sheer amount of units are being developed, but how they link with the physical units is still challenging, even with today's digital technologies.

2.2. Reversible Connection

Connectivity is an essential aspect for building elements to be reassembled. Conventionally, most methods of fixation in construction are irreversible. Adhesives or nails are hard to be retrained and might harm the building elements. Instead, designs for reassembly should focus on exposed connections and mechanical fasteners (American Institute of Architects, 2016). Even if elements are designed for on-site assembly and suited for disassembly, this does not constitute them for several cycles of reassembly. The publication Design for Disassembly in the Built Environment: A Guide to Closed-loop Design and Building (B. Guy et al., 2008) lists the following principles focusing on the connection details for reversible connections.

- Design connections that are accessible. Visually, physically, and ergonomically accessible connections will increase efficiency and avoid requirements for expensive equipment or extensive environmental health and safety protections for workers.
- Minimize or eliminate chemical connections. Binders, sealers and glues on or in materials make them difficult to separate and recycle and increase the potential for negative human and ecological health impacts from their use.
- Provide adequate tolerances to allow for disassembly to minimize the need for destructive methods that will impact adjacent components.
- Minimize the numbers of fasteners and connectors to increase speed of disassembly.
- Design joints and connectors to withstand repeated assembly and disassembly to allow for adaptation and for the connectors to be reused.
- Allow for parallel disassembly to decrease the time on-site in the disassembly process.

Following these fixations principles, this section discusses different concepts for reversible connections for building elements. The concepts for joining are organized from simple to complex joint design, referring to the geometrical parameters integrated into the joining method.

The focus is put on mechanical joining. These connections rely only on mechanical forces applied, most commonly gravity, opposed to chemical bonds through adhesives or physical bonds like welding. These joints are designed to prevent movement or provide only movement in desired directions. They are commonly designed for the assembly of products or structures (Brandon & Kaplan, 1997). Compared to the two opposed fixation methods, this method is fit for controlled and intended disassembly.

2.2.1. Interlocking

In the early ages of architecture, assemblies were carried out reversibly because adhesives like nails, screws, mortar, or glue were not available. These joining methods relied on mechanical forces between the physically assembled elements at their interfaces, properly shaped to interlock with one another (Messler, 2006, p. 3). In interlocking assemblies, all elements are immobilized by their geometric arrangement, preventing the assembly from falling apart (Z. Wang et al., 2018). One of the oldest and most straightforward ways to create structures from smaller elements is stacking. Most buildings made from stone walls were built following this approach (Foraboschi, 2019). In these instances, their joining mainly relied on gravity and transferred thrust. For more complex arrangements, external forces were induced through tension cables or compression elements. The orientation and alignments of stone interfaces enabled building arches and today even more complex shapes through topological interlocking (Tessmann, 2012). Bricks were mostly aligned using lime or sand mortar which was easier to be removed from reclaimed bricks than modern Portland cement. As a result, preparation for reuse calls for a time-consuming cleaning of each block (Brick Development Association, 2014). However, when the connecting interfaces of such stones are planar, they are relatively sensitive to external forces and buckling. Various patents propose interlocking connection details for the stacking of blocks (Figure 2-37).

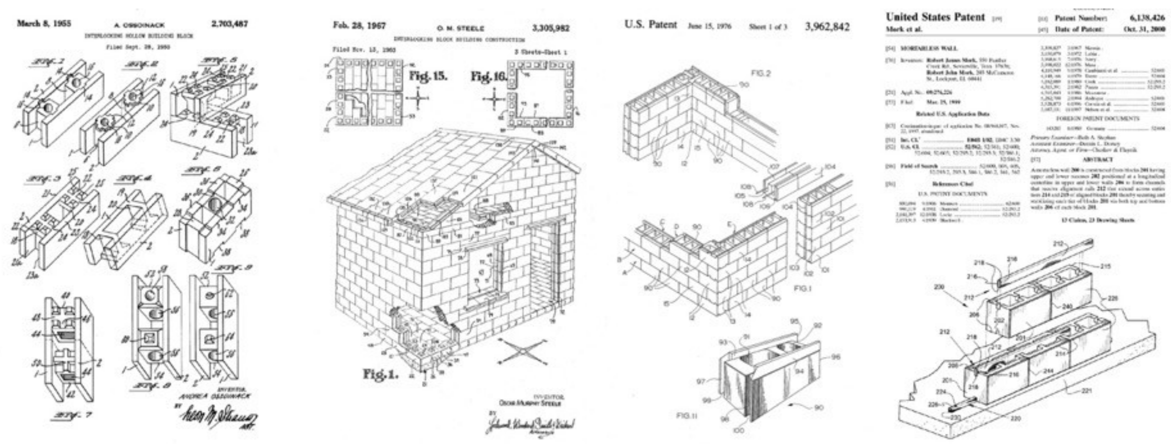


Figure 2-37 Selection of patents for interlocking blocks. From left to right: Interlocking Hollow Building Block (Ossoinack, 1955), Interlocking Block Building Construction (Murphy, 1967), Mortarless interlocking blocks (Wilhelm, 1975), and Mortarless Wall (Mork & Mork, 2000).

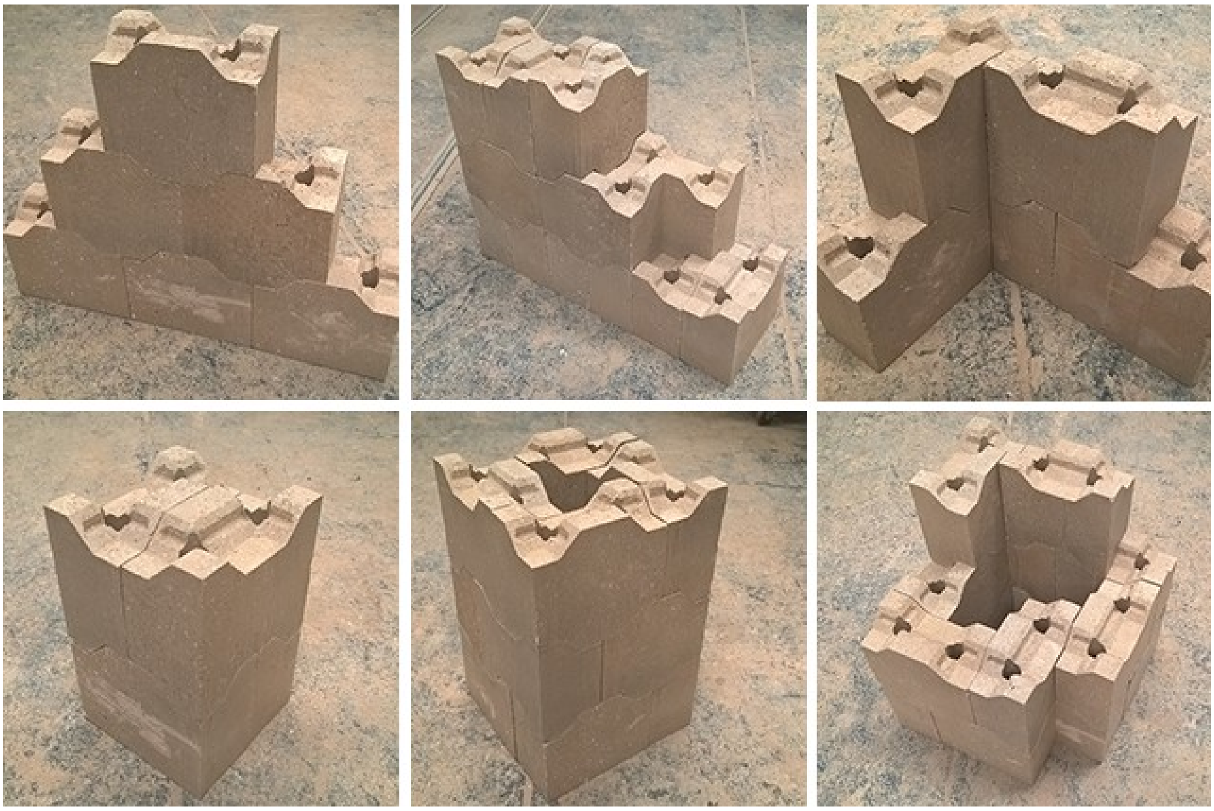


Figure 2-38 The Tetraloc bricks are one of the many examples of dry-fitted and interlocking building blocks available as a product today. Here, different configurations for the blocks are exemplified (*Technical Details – TETRALOC*, n.d.).

This subclass of mechanical joining is called integral mechanical attachment. Here, the movement of elements is restricted by integrated geometrical features in which two or more elements interfere with each other to create an interlocking assembly. The abutting elements are kept in contact while a retaining force works against their separation and maintains their alignment and orientation. These connections perform without extra fastening like clamps or threads (Messler, 2006, p. 10). Such geometrical connections were also used in wooden constructions as mortise and tenon joints (*Mortise and Tenon - Wikipedia*, n.d.). Figure 2-39 shows the geometrical repertoire available for wooden construction in the 19th century. Here, the linear elements are primarily pressed together by gravity while the joints prevent shear through integral mechanical attachment.

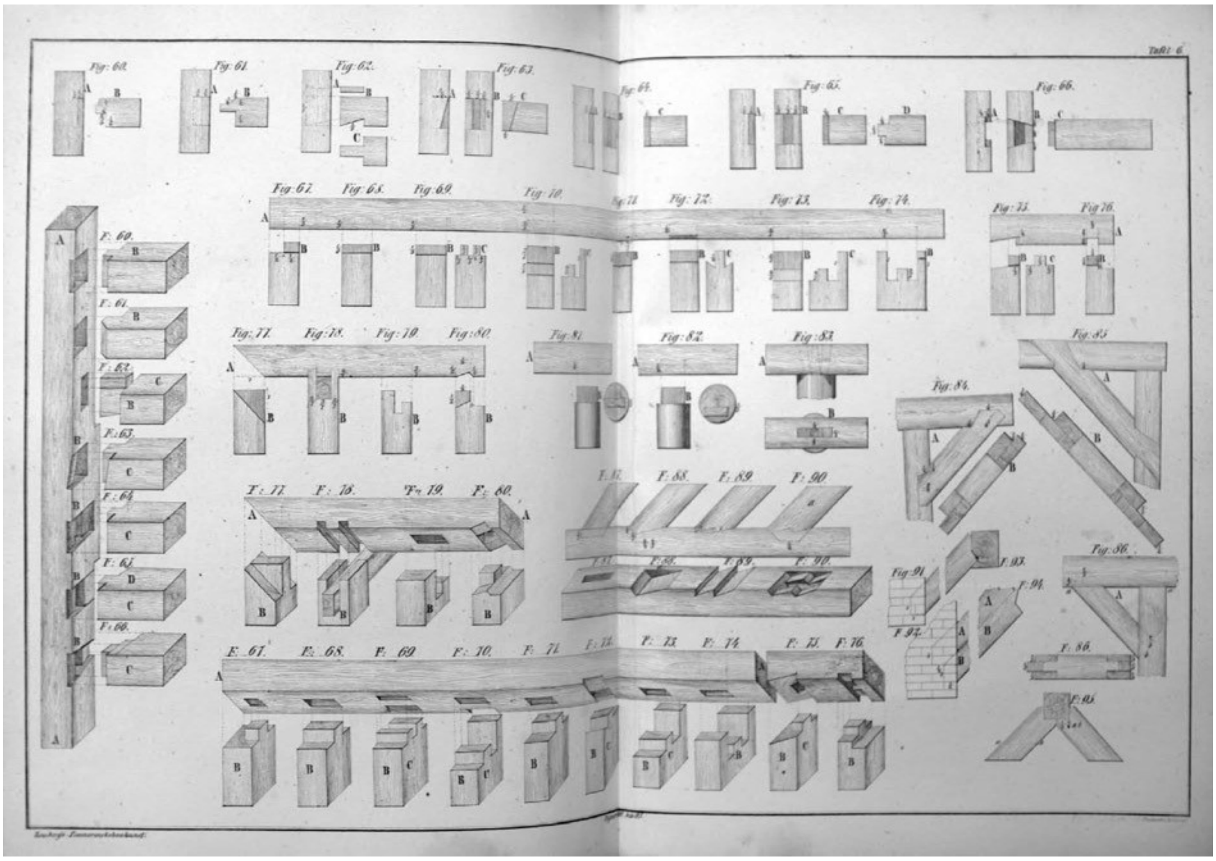


Figure 2-39 Hand-crafted wood connections (Romberg, 1846)

These geometrical principles of dry-fitted joining can be appropriated for concrete assembly of prefabricated elements (Mainka et al., 2013). Material research in combination with precise computer-controlled manufacturing enables a revival of detailed concrete connections. At the Institute of Structural Design (ITE) and the Institute of Building Materials, Concrete Construction and Fire Safety (iBMB) at the Technische Universität Braunschweig, researchers started investigating dry joining of 3D printed elements (Kloft et al., 2019). The dry joints can be directly cut into the manufactured elements during the curing process or afterwards (Figure 2-40). By cutting self-aligning interfaces into the components, their assembly is simplified and more error resistant. Pre-tensioning mechanisms like internal cables are used to fix the hollow components into complex structures (Figure 2-41).

Figure 2-40 Printing of hollow concrete columns (a), CNC cutting of the joint geometry (b), and the pre-stressed concrete column made from four dry joined segments (c) (Kloft et al., 2019)

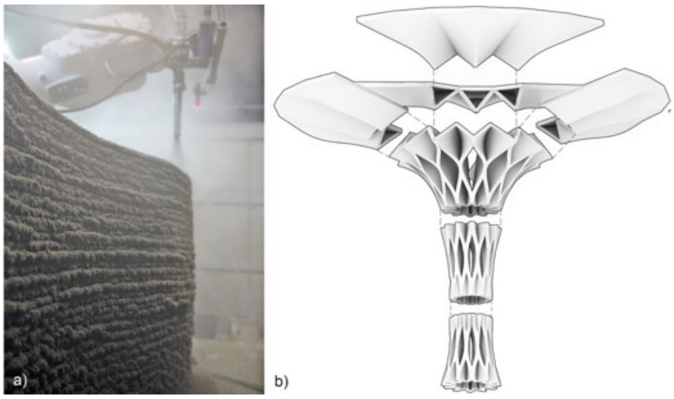


Figure 2-41 The robotic 3D shotcrete process (a) and segmentation drawing of an articulated calyx-like column (b) (Kloft et al., 2019)

The robotic aided fabrication of such joints can become highly articulated (Figure 2-42). The interlocking connection detail enables the construction of cantilevering and arching structures without fasteners. Such robotically stone-cut details offer versatility and reduce labor costs compared to traditional bricklaying and mortar methods (Fernando, 2019). The joint geometry is self-aligning and reduces alignment errors.

Figure 2-42 The roughing process using a saw blade end effector (a), the coarse robotic carving (b), individually cut block modules (c), wave joint assembly (d), visualizations of the twisted catenary arch structure with FEA mesh (e), and fabricated prototype (f) (Fernando, 2019).

Both examples of computer-aided manufacturing present geometrical connection details benefitting the assembly process. Their connections have self-aligning properties to calibrate the positioning of elements. However, both approaches focus on subdividing global geometries into smaller segments. Thus, the elements have predefined places in the overall assembly; their reassembly into other formations would require postprocessing. In the case of the 3D printed elements, the subdivision also relies on cables for fixation as additional fasteners, making sequential disassembly difficult. In both cases, the automated assembly for these connections has not been addressed.

2.2.2. Accessory Fastener

Mechanical joining of elements can be achieved with additional fasteners. The accessory can be attached externally or internally. The internal connection is more protected but might also be harder to disassemble. The external accessory makes dismantling easier but is more exposed to mechanical or chemical degeneration. The assembly is easier to read with external accessories. The accessory connection is most dominant in grid spatial structures for the joining of truss members. The node connectors mainly used in steel-based construction of grid shells or free-form spatial structures were of interest in architectural practice as well as research in the last decades (Hwang, 2010). Most of the nodal connections in such space structures would be fit to be disassembled. However, they primarily rely on fixation through screws which are not recommended for several cycles of reassembly.

Accessory connections exist for all sorts of building elements, including wall panels. In an early patent from Walter Gropius and Konrad Wachsmann, a releasable interlocking system was proposed in 1942. The joint system could connect 12 panels in three different planes at one point (Figure 2-43). It was intended to “eliminate practically all of the necessity for using nails, screws, hooks, and similar fastenings during [...] assembly” (K. L. Wachsmann & Walter, 1942). The panels came with a sectional J-shaped edge to be joined with neighboring panels by the use of extra connecting parts. The panels could be composed of different materials as long as they were fit for the geometrical principle. Due to the reversible connection, buildings could also be disassembled and later reassembled at other locations. In their patent, the two architects highlight the idea of on-site construction becoming a pure assembly problem.

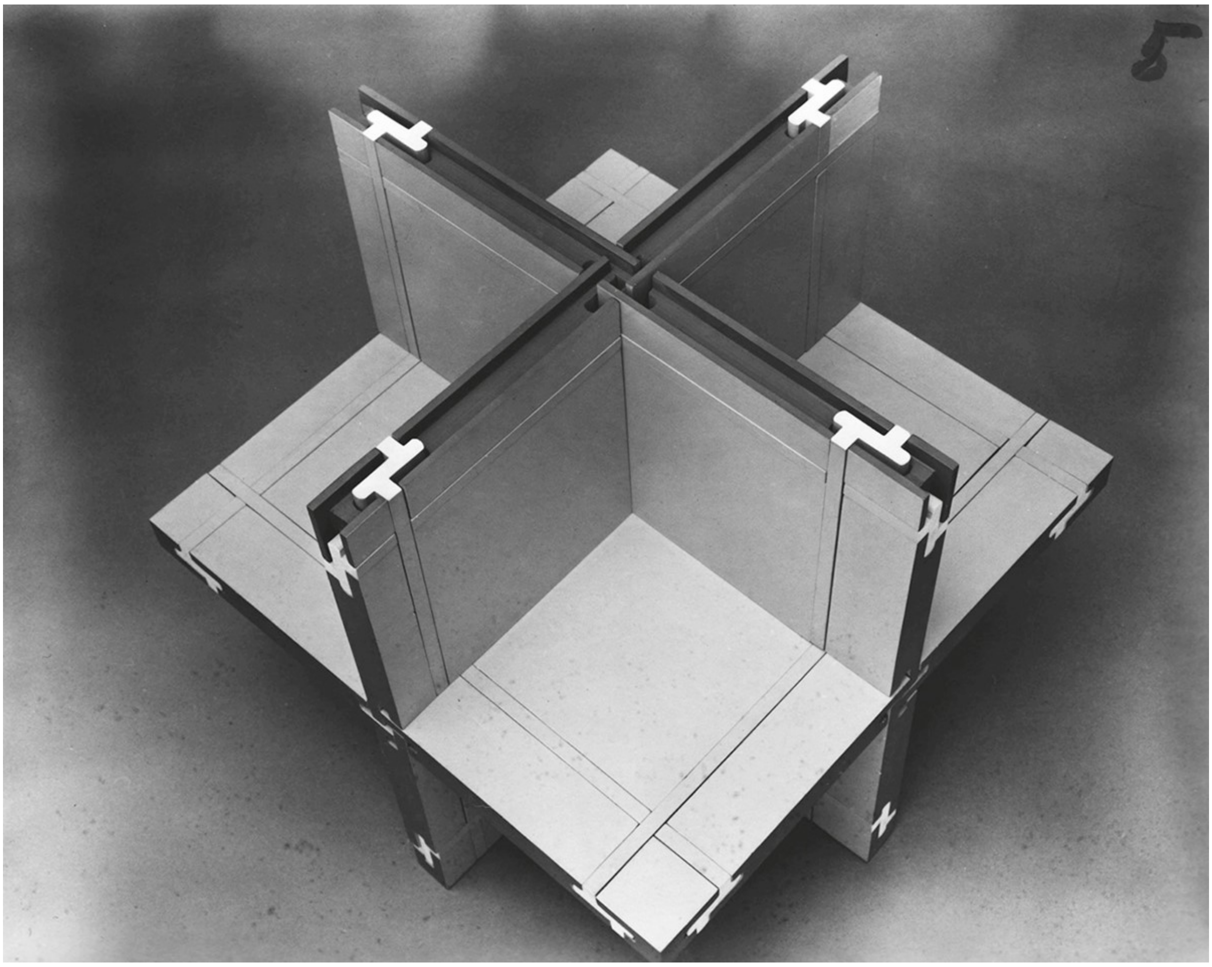
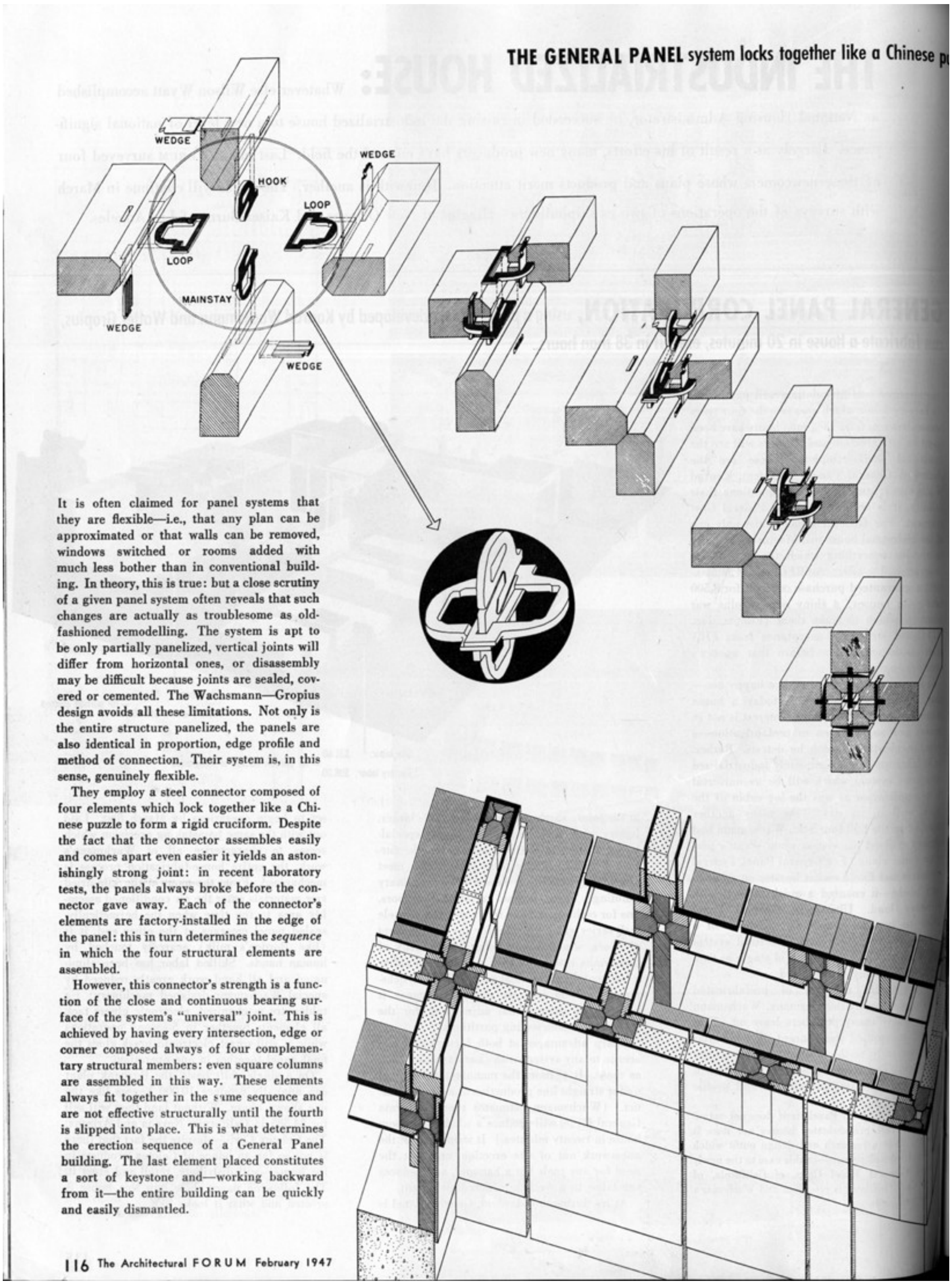


Figure 2-43 Three-dimensional node for demountable office partition system by Konrad Wachsmann with its panel interconnectors (white elements). Photo: Akademie der Künste, Berlin, Konrad-Wachsmann-Archive

Only two years after the first patent, Wachsmann and Gropius filed a patent for a second connecting type. The metal connector can inserted into the edges of wall panels, these have to be assembled in their predetermined sequence. First, the placement of the mainstay, then two hook elements are placed one after the other, and finally, the hook fixes the elements in place (Figure 2-44). Stability is only achieved once the last of the four pieces at a connection point is placed. This key piece can easily be taken away, enabling disassembly in the same sequence, just backwards. The universal panel system never made it into serial production, which might be related to the complexity of this connection (K. Wachsmann, 1961).



THE GENERAL PANEL system locks together like a Chinese p

It is often claimed for panel systems that they are flexible—i.e., that any plan can be approximated or that walls can be removed, windows switched or rooms added with much less bother than in conventional building. In theory, this is true: but a close scrutiny of a given panel system often reveals that such changes are actually as troublesome as old-fashioned remodelling. The system is apt to be only partially panelized, vertical joints will differ from horizontal ones, or disassembly may be difficult because joints are sealed, covered or cemented. The Wachsmann—Gropius design avoids all these limitations. Not only is the entire structure panelized, the panels are also identical in proportion, edge profile and method of connection. Their system is, in this sense, genuinely flexible.

They employ a steel connector composed of four elements which lock together like a Chinese puzzle to form a rigid cruciform. Despite the fact that the connector assembles easily and comes apart even easier it yields an astonishingly strong joint: in recent laboratory tests, the panels always broke before the connector gave away. Each of the connector's elements are factory-installed in the edge of the panel: this in turn determines the *sequence* in which the four structural elements are assembled.

However, this connector's strength is a function of the close and continuous bearing surface of the system's "universal" joint. This is achieved by having every intersection, edge or corner composed always of four complementary structural members: even square columns are assembled in this way. These elements always fit together in the same sequence and are not effective structurally until the fourth is slipped into place. This is what determines the erection sequence of a General Panel building. The last element placed constitutes a sort of keystone and—working backward from it—the entire building can be quickly and easily dismantled.

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Figure 2-44 The joint of the General Panel system explained in detail (Henry R. Luce, 1947).

On a conceptual level, Philippe Morel presented cubic blocks that were to be assembled reversibly. The slotted cubes were to be connected with slide joints (Figure 2-45). As opposed to the two approaches mentioned above, the elements' non-functional programming is a crucial aspect of the units. The cubic elements do not have any predefined assignments in a later assembly. Additionally, the project attempts a volumetric unit that can take on any place in an assembly, similar to the Bemis cubical modules. However, the cubes were not physically tested and remained on the conceptual level.

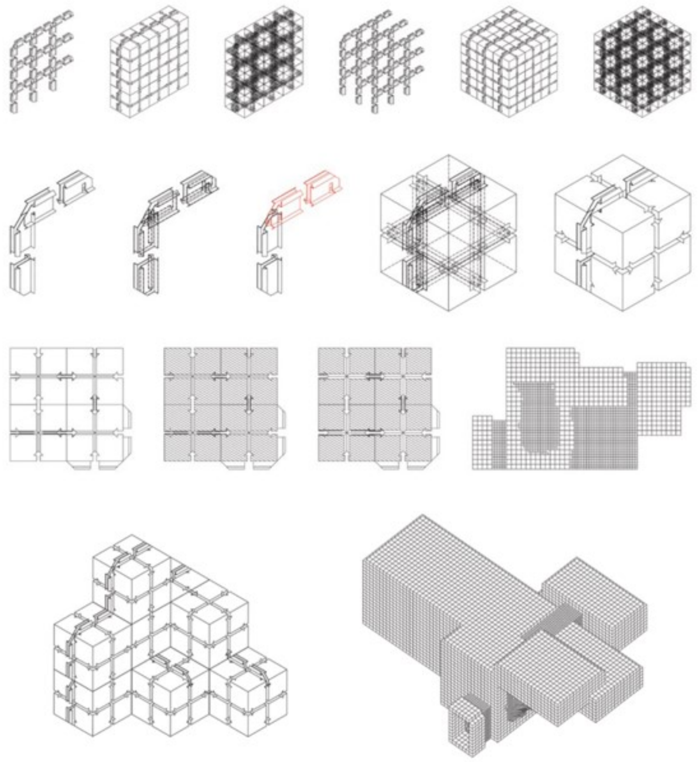


Figure 2-45 The building system for the Universal House is made of self-interlocking discrete blocks. Philippe Morel/EZCT Architecture & Design, Universal House, 2009 (Morel, 2019)

An accessory connection that combines geometrical principles with material flexibility is the snap-fit connection. In automotive manufacturing, this is a standard method for fixation. These types of connections are very detailed and usually depend on flexible and bendable materials. Different elements are just snapped together to stay in place. These joints are more durable compared to a press-fit connection when it comes to wear. However, the joints are very delicate pieces that tend to break easily. The fixation with this connection type is relatively easy, while the dismantling can become difficult as the snapped fingers have to be pressed aside for release. Architects proposed a whole building system for this connection type; the Loq kit. The different assembly scenarios for a house were conceptualized in very detailed drawings (Figure 2-46). However, the feasibility and durability of this system are still to be tested.

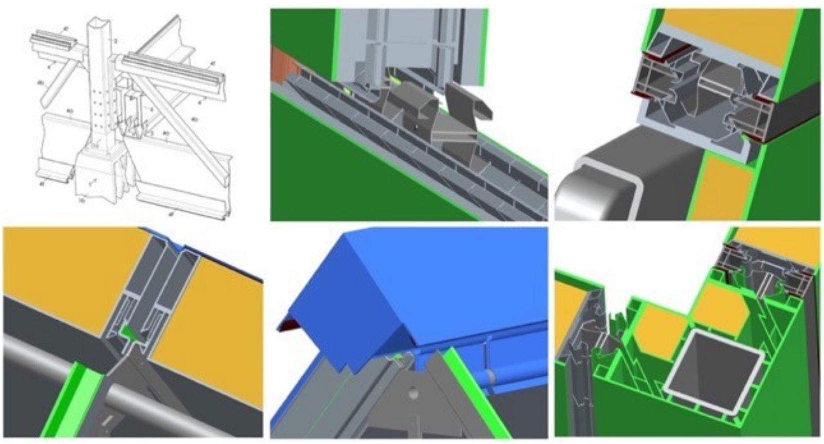


Figure 2-46 Drawing and renderings showing the conceptual depth of the accessory connection of the Loq kit (PAF Architecture, n.d.)

Accessory connections usually rely on more complex manufacturing processes. Often the connectors are made from different materials and can be less durable, which is problematic for multiple reassemblies. Their complexity makes them sensitive, resulting in fasteners breaking. Moreover, they come with an extra assembly and disassembly step that has to be implemented. The additional accessory demands extra logistics and might even lead to missing fasteners.

2.2.3. Press-Fit

Other industries that rely on the assembly of their products make use of press-fit connections. These connections are commonly used for prefabricated elements. Press-fit connections fix elements by micro bonding or friction between their touching surfaces. Sometimes, these connections are referred to as interference fit because the elements interfere in their opposing space. A press-fit connection can be defined by the following equations.

$f=kx$ (where x is the slot width)

$S=x^2$ (S is contact surface area)

$k=YS$ (Y is the material's Young modulus)

$f=YS^3$ (f is the force required to pull apart two slotted press-fit parts)

Thus, the quality of press-fit connections is affected by force, friction, area, surface finish, and material and fabrication tolerances. External forces like gravity or loads between two connections can increase the contact area. Finally, all of these factors have an impact on the repeatability of a press-fit connection. For instance, a brittle material might lose contact area and friction with every new dispatching and reconnecting.

The Wikihouse is one example predominately depending on press-fit connections (Figure 2-47), which, in the Wikihouse, are described as crush joints that are malleted together once only (*WikiHouse*, n.d.). Here lies the problem with most press-fit connections for reversible construction as they wear out easily. Moreover, press-fit connections rely on exact and complex movements during assembly, making them relatively labor-intensive and unprepared for automated assembly (Figure 2-48).

Figure 2-47 The manual assembly process of a WikiHouse (*WikiHouse*, n.d.)

Figure 2-48 The wooden plates with integral connections rely on hammering during assembly (Robeller & Weinand, 2016)

2.2.4. Digital Materials

While the previous architectural connections are intended as interfaces between parts, components, or elements, there is also an approach from reversible connections on the scale of matter. Usually, the behavior of material was determined through chemical and physical processes. Lately, scientists have begun to engineer the precise distribution of the compounds in materials (Schaedler & Carter, 2016). The composition is altered on the material scale, between micro and macro scale, resulting in fine distributed properties. For instance, lattice materials can present unseen behaviors in stiffness, strength, and damage tolerance due to their adapted structure (Fleck et al., 2010). These materials are created with a controlled material deposition. The compounds produced rely on their material and geometrical arrangement. However, Architectured Materials make fixed structures whose arrangement cannot be altered reversibly.

One attempt to create materials that can be changed was coined under the concept of Digital Materials. It refers to the concept of processing information as discrete values, reducing noise and distortion, in assembled compositions from the micro scale, up to the macro scale (Cheung & Gershenfeld, 2013). The material compounds assembled in pursuit of this approach have the following properties.

> Digital parts are error-correcting and self-aligning, which allows them to be assembled into structures with higher accuracy than the placement accuracy of the assembling person or machine. For example, a Lego™ set consists of discrete parts that have a finite number of joints. The male/female pin joints on the top and bottom of the Lego™ block are discrete connections, which either make or do not make a connection to another block. By contrast, a masonry construction is a continuous (analog) material; while the masonry brick is a discrete unit, the mortar in its fluid state allow one brick to be placed on top of another in an infinite number of positions. Because the joint is not discrete, masonry construction is analog while Lego™ construction is digital.
>
> (N. A. Gershenfeld & Ward, 2012, p. 13)

Digital Materials have different indices for their connection. While most connections intend to arrange elements along their edges or faces in one predefined position, another approach is that of indexed interfaces. These connections allow multiple ways of connecting elements along with their interface. The Lego block is such an example. The connection between the conventional block is always between the top and bottom interface of the block with male and female connectors. The elements can be placed using different indices of the interfaces, thus resulting in a different fixed position. Thereby, the elements allow a multitude of configurations to be assembled from the same set of elements. In digital materials, these connections are finite and discrete; thereby, the connections can be indexed.

With Digital Materials, the elements to be placed come without additional fasteners or fixtures; instead, the elements are the fasteners themselves. The goal is to reduce complex shapes, fixtures, and jigs to keep assemblies as straightforward as possible. One significant advantage of this approach is the reversibility of the arrangement in these materials.

Moreover, one crucial aspect of Digital Materials is error correction during the assembly. As opposed to other connections that focus on fixing elements in place, Digital Materials have to address error correction for many elements. While the press-fit connection focuses on the fixation of elements to each other, Digital Materials seek to guarantee the alignment of the elements throughout the assembly, avoiding the accumulation of tolerances. Nevertheless, one can find press-fit connections in Digital Materials with error-correcting properties (Figure 2-49). While previously material processes were considered messy, this approach embeds digital behavior into materials assembled from small-scale elements, enabling novel logistics of materials.

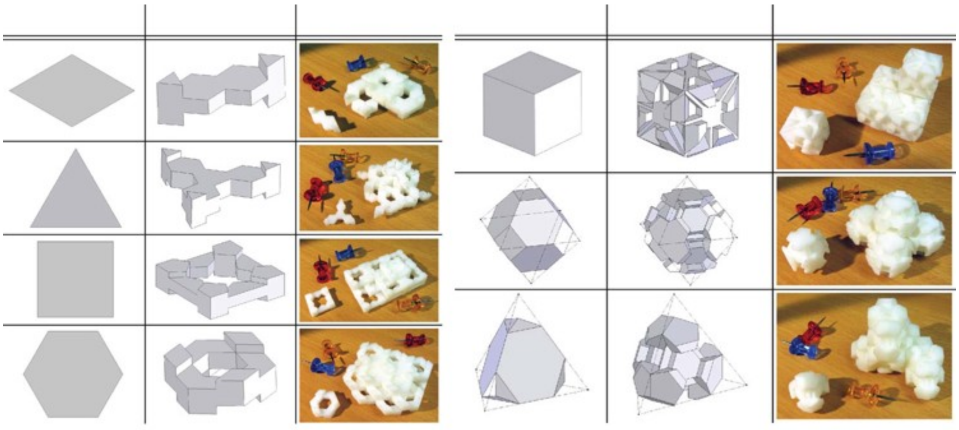


Figure 2-49 Interlocking, self-aligning 2.5D voxels suitable as digital materials for vertical stacking (left) and Interlocking, space-filling 3D voxels (J. Hiller & Lipson, 2009).

The concept of Digital Materials has been tested for lightweight lattice structures on a medium scale. Using the same building kit, a small team assembled three different structures: a bridge, a boat, and a shelter (Figure 2-50). The modular elements were designed as volumetric lattice blocks (Figure 2-51). As multifunctional blocks, they are fit for different locations within various configurations. Although in the case study, the elements were manually assembled, they come with the potential for automated assembly (Jenett et al., 2016).

Figure 2-50 Three different configurations with the same construction kit (Jenett et al., 2016).

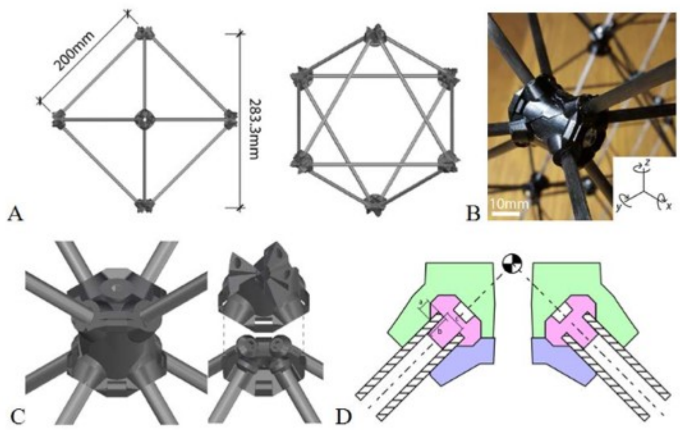


Figure 2-51 The error-correcting connection detail of the volumetric lattice blocks (Jenett et al., 2016)

As illuminated in this section, most reusable connections do not cope with the automation of the assembly procedure. While extensive research has been conducted on elaborate prefabrication methods, the assembly of these structures follows conventional human labor approaches. The press-fit connection is too tight for most conventional automated assembly methods and wears off after several assembly cycles. The accessory fastener adds complexity and fragility to the connection, as opposed to the robust and simple connections desired for reassembly. The interlocking connections offer robust details but might be too constraining as they depend on a clearly defined assembly sequence. One promising concept can be found in Digital Materials, which are often fit for the assembly with a computer-controlled assembler. Relatively little is understood about adopting the principles of Digital Materials into the architectural scale, especially when it comes to automated physical editing.

2.3. Automated Reassembly

> […] the robot no longer is tied to the making of things, it also connects with the thinking of things.
> (Jan Willmann et al., 2014)

Most construction methods have reached various limits in terms of growth, performance, defect rates, etc. Simultaneously, robotic service systems are becoming an inherent element of the built environment (T. Bock, 2015). While other manufacturing industries already embed robotics into their manufacturing processes, construction faces industry-specific challenges (Loveridge & Coray, 2017). These include economic contractor-side factors, economic client-side factors, technical and work-culture factors, and weak business case factors (Delgado et al., 2019). Especially automated assembly is still underdeveloped compared to other industry sectors (Neelamkavil, 2009). At the same time, robots for construction might become a necessity due to the current socio-economic changes of societies (Brehm, 2019).

These trends in other industries suggest that construction could benefit from teaming up with other disciplines, e.g., roboticists, to overcome these challenges. Especially assembly and reassembly tasks reveal the limitations of current construction robots. One of the biggest challenges in assembling prefabricated elements can be found in the legacy of old construction methods dominating most existing construction firms (Open System Lab, 2018). Prefabrication in line with well-developed assembly strategies could be one way of overcoming these hindrances is to involve other parties in the procurement. In non-automated approaches, these could be achieved by simplifying the procurement for untrained workforces. However, this path of reducing the requirements during assembly seems short-sighted. Instead, current developments in robotics raise the possibility to embed automation for complex and autonomous construction tasks (Melenbrink et al., 2020).

At the same time, technologies like generative digital design tools and computer-aided fabrication techniques are well suited for automation (Wit & Daas, 2018, p. 37). Previous labor-intensive processes become automated and allow for an immense flow of information. The digitalization of design and fabrication introduces concepts for automation in different stages of architectural production: design, planning, and construction (Sawhney et al., 2020). Yet, the flow is often disrupted between these different stages, most prominently in the assembly processes. Considering today's construction processes, one recognizes that even within a digital chain of procedures, human labor is still crucial to most assembly tasks. One solution to overcome this shortcoming might be integrating automation and robots into the whole construction sequence (Warszawski & Sacks, 1995).

The robot systems currently used in construction derive from industrial robots from other manufacturing sectors like the automotive sector with way smaller products. Additionally, the automotive industry produces big series of the same product in highly structured factories, making their automation more efficient. In contrast, the construction industry faces one-off production scenarios on very unstructured and dynamic construction sites (Balaguer & Abderrahim, 2008). And although there are many differences between the industries, construction can benefit from adapting the industrial robots for construction tasks. The six-axis robot arm is a very generic tool that can be applied to many different tasks. It can carry out tasks of a 5-axis milling machine; it can be used to assemble things when equipped with a gripper or use many other tools like 3D printing nozzles, heat guns, vacuum suckers, etc. (Gramazio et al., 2014b). The robot becomes a specific machine only by adding these kinds of task-specific tools – the end effector.

The sheer amount of scientific publications targeting construction scenarios with robots involved has experienced significant growth over the last two decades (Carra et al., 2018). A survey among businesses and technological leaders at Arup, one of the leading companies in architectural planning, maps already existing construction robots into their corresponding application fields (Carra et al., 2018). The survey focuses on robots in various areas, e.g., construction and maintenance (Figure 2-52). Among the identified life cycle phases of the building, Arup's experts identified demolition, production, and quality check as the phases where robotic technologies could have the most significant impact in terms of improved safety and reduced costs. To develop such robots, the capability to robustly perform complex tasks inside heavily unstructured environments remains the most demanding challenge to tackle from the research point of view (Carra et al., 2018).

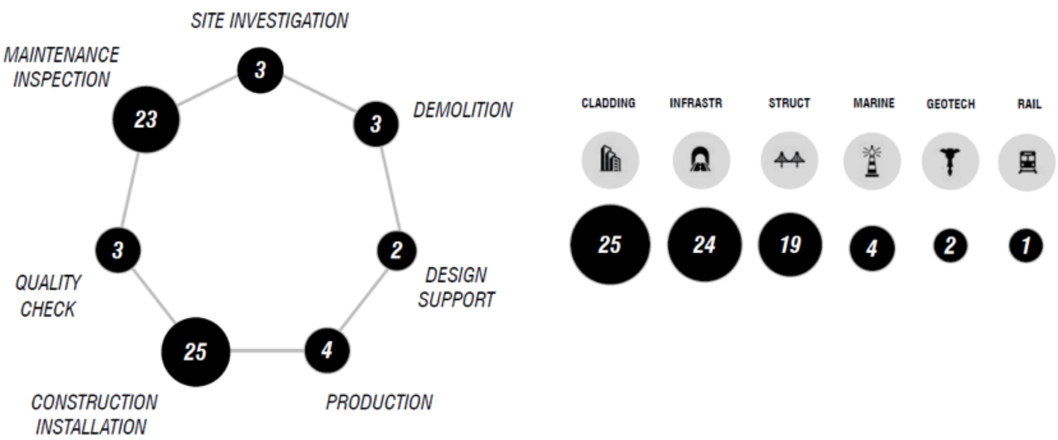


Figure 2-52 Survey results by Arup showing the applications of 52 identified robots in the building life cycle (left) and in the distinct construction sectors (right) (Carra et al., 2018).

The robot can cope with high resolution of instruction data. A robot can easily execute the same instruction thousands of times, even if they differ slightly. As long as described accurately, the robot will carry out the instructions. Nevertheless, it is crucial to shape the robot's tasks accordingly, as its capabilities still come with certain limitations, e.g., limited sensory skills. One way of addressing these limitations might be the design of elements for robotic assembly. Figure 2-53 suggests that robotized building elements could speed up the construction of houses while offering the design flexibility of small-scale building blocks. Hence, robots may not only change the way we construct buildings, but the technology also questions the epistemological role of robots in the design of our built environment (Picon, 2014).

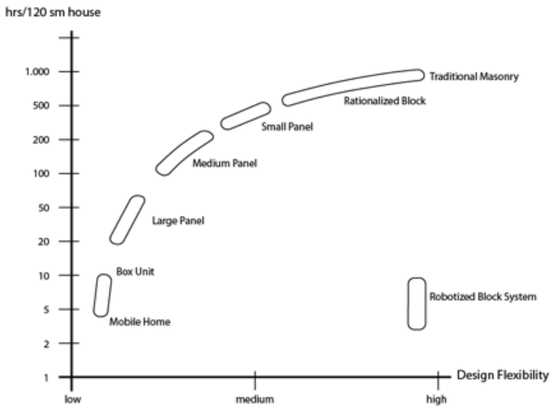


Figure 2-53 The high working speed of robots and the capability to handle complex building plans of even small elements can result in high design flexibility and minimized construction time (redrawn based on T.-A. Bock, 1988).

The following section introduces the current state of the art of construction robotics in the domain of assembly. It starts with an overview of robots being applied in construction. Different programming methods for robots are presented, some of them embedded into architectural design environments. Considering the robot at an early design stage can help integrate the various steps of designing, connection detailing, and defining robotic instructions.

2.3.1. Assembly with Robotic Assembly

Before the event of heavy machinery, construction depended on the human workforce (Swenson & Chang, 2020). Today, powerful machines enable the lifting of heavy prefabricated components, and in the near future, one might see automation technologies again change the way we construct (Claypool et al., 2019). A fundamental difference between conventional robotic applications, e.g., in mechanical engineering to robotized construction, is the number of repeatable robot movements. Unlike traditional applications, where the sequence of movements can be repeated thousands of times for the same parts, each house is unique. Each element has to be moved with an individual motion sequence. However, the structure of the movement sequence during the assembly processes can be traced back to some basic patterns such as grasping, moving, and placement which helps to limit the complexity.

The programming of the robot is of crucial importance. While regular robots can be programmed by teaching or with off-line programming systems, which require a multiple of the execution time in programming time per sequence (the same effort is distributed over the number of the same cycles), this is not possible for one-off production of buildings. Here, automatic programming based on the geometrical data is necessary. For this purpose, the starting and end position of each element to be assembled must be known, as well as the place of the pallets to the robot and the robot's position. This leads to another fundamental difference to stationary, industrial robots. On the construction site, the robot is exposed to constantly changing environmental conditions. It is necessary to recalibrate the robot and the workpieces at each site of operation. Besides, other unpredictable events and obstacles make it hard to adapt the robot to the site conditions. The challenges of automation in construction are fundamentally different from those encountered in other industrial fields, owing to the prevalence of complexities and the one-off characteristics of buildings. In this section, various approaches to robotic assembly in construction are presented.

The RObotic assembly system for Computer integrated COnstruction (ROCCO)

Figure 2-54) project was developed from 1992 to 1996 and was able to lift heavy bricks of a dimension of 100 x 50 x 50 cm with a maximum weight of 350 kg (T. Bock, 2017). The research project didn’t succeed commercially due to the complex handling of dimension tolerances and the time-consuming repositioning of the robot on the construction site. Based on these problems, the further development of ROCCO intended to use a special brick system optimized for robotic assembly (Bonwetsch, 2015a), already pointing to the difficulty of integrating robotic construction with building elements designed for human assembly.

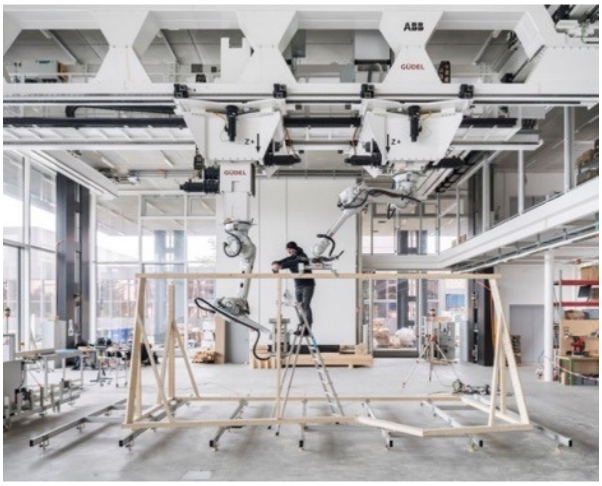
Figure 2-54 The ROCCO robotic masonry systems for brick placement with a mortar bed (Balaguer & Abderrahim, 2008).

Today, a small spectrum of commercial projects in masonry robots exists, like the SAM100 (Semi-Automated Masonry)(*SAM100 – Construction Robotics*, n.d.) and the Hadrian X ROBOT (*Hadrian X® | Outdoor Construction & Bricklaying Robot from FBR*, n.d.). At the same time, there is extensive research interest in the field of masonry automation (Dakhli & Lafhaj, 2017). These efforts increase speed and precision, aiming at an affordable construction method. The bricklaying robots are inspired by human bricklaying. They rely on special bricks, optimized by increasing their size and using special adhesives for the robotic assembly.

Many of these robotic systems were implemented to automate processes usually carried out by humans. The material system or building elements are unchanged, and instead, the focus is put on the automation and handling of complex information. Impressive results have been achieved by integrating robots early on in the design process (Gramazio et al., 2014b). In recent years, we have seen numerous projects dealing with topics of robotic assembly in architecture following the concept of Digital Materiality (Jan Willmann et al., 2014). It has to be noted that this concept differs from Digital Materials. While Digital Materials merge digital properties into the physical world, Digital Materiality focuses on techniques of digital fabrication to inform material with digital design data. Instead of inscribing instructions on paper plans, the focus is put on the numerical representation of the instructions. The majority of them deal with vertical stacking of elements that allow building highly articulated structures. Although these investigations are very impressive and novel, they primarily focus on geometrical differentiation of the placement of elements. These designs can yield curved brick walls with precise rotations of all the bricks (Figure 2-55). Thereby, the vast data streams are exploited in these designs, which would otherwise be inaccessible or too complex for human-made masonry.

Figure 2-55 The ROB Unit assembling a segment of the Structural Oscillation installation. The final installation was exhibited at the 11th Venice Architectural Biennale and consisted of 14,961 individually rotated bricks forming a 100-meter-long brick wall (Copyright: Gramazio Kohler Research).

Similarly, one can observe robotic fabrication and collaborative assembly processes for different material systems such as wooden (Thoma et al., 2019) (Figure 2-56) or metal constructions (Parascho et al., 2017) (Figure 2-57). The focus on a limited set of operations with unified geometries enables the automation of tedious assembly tasks. The research projects focus on non-regular spatial structures by integrating computational design, robotic simulation, and digital fabrication (Reinhardt et al., 2020). However, these processes make use of building elements already used in conventional construction, mimicking human assembly procedures.



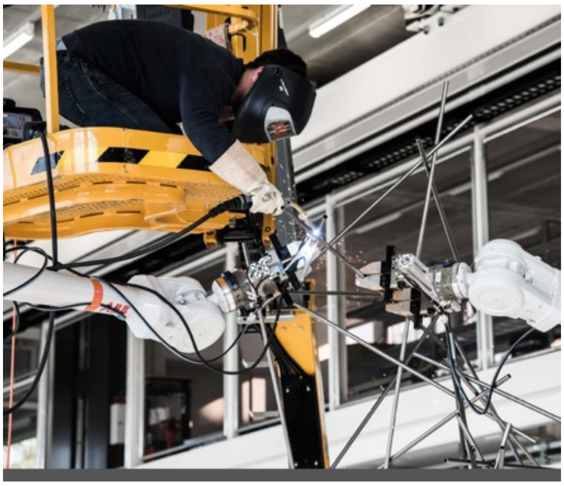


Figure 2-56 In the project Spatial Timber Assemblies by Gramazio & Kohler Research at ETH Zürich (2016-2018), two robots hold wooden beams in place, and a human worker fixates the beams. (c) NCCR Digital Fabrication / Photo by Roman Keller (Thoma et al., 2019).

Figure 2-57 Metal tubes manually welded at their connection points during robotic placement (Parascho et al., 2017)

One other advantage of robots for construction, besides the sheer amount of repetition and precision, is the capability of keeping an exact position without getting tired. This was highlighted in the assembly of an arch without falsework. The assembly purely relies on the sequential placement and holding of two robot arms (Figure 2-58). The project clearly illustrates how robotic capabilities allow reconceptualizing certain construction techniques.

Figure 2-58 The robotic assembly sequence with the constant equilibrium of a compression-only arch (Wu & Kilian, 2018)

The press-fit connection or mortise and tenon joints are strong and stable joints. For the assembly of such complex joints, a robot needs to be equipped with additional tools. In the research project for the assembly of wooden plates, an effector was used with an integrated plate for vibration-inducing (Figure 2-59). The project reveals the difficulties found in complex architectural connections. Robots without sensing capabilities face the problem of getting stuck in such complex insertion tasks.

Figure 2-59 The robot equipped with the vibration end effector carrying a plate into position (Robeller et al., 2017)

From this summarized collection of robotic research and application in construction, we understand that robots can improve existing assembly processes. However, the building elements in these examples follow conventional human-oriented assembly procedures. In the case of the bricklaying robots, it can be observed that the complexity of the arrangement of the bricks can become highly articulated. Nevertheless, in these examples, the robots have to adapt to the task. The machines are appropriated by or with architects to meet already existing material or assembly handling approaches, coined as machine crafting or robot crafting (Nan, 2015). Historically, crafting was defined by the requirement of a particular skill and knowledge regarding material and manufacturing processes. When applied to robots, these skills seem to be a human projection of craftsmanship focusing on replacing manual labor with increasing performance (Fernando, 2019, p. 113). What these projects lack is an approach to the robotic assembly of appropriately designed building elements for robots.

2.3.2. Robot Control

The fragmentation of the architectural practice between design and construction was well anchored in the industrialization principles of specialization and segmentation (Callicott, 2003). It has been argued that digital fabrication starts to challenge this long-existing Albertian separation (Carpo, 2009). The linkage between the design data to computer-aided fabrication technologies like CNC milling machines or robotic fabrication improves due to novel tools. However, in many cases, digital fabrication and assembly procedures are developed externally by geometry and fabrication specialists such as the companies Design to Production, Fibr, or Imagine Computation. These companies often use the same software tools as the architectural companies but do so to generate fabrication data. Expertise in geometrical understanding is coupled with skills of formalizing this knowledge into code and machine instructions. Hence, one can still identify two disconnected processes: design and fabrication.

Nevertheless, design environments become more and more managing hubs for a wide variety of tools (Davis & Peters, 2013). Recently developed design tools offer designers a lot of freedom when designing with modular elements; instead of modeling with surfaces and polygons, the focus shifts towards object-oriented approaches (see the section on building elements). Simultaneously, the computer can store the assembly sequence of the elements, making it possible to derive robot instructions (Andrea Rossi & Tessmann, 2017b). The integration of robot programming tools into the architect's workflow makes them more applicable. The number of tools connecting a common design environment, e.g., Rhino 3D, with various industrial robots, is constantly growing (Table 2). Integrating a design tool with a robot control program requires specific implementation steps. Figure 2-60 shows a simple program for a linear robot movement implemented in Rhino/Grasshopper. The simulated robot inside the design software presents immediate feedback about robot movements and actions. Defining these instructions for the robot is referred to as robot programming.

Table 2 Robot control plugins for Rhino/Grasshopper

Logo	Name	Developer	Supported Robots	Link	Publishing Date
	FUROBOT	FabUnion	KUKA,ABB,UR and external axis	https://www.food4rhino.com/app/furobot	2020-1-20
	HAL ROBOTICS FRAMEWORK	HAL Robotics	ABB RAPID, KUKA KRL or Universal Robots	https://www.food4rhino.com/app/hal-robotics-framework	2020-03-06
	KUKA PRC	Association for Robots in Architecture	KUKA robots	https://www.food4rhino.com/app/kukaprc-parametric-robot-control-grasshopper	-
	MACHINA	Garciadel Castillo	ABB (tested offline, wip online), KUKA (untested offline), UR (pseudo-tested offline)	https://www.food4rhino.com/app/machina	2018-12-20
	RFD (ROBOTIC FABRICATION DESIGN)	Kim Taeyong	KUKA Robot "KR 120 R2500". (other robots will be added later.)	https://www.food4rhino.com/app/rfdrobotic-fabrication-design	2020-3-12
	ROBODK	RoboDK	Connection between Rhino and RobotDK - more than 50 different robot manufacturers	https://www.food4rhino.com/app/robodk	2019-02-05
	Robots	Vicente Soler	ABB, KUKA and Universal Robots	https://github.com/visose/Robots/wiki#download	2020-1-20
	SCORPION	Khaled ElAshry, Vincent Huyghe, and Ruairi Glynn	universal robots	https://www.food4rhino.com/app/scorpion	2015
	TACO ABB	Shih-Yuan Wang, Yu-Ting Sheng, and Florian Frank	ABB robots	https://www.food4rhino.com/app/taco-abb	2016

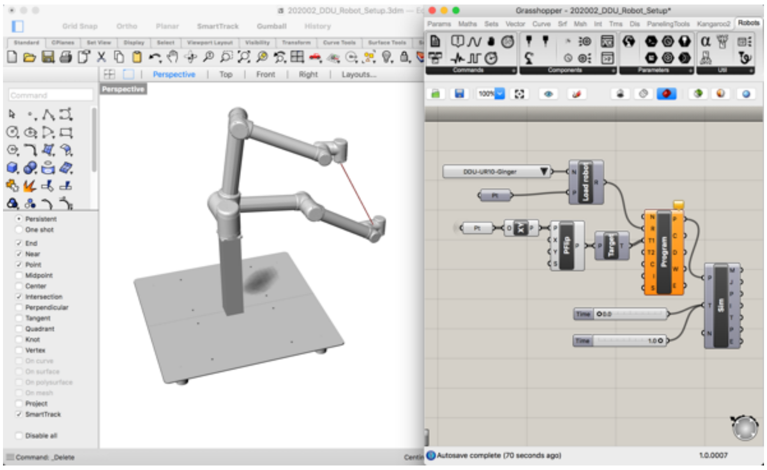


Figure 2-60 The Grasshopper script with the Robots Plugin by Vicente Soler in Rhino 3D shows the start and end positions of the robot that are input through points.

Robot programming can be differentiated into online programming – teaching by demonstration via the teach pendant, offline programming – writing an instruction manual that is saved and uploaded to the robot, and live programming – in which the program can be changed, yielding immediate changes of the robot's actions (Lim, 2016). Industrial robots, in most factories, are programmed following the concept of online programming, which is feasible as most tasks are pure repetitions of the same instructions. Instead, the construction examples mentioned above rely primarily on offline programming; here, the instructions change according to input variables such as brick positions, etc., and would be unfeasible to be programmed by demonstration (online programming). In contrast, live-robot programming enables the robot to operate in a continuous state of attention and instant reactions through changing instructions (Lim, 2014). Due to the fast connection between the existing robot plugins, it is possible to embed live programming features within most of the tools from Table 2.

This live programming approach enables an immediate connection between the construction system and the design environment. One example is the Never-Ending Wall, in which a design interface is connected with the automated and continuously re-stacking of bricks along a hand-drawn curve (Figure 2-61). The project presents speculations about on-site design decisions and their translation into robot instructions (Helm, 2014). A human gesture, indicated by a drawn line, is directly executed by the robot.

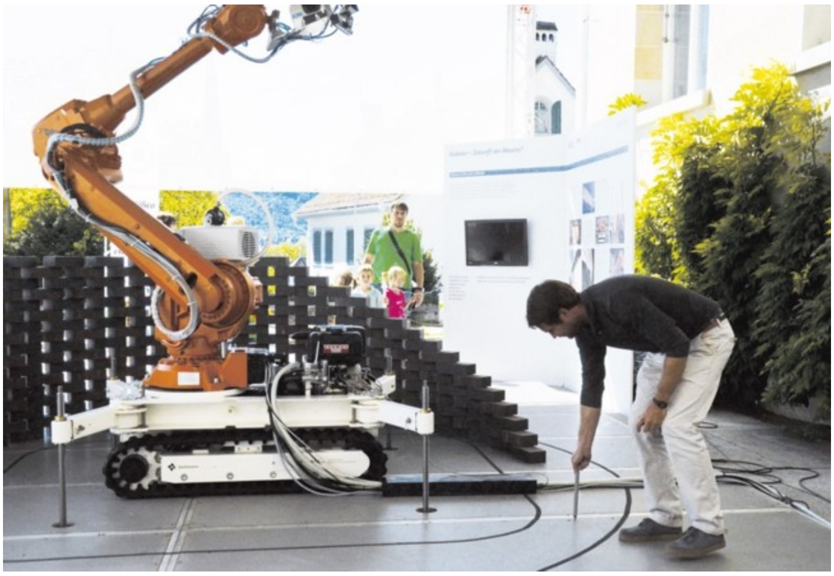


Figure 2-61 Human gestures are captured and translated via Microsoft Kinect (Helm, 2014).

The usage of building elements as the input for generating the robot instructions was investigated in a small-scale prototype consisting of wooden lamellas by the author (Wibranek, 2019). The robot captures the shape of a manually fixated lamella with rods through 3D scanning. From these input lamellas, the instructions for robotically placing the following rods were interpolated. The human co-worker only has to insert the bendable lamellas following the precisely oriented rods (Figure 2-62).

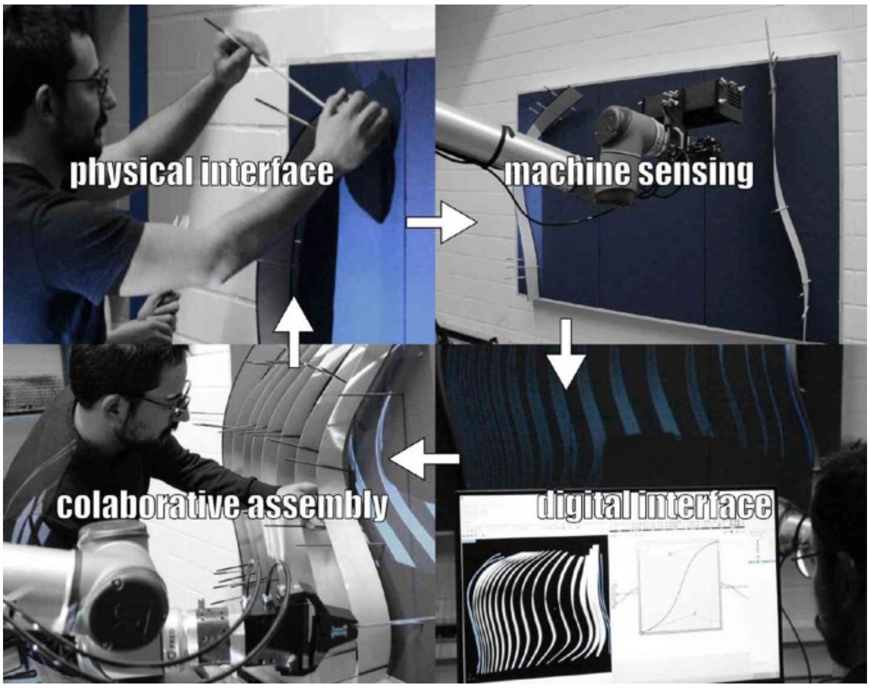


Figure 2-62 The overall process of physical input, machine sensing, digital interpolation, and collaborative assembly (Wibranek, 2019)

Furthermore, building elements can be linked with different robot instructions. While the projects, as mentioned earlier, consistently execute the same types of instructions at other positions, it is also possible to embed various types of instruction (Andrea Rossi & Tessmann, 2017b). Based on previously placed elements, the assembly can differ, e.g., the placement of new blocks can be blocked, the orientation of blocks can be changed, or the placement of blocks can be prioritized (Figure 2-63). Thereby, the usually fixed assembly plan can be altered by the human co-worker introducing new decisions at any stage.

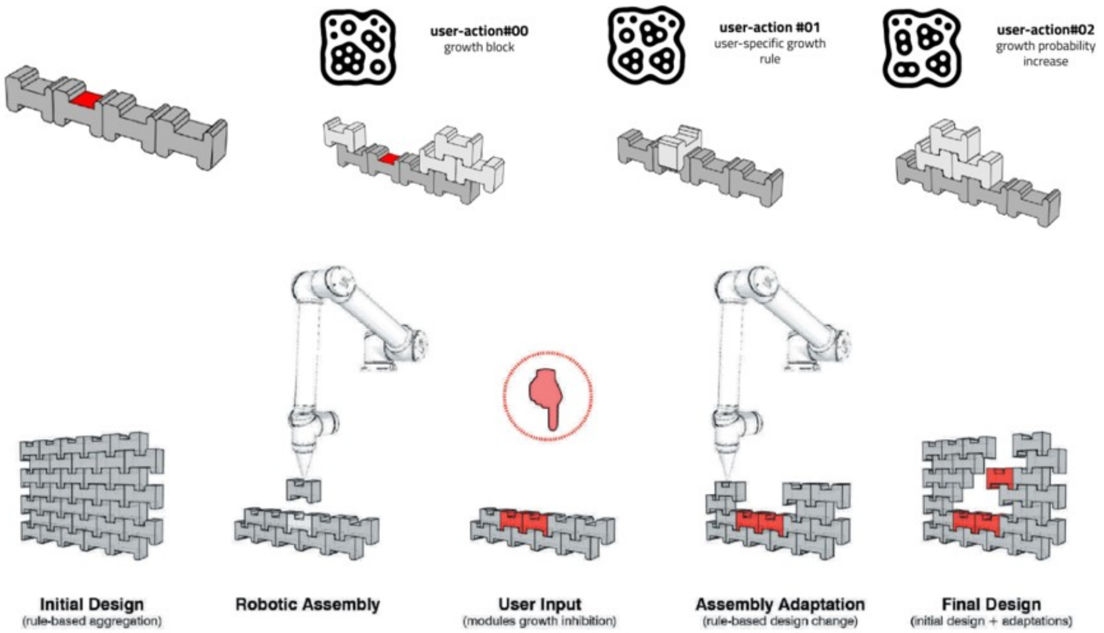


Figure 2-63 Growth control via fiducial markers and the robot's different assembly instructions (Andrea Rossi & Tessmann, 2017b)

These approaches to live programming enable a more immediate connection between the acts of design and construction. However, the sensing capabilities in these examples are limited and will not allow any adaptation to tolerances or unexpected events during construction. These limitations cause several problems during the contact-rich assembly as it requires interaction between the robot, the elements, and the already assembled structure, which is often hard to program (Vukobratovic & Tuneski, 1994). Simultaneously, the embodiment of the robot, situated in the real world, provides specific difficulties (e.g., high-dimensionality, real-time constraints for collecting data and learning) and various opportunities to explore physical behaviors. One promising approach for on-site construction is Robot Learning. It is a research field combining machine learning and robotics to allow a robot to acquire novel skills or adapt to its environment, as described in the following quote.

> "While classical artificial intelligence-based robotics approaches have often attempted to manually generate a set of rules and models that allows the robot systems to sense and act in the real world, robot learning centers around the idea that it is unlikely that we can foresee all interesting real-world situations sufficiently accurate. Hence, the field of robot learning assumes that future robots need to be able to adapt to the real

world, and domain-appropriate machine learning might offer the most approach in this direction." (J. Peters et al., 2017).

In architectural assembly, contact between parts, friction, and deviations between planned and actual elements require on-the-fly adaptation, a core strength of the learning-based approach (Inoue et al., 2017). Furthermore, instead of specifying the exact movements for the robot's end-effector or providing similar low-level instructions, the designer specifies an overall construction goal for the robot and lets the learning system figure out the optimal assembly sequence. Finally, the use of rich high-dimensional sensors, such as depth cameras, Lidar, tactile sensors, etc., calls for scalable methods that can work with such inputs. Robot Learning enables the use of such rich feedback signals for robot control. Different types of algorithms can be applied, including adaptive control, machine learning, and developmental robotics. An example of this approach has been presented for robotic wood carving (Brugnaro & Hanna, 2019). Instead of programming the robot, the available carving moves were demonstrated by a human and were recorded using motion-capture cameras to track the position and orientation of the carving tool (Figure 2-64). The recorded demonstrations were used for a supervised machine learning procedure, an Artificial Neural Network (ANN). Preferred and unpreferred carvings were flagged to narrow the scope of robotic actions. Thereby, the robot learned to only apply carving movements within an optimal fabrication range.

Figure 2-64 Human demonstration of the carving (left), carving examples, and the capturing head mounted to the carving tool (middle), and a robotic carving test (right) (Brugnaro & Hanna, 2019)

Other approaches of Robot Learning algorithms foster learning through reinforcing desired behavior through rewards—Reinforcement Learning. It is a general framework for developing controllers for settings that are hard to model analytically (Sutton & Barto, 1998). These algorithms are suitable for solving a well-defined task by trial and error, which is otherwise hard to solve via programming by hand (e.g., involves high-dimensional input such as pixels in Atari games or video/tactile sensation in robot control).

Problems in the language of Reinforcement Learning have to specify states, environment, actions, and the reward function. For robotic assembly tasks, these translate as follows. The robot can take actions such as moving around, grasping an element, placing it, etc. These actions cause a change in the environment observable by the robot, including new positions of elements or changes in static behavior. These observations yield a new state of the environment. The new state comes with a reward for the actions taken with regards to their outcomes. For instance, if an element is placed correctly, the robot receives a higher compensation than suboptimal or even false placement. Thus, the reward signal evaluates how well the task is solved (e.g., position error between the desired and current part position). Based on these interactions, the robot develops a mapping from states to distributions over actions that yields the highest expected reward. The robot finds a successful policy; it learned to predict the best actions given a particular setting.

The Reinforcement Learning approach was applied to control robot movements in contact-rich and tolerance-prone assembly tasks of integrated timber joints (Apolinarska et al., 2021). Exemplified by the assembly of lap joints for custom timber frames, robot movements are guided by readings from a force/torque sensor and the timber elements' position to insert mating counterpart(s). A human operator demonstrates the desired assembly in a simulation. Based on this demonstration, the Reinforcement Learning agent trains the correct assembly in multiple iterations. Finally, the learned controller is tested on the real robot (Figure 2-65).

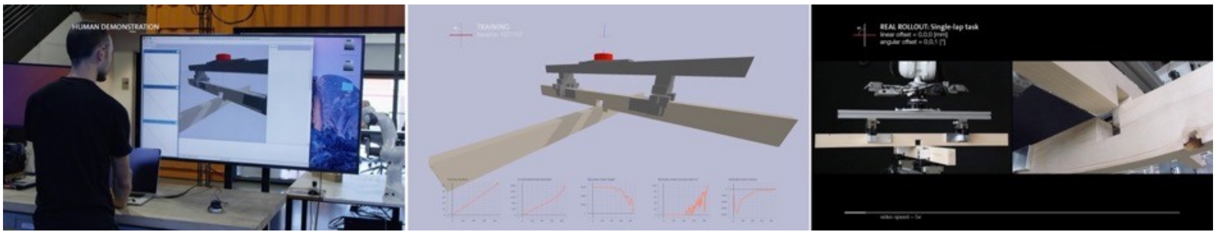


Figure 2-65 The demonstrations are conducted exclusively within a simulation environment, using a game controller to drive the end-effector until the timber member and the timber assembly are successfully joined (left). (Apolinarska et al., 2021)

Currently, accessibility of the different robot programming and control strategies is a limiting factor. The ongoing research for programming interfaces for construction is promising. Techniques to train robots with demonstrations add to these ideas. Finally, robot learning seeks to embed intelligence into robots to give them autonomy during tasks that would be hard to program or infeasible due to material tolerances or other unforeseen obstacles.

2.3.3. Robot Oriented Design

Components for the assembly with a robot can benefit from robot-specific design. If one wants to avoid a sensory overhead in the robot, the design of the elements has to be adapted. Machines like robots have other strengths than human workers but also some limitations. For instance, a robot can perform the same dull and tedious tasks for hours or even days without any break but needs sensors to recognize tolerances or errors during their execution.

First conceived by Thomas Bock in 1988, robot-oriented design (ROD) emphasizes the idea to consider robot-related parameters in the earlier design and production phases. In order to create defined conditions for robot use on-site, building subsystems, e.g., building structure, components, elements, assembly procedures, and equipment selection, etc., must be geometrically and physically defined following robot capabilities (T.-A. Bock, 1988).

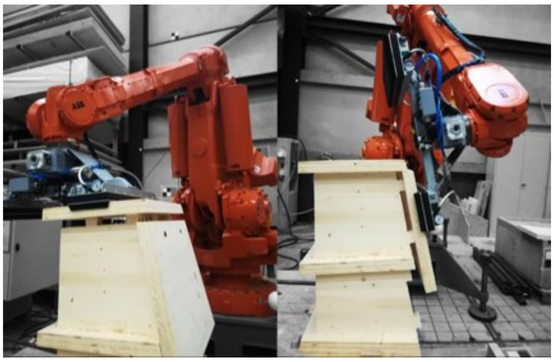


Figure 2-66 Assembly of 13 non-orthogonal timber panels without using the visual feedback loop

One example of adjusting element connections for the robotic assembly was tested on integrally attached timber plate structures. The design of the timber joints was chamfered to address material tolerances (Rogeau et al., 2020). The initial approach focused on making the robot fit for the task by equipping it with a visual sensing system. However, the vision system was not suitable for the insertion task, which led to an adaptation of the joints. These insights highlight the necessity for a deeper understanding of robot capabilities. Two consequences can be derived from these findings. First, the joints have to be adapted for robotic assembly, and second, the capabilities of the robots for construction have to be extended.

One of the few examples in which a building block was specifically designed for robotic assembly is the Acoustic Brick Wall by Gramazio and Kohler Research. The project consists of a wall made from hollow plastic bricks that can be customized with an infill plate. Depending on the insertion depth of the infill, the brick behaves differently when it comes to its sound reflection properties. The geometry of the bricks is determined by a low-tech yet self-correcting “fall in place” mechanism to automatically avoid horizontal misplacement (Vomhof et al., al 2014). The handling of possible vertical tolerances happens through a sensitive placement of the Sonotrode. To initialize the welding procedure, the Sonotrode is lowered to the piece without pressure. Once contact is established, a pressure of 1.8 bar is applied, whether the Sonotrode has already reached the programmed final position or not. This way, tolerances of up to 5mm can be handled without losing weld quality (Figure 2-67). The combination of the customized bricks and the shape of the wall enables the programming of sound reflection.

Figure 2-67 The welding (left), transport (middle), and placement of the acoustic bricks (right) (Vomhof et al., 2014)

The attempt to create structures from a robot-oriented design standpoint can also have implications for generating the elements depending on the designed overall structure. As robots come with certain constraints, some of which are related to their workspace, the subdivision of the structure to be assembled can be altered (Ariza & Gazit, 2015a). Figure 2-68 shows a cantilevering structure that is assembled from elements subdivided for robotic assembly. The cantilevering mushroom-like form was subdivided using a diagrid with considerations of the robot's maximum reach. Furthermore, the joints are specifically designed for the robotic assembly process. The prototype highlights the importance of embedding machine constraints into the design early on while presenting the possibility to adapt designs to robotic assembly.

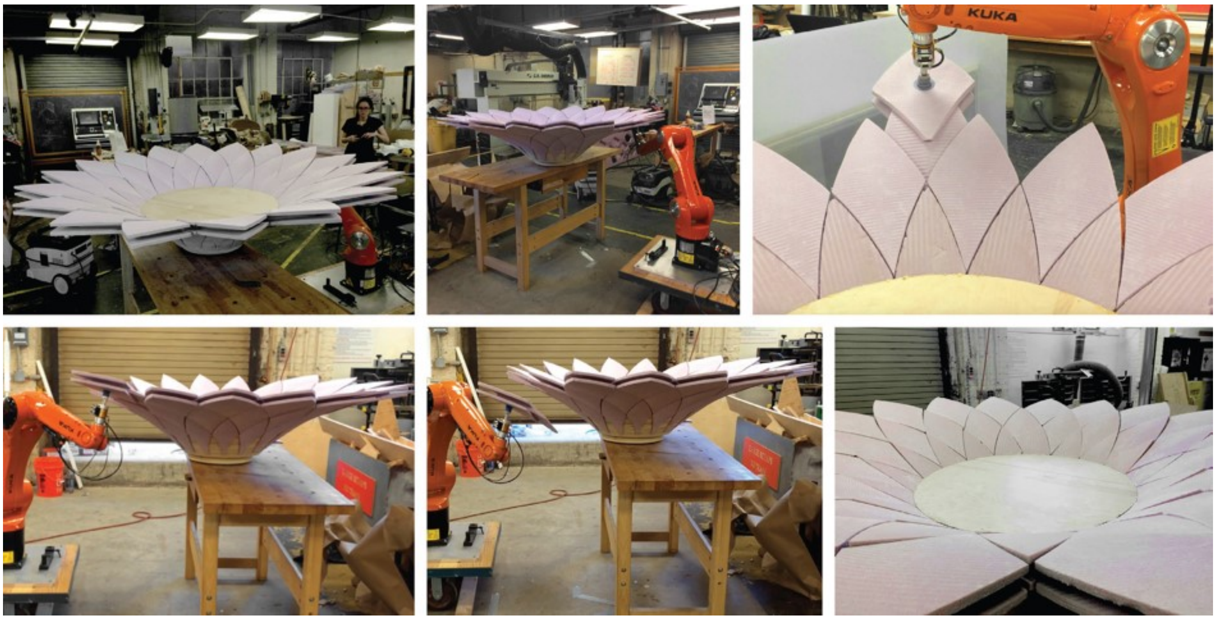


Figure 2-68 The robotic assembly process of cantilever structure (Ariza & Gazit, 2015a)

Due to the limited amount of robot-oriented design with industrial robots, it is worth illuminating how building elements change due to the limitation of the robot. For instance, drones come with more obvious limitations than industrial robots. They can only lift a limited weight, have higher placement tolerances, and apply less force during assembly. These constraints lead to a more obvious adaption of building elements towards the robotic system.

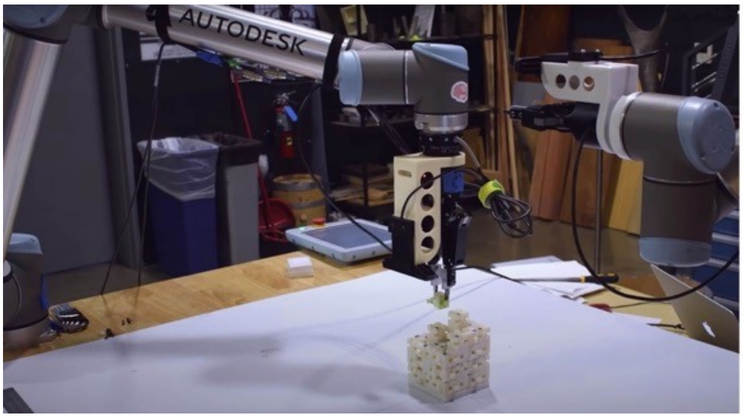
The construction of masonry construction with drones is currently under investigation. A variety of stackable building blocks were designed with an interlocking detail suitable for drone assembly. The designed and fabricated elements are called dricks, combining the word drone and bricks, highlighting the robot-oriented design approach of these elements. Compared to industrial robot arms, drones are less precise in the placement and handling of elements; thus, the elements should have self-aligning properties (Goessens et al., 2018). The 20 kg dricks are drone-compatible with geometrical details for vertical stacking.

Figure 2-69 Construction of a wall composed of rectangular dricks and four different types of dricks (Goessens et al., 2018).

The design of building elements for robotic assembly can have further advantages than a simplified and error-correcting connection. As robots can endlessly repeat their actions, it would be possible to integrate this capacity for elements to be constantly reconfigured. For such cases, the building elements need to be programmable following the logic of Digital Materials. Predefined and limited connections have to guarantee sound configurations. Such systems could also highly benefit from integrated electronics for communication and sensing. These Cyber-Physical Systems enable the structure to self-check the distribution of the elements and their communication to the assembler. In the case of a reconfigurable canopy, these ideas were exemplified with a drone for assembly and reconfiguration (Wood et al., 2018). The smart roof tiles are lightweight elements made from carbon fiber with an integrated microchip and a sensor (Figure 2-70). At each edge of the tile, the magnetic connectors come with pins for communication between the elements. The connectors have only limited load-bearing capacity and rely only on the embedded magnets. However, it is a prototypical project, the integration of the communication within the elements drives the conceptualization of buildings as information processors further.

Figure 2-70 Smart roof tiles are snapping together during the placement with a drone (Wood et al., 2018)

Attempts to explore the vast space of combinations of various connections with mechanical fasteners were implemented in a voxel-based assembly system. Nine different voxel types can be robotically assembled into interlocking structures. The proposed joints were explicitly designed for the robotic assembly. Their geometrical joints provide a variety of engagements while overcoming permanent adhesives. The building plans for such structures are relatively complex, rendering them most likely unfeasible for humans. Without any means of dictating the voxels' orientation and sequence, it becomes a challenging puzzle to solve. Hence, the project highlights the complexity and variety, which can be embedded into the building kit. The digital storage of the assembly sequence and its translation into robot instructions might call for a rethinking of building elements.



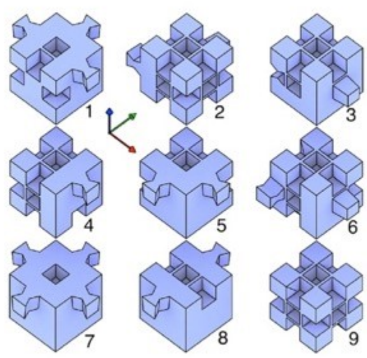


Figure 2-71 Robotic assembly of 48 pieces of re-usable interlocking blocks (left) and the nine different types of cubes used (right) (Zhang & Balkcom, 2016).

The precedents presented so far rely on existing robot systems like the industrial six-axis robot or a drone. Both robot systems are fitted for assembly through the use of a specialized robot hand – the gripper. The design of the gripper is a crucial element in bringing together the robot as an assembler and the building elements. Interestingly, the attempts to address robot limitations become more dominant in the design of elements for drone assembly due to more obvious limitations. However, the ties between robot and element design are something that has to be considered. There are also approaches to build robots highly integrated within a material system.

2.3.4. Material-Robot Systems

An emerging trend in robotic research is the modularization of robots, itself strongly linked to a material system. These Material-Robot Systems (MaRS) are mobile robots that can assemble discrete cellular structures (Jenett & Cheung, 2017). The robot and the material are designed to form a coherent system in which both entities match. The elements are designed for robotic assembly, and the robots are engineered for their assembly. This process is a negotiation starting from both sides, influenced by technical and material constraints (N. Gershenfeld et al., 2015).

A discrete cellular structure has been assembled from manufactured cuboctahedra unit cells (Figure 2-72). These cuboct voxels can be connected at the six faces with press-fit magnets. The engineered mobile robots are capable of maneuvering within the space-filling lattice structure and can reconfigure the spatial arrangement of the voxels (Figure 2-73) (Jenett et al., 2019). The voxels and the robots form an integrated system, reducing many of the redundancies, as mentioned earlier.

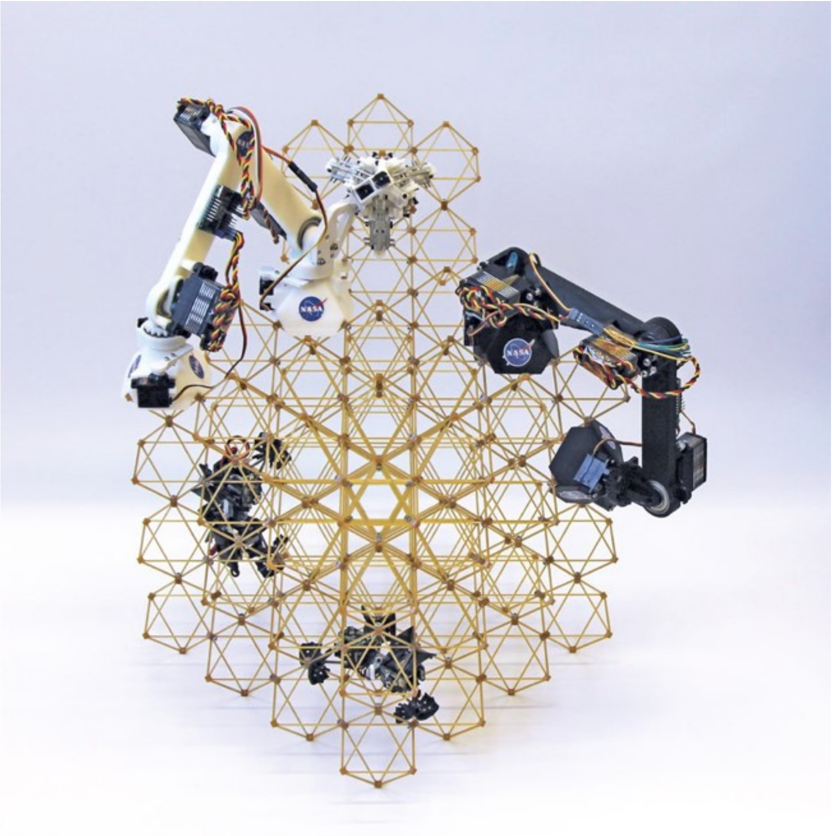


Figure 2-72 A space-filling lattice structure assembled from multiple mobile robots (Jenett et al., 2019)

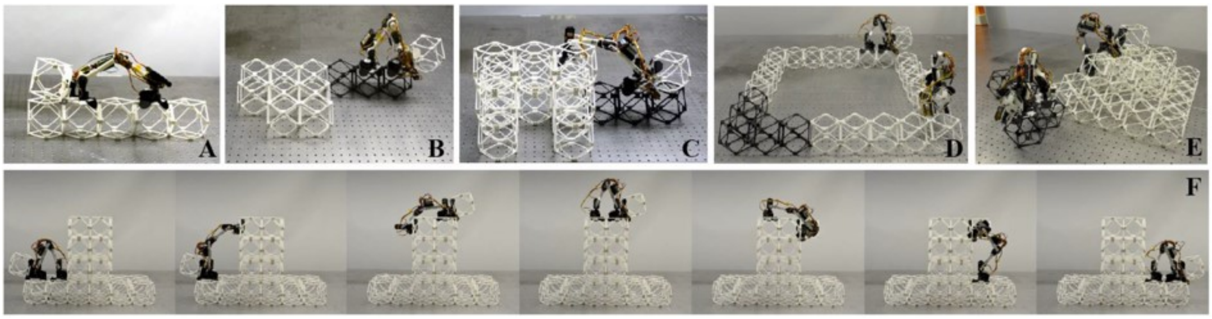


Figure 2-73 Various robot experiments that can be assembled with the voxels: A) 1D beam, B) 2D plate, C) 3D enclosure, D) branching structure assembled with two robots, E) construction of 35 voxel pyramid, F) 3D voxel transport (Jenett et al., 2019).

Another example of integrating the two systems is the MaRS truss. A truss system was engineered in relation to a robot. While the robot was engineered to climb along the truss structure and screw or unscrew the truss elements (Figure 2-74), the rods were enhanced for the robot by adding texture to the rods (Figure 2-75)(Nigl et al., 2013). The rippling surface finish of the rods prevented slippage during climbing and assembly. The negotiation between the modalities of the robot and the building elements show how the two condition each other. A lot of effort could be put into the engineering of the robot to rotate the rods, but instead, the effort is transferred to the rods.

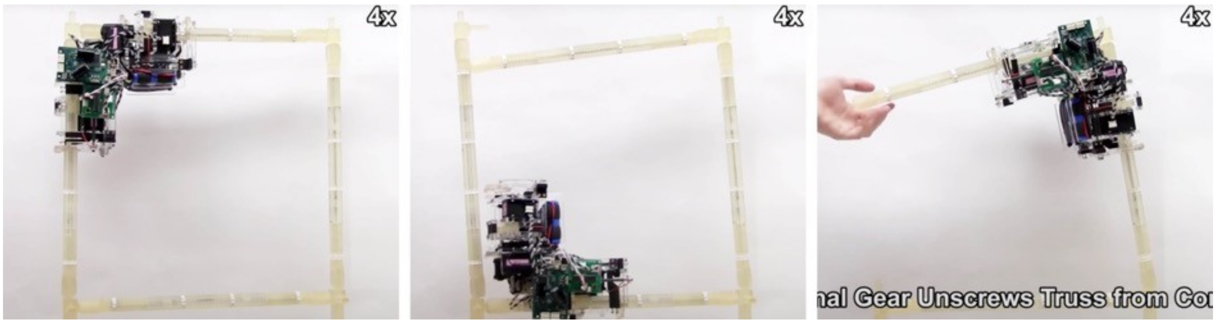


Figure 2-74 Stills from a video showing the disassembly of a truss system (*Machine Metabolism: Structure-Reconfiguring Robots | Hackaday*, n.d.)

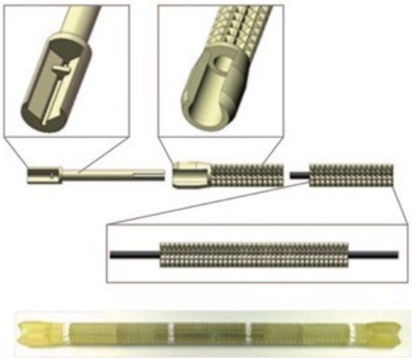


Figure 2-75 Assembly of a rod with the female part of lockable connector and photo of 3D printed connector node (Nigl et al., 2013)

Figure 2-76 The discrete timber bricks are designed for fully autonomous manipulation by integrated and distributed robots (Tedbury, 2017b)

The robot and building elements can become very similar. The AssemblerAssemble project is a box robot that is highly integrated and similar to the building blocks (Figure 2-77). The study highlights aspects of robot systems that might reside indistinguishable in the building. The project opens up speculations about robotized buildings in which the building elements can automatically reconfigure themselves.

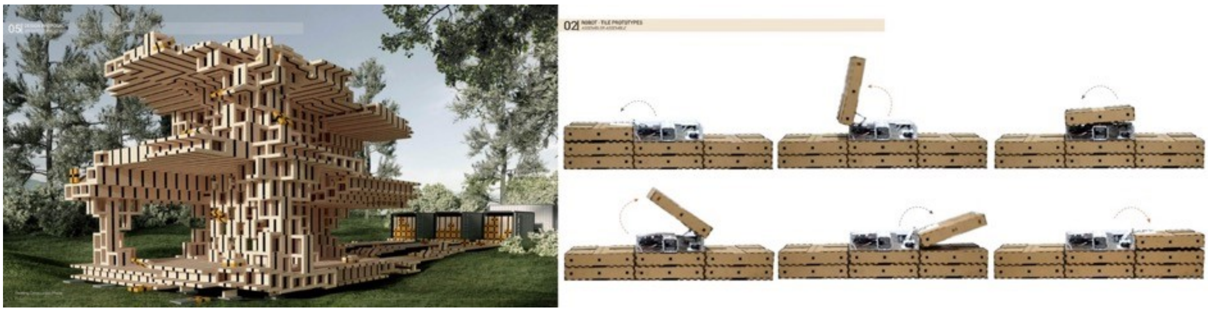


Figure 2-77 Rendering of a two-story building assembled from AssemblerAssemble blocks (left) and a physical prototype of a robot moving one block from left to right on an existing, assembled stack of blocks (right) (Dafni Katrakalidi, Martha Masli, Mengyu Huang, Man Nguyen and Wenji Zhang, B-Pro Research Cluster 4, Bartlett School of Architecture, University College London) (Retsin, 2019b).

One of the challenges in building structures with robotic assembly is that most current building elements are designed for manipulation by humans, not by machines (Nigl et al., 2013). These human-oriented building elements often require complex assembly and are often cumbersome to manipulate. Researchers started merging the two fields of robot engineering and robot-oriented design. They started to build an understanding of integrating the machine and the building system. The Semblr robot is such an attempt to engineer a construction robot specifically for a building block (Figure 2-76). At the same time, the building elements were becoming appropriated for robotic assembly. While this might seem constraining in some cases, the error-correcting and dry-fitted connection properties can be explored for concepts like combinatorics and reassembly. The editing of building elements becomes accessible for the robot through such implementations.

2.3.5. Disassembly with Robots

The reassembly of structures depends on their capacity of disassembly before a new loop of assembly can start. The disassembly of existing structures presents an even more extensive set of difficulties compared to assembly processes. Although it is an essential aspect of a more sustainable built environment in the sense of circular economy, very little research was done on novel robotic technologies for disassembly (Lee et al., 2015). Among others, well-known problems are the unstructured environment, high tolerances, and the lack of a closed digital data flow in planning and execution (Lublasser et al., 2016).

Most existing robots used in deconstruction are mainly applied in demolition rather than disassembly (*CDi Demolition - Demolition, Robot | CDi Demolition*, n.d.; e.g., *Demolition |*

Kera-Mix, n.d.; *Remote-Controlled Demolition Machines- Brokk USA*, n.d.). These robots are teleoperated and work similarly to other heavy-duty machines like mini-diggers with an operator cabin (Figure 2-78)(Derlukiewicz, 2019). Here, the robot is not programmed, and the sensory input comes from the human operator. The debris created in such scenarios does not differ from conventional waste, nor does the overall logistics of demolition waste.

Figure 2-78 A remote-controlled demolition robot with the operator right next to the demolition (*CDi Demolition - Demolition, Robot | CDi Demolition*, n.d.)

Kajima Corporation developed an approach with different logistics when it comes to deconstruction in Japan. Instead of demolishing the building from the top down, the whole building is slowly demolished on the ground level (Figure 2-79). The approach drastically reduces the demolition logistics and emissions. Thus, presenting ways to rethink the order of taking apart the built environment.

Figure 2-79 The sequential demolishing process is not only layer-based but follows the same approach on different levels. The building is first demolished on one floor (middle) and lowered (*The Kajima Cut and Take Down Method | Technology & Services | KAJIMA CORPORATION*, n.d.).

A more structured way to extract entire building components or elements was proposed in the form of a robotic system. The deconstruction robot comes with all the equipment necessary for cutting out components from existing structures. Although the robot was presented on a conceptual level (Figure 2-80), it shows the growing interest to reconsider how buildings are demolished. This robot combines different tasks in one robot platform. Even the temporary storing of elements is part of the system.

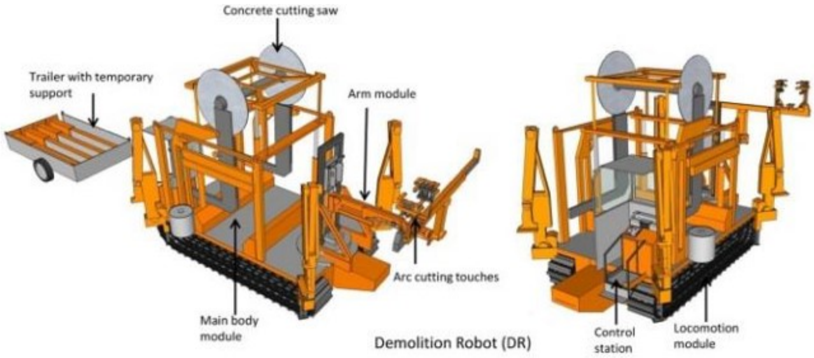


Figure 2-80 The proposed design for a deconstruction robot for cutting down a building (Lee et al., 2015)

Another option to extending the lifetime for buildings is refurbishment. Automation of building refurbishment is a complex endeavor due to the multiplicity of various tasks involved; thus, making it necessary to implement multiple robot systems (Hu et al., 2016). Nevertheless, first experiments in applying robots for the disassembly of facade panels were conducted (Lublasser et al., 2017). A robot mills the plaster layer of a facade into small tiles and removes these tiles from the insulation layer below. In the next step, the robot cuts the insulation foam into small pieces using a hotwire end effector. Finally, the glue is removed from the underlying wall (Figure 2-81). The project illuminates the necessary disassembly steps caused by gluing while presenting a way of structured disassembly.

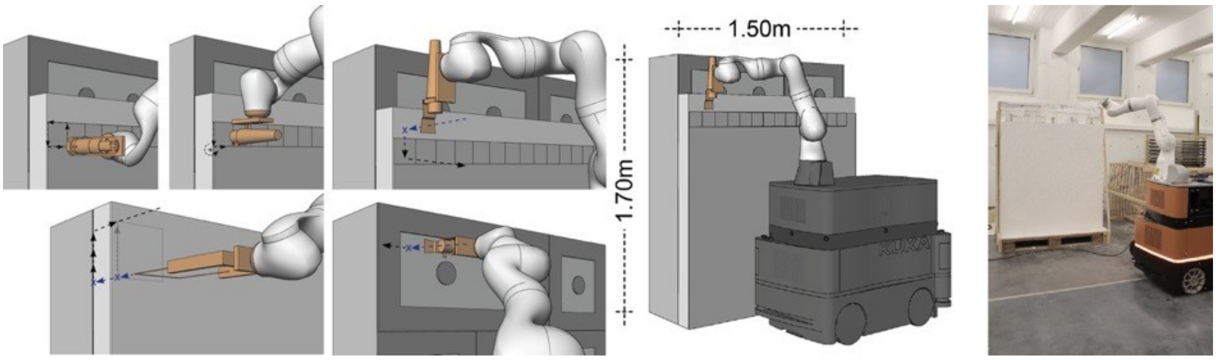


Figure 2-81 The different steps and end effectors involved during the deconstruction of a multi-layered facade and the mobile platform with the six-axis robot arm (Lublasser et al., 2017)

One proposal for the reassembly of prefabricated elements was proposed as a Robotic Prefabrication System focusing on re-fabrication. The system would be capable of automatically disassembling structures made from prefabricated elements and its reconstruction according to a new design (Kasperzyk et al., 2017). The project goes beyond a theoretical explanation of such a system and presents it in a small-scale model consisting of LEGO Duplo and LEGO Mindstorm components. The results from this study need to be scaled up and applied to a more realistic problem set by incorporating 3D assembly operations. Nevertheless, it presents a formalized approach to planned reassembly inscribed in algorithms and machinery.

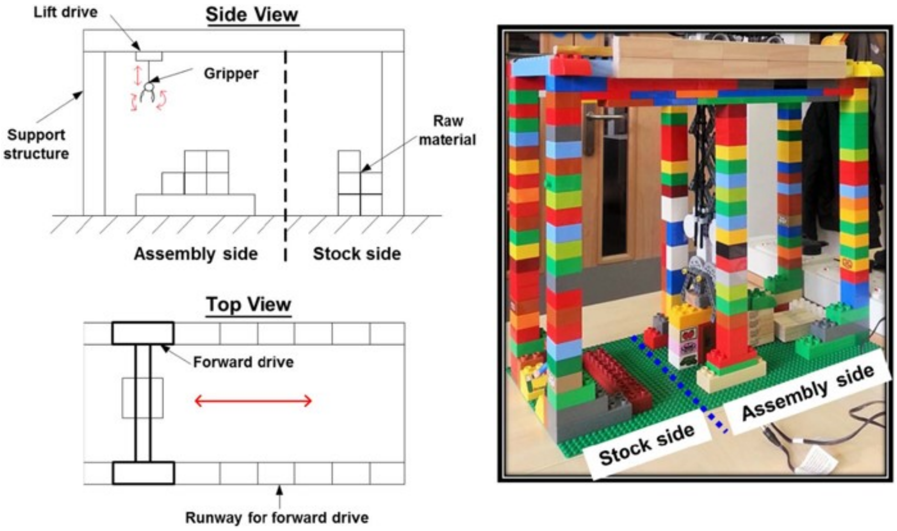


Figure 2-82 The small-scale prototype made from LEGO Duplo and LEGO Mindstorm (Kasperzyk et al., 2017)

The disassembly with robots is still challenging due to the high dependence on recognizing the robot's environment (Corucci & Ruffaldi, 2015). Robotic skills are constantly growing, like unscrewing for automated disassembly is being developed in research projects (Mironov et al., 2018). While the assembly of building elements can benefit from the robot-oriented design of the elements, the same is true when the elements are designed for disassembly. However, even in the case of building elements that are fit for easy disassembly, there are a set of perceptual challenges for robots. These include both the reversibility of the disassembly planning and the perception of the physical product, which might differ from a digital building model. Instead, it is most likely that the robot needs to adapt during the dis- and reassembly of existing structures due to unforeseen events. Disassembly cannot be considered as the reversed assembly process as uncertainties increase. The unpredictable characteristics of deconstruction due to misalignments, defects, damages, or any other mismatch between the original model and the actual physical product are still to be developed (Poschmann et al., 2020).

Conclusion

In the history of architecture, several attempts have addressed the reassembly of buildings. This is true for different scales in the hierarchy of the building system. Reassembly starts as a design problem that has to be embedded early on into the building system to become actionable. Even if the building elements are fit for reassembly, related technologies have to be implemented to foster such processes. Nevertheless, there are various challenges when it comes to the reuse of building elements. These include the lack of reversed logistic strategies and the lack of design protocols for disassembly (Durmisevic et al., 2017). Emerging concepts like Discrete Design, Programmable Matter, and Digital Materials offer promising paths for reversible and reprogrammable architectures. The concepts are inherently linked with computational tools, formalizing them into algorithms, strategies, and protocols towards reassembly.

For reassembly, gluing techniques used in construction are not suitable. Instead, we need to design modular systems that can be fixed through other mechanisms, for example, self-load, dry fit, and self-alignment. The many attempts by engineers and designers to create universal connectors show that the universal joint is more of an illusion than an actual solution (Makowski, 2002). Moreover, most of the existing connections were developed for manual joining, making them unhandy for automation. The concept of Digital Materials presents interesting insights into programmable matter with considerations towards automation of the assembly of the vast number of elements. Yet, their implementation for automated construction still seeks validation.

Investigating reassembly through computational design, reversible connection, and automated assembly technologies requires a rethinking of current modes of architectural production. The biggest challenge is understanding how the building systems, connection details, and robot systems constitute each other. The capabilities of robots in architecture are already impressive. Robots can lift heavy objects with precision and repeatability that outperforms every human. Nevertheless, significant limitations such as robotic sensing skills and their comprehension into meaningful actions still exist. Especially for autonomous construction processes, these challenges are yet to overcome (Ardiny et al., 2015). The introduction of robots into construction offers opportunities to further formalize the digital connection between design, planning, and construction. While this trend is up-and-coming, the number of precedents for the robot-oriented design of building elements are limited. Even for small-scale structures, only a small number of prototypes tie a strong relationship between the robot system and the elements to be assembled. Most research on robots in the field of architecture is conducted using the case studies method (e.g., Dörfler, 2018; Lim, 2016; Parascho, 2019). Physical prototypes and demonstrations could provide adequate information and evidence for decision making and directing future implementations of robotics in construction (M. Wang et al., 2020). The next chapter introduces the case studies method, focusing on the production of prototypes and demonstrators. While prototypes allow first tests of an idea, final demonstrators could serve as proofs and communication devices towards Design for Reassembly.

3. Methodology

> "Science is about model building, not facts. Every experiment is a model, a form imposed on a piece of world to produce an effect, isolate a behavior, generate a fact that can be transposed to another milieu. […] Any practice […] which approaches this place and world with something other than a superstitious and magical attitude, is fundamentally science."
>
> Sanford Kwinter (Kwinter & Risteen, 2007)

In recent years, researchers in the field of computational design and robotic fabrication have shown the advancement of knowledge through the production of prototypes and demonstrators (see e.g., Gramazio & Kohler Research, n.d.; Projects | Institute for Computational Design and Construction | University of Stuttgart, n.d.). This creation of examples is especially fruitful for endeavors for which only few physical demonstrations exist, such as technology-driven investigation linking digital design with robotic fabrication. The production and qualities of such physical artifacts were reported in dissertations, conference and journal papers. Following these approaches, the methodology of this research focuses on the production of physical examples and insights to identify the necessities and develop questions around the topic of Design for Reassembly.

The technology-centered research on computational design and robotic fabrication has led to a stronger relationship between designing and materialization (Carpo, 2013b). The robot as a physical manipulator merges these two often separated acts (Picon, 2014). Due to the emergence of these technologies and their deriving processes, the field of digital design and fabrication has been building a novel paradigm for architectural production. There are fundamental changes for architecture that dissipate from these technologies. Leading researchers in the field present their views on the paradigmatic shift as follows.

> "[...] what we are observing today is the comprehensive digitalization of architecture, which entails a radical paradigm shift in its production conditions. The employment of robotics in architecture is opening up the prospect of entirely new aesthetic and functional potentials that could fundamentally alter architectural design and the building culture at large."
>
> (Gramazio & Kohler, 2008)

For this paradigm shift, novel techniques and methods started being utilized. Gramazio and Kohler, for instance, began their investigation on robots in architecture by setting up the Architectural Robotics Laboratory at the Department of Architecture at ETH Zürich in 2005. Equipped with industrial robots', architects were confronted with the technological medium of this generic machine as their inquiry. Their book The Robotic Touch illustrates almost one decade of investigations and academic projects on architectural design with robots (Gramazio et al., 2014a). The 33 projects in the book circle around demonstrations of robots interacting with different materials (Figure 3-1). Their emphasis on physical demonstrations illustrates the path creating knowledge in this discipline and became a role model for this dissertation.

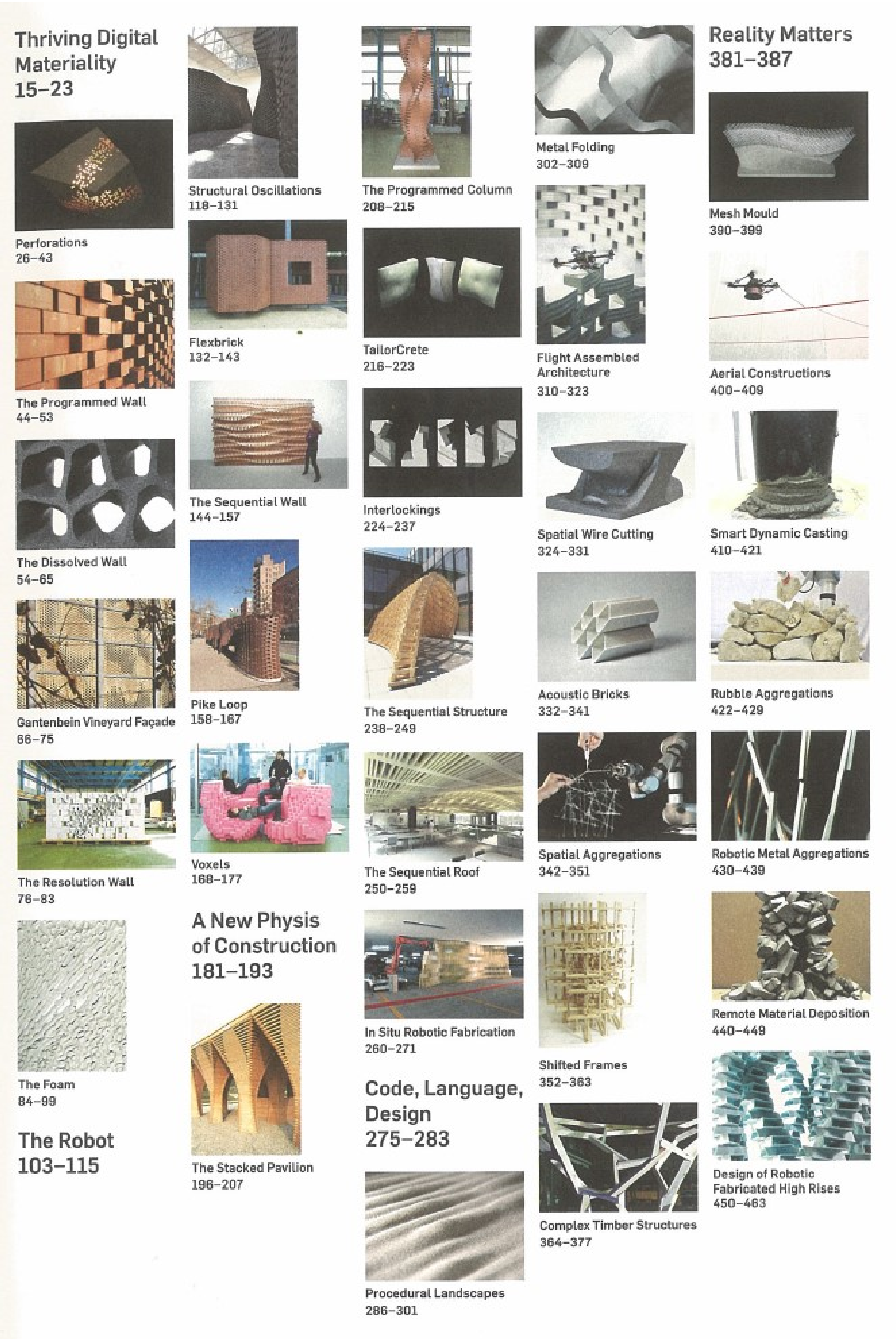


Figure 3-1 The project overview from the book The Robotic Touch by Gramazio and Kohler Research (2014a)

Only through interacting with the technology, the researchers can build an understanding of the technology. These insights are crucial for the building of a theory of robot-aided architecture. The production of examples is carried out by an in-depth investigation with materials and by programming and physically interacting with a six-axis robot. In many research projects on the topic, different tools have been developed that enable the usage of robots for architecture relevant tasks. Almost all of the presented projects were reported in scientific papers (Gramazio & Kohler Research, n.d.). And although the term is rarely defined in their papers, they were frequently referred to as case studies.

In the case of the Gramazio and Kohler Research, these studies focus on demystifying the robot and making it operational for the discipline of architecture. Such qualitative research usually starts with an open-ended research question that often changes during the process of research to reflect an increased understanding of the problem (Creswell, 2007), or in this case, the technology. In such cases, the analytical research paradigm would be insufficient for investigating complex issues. Quantitative studies like the experiments focus too much on relatable variables. The control and observability of the variables are at the core of the experiment with the desired outcome to test a hypothesis. Instead, this research seeks to build theories through the interaction with the technology to be tested in future research.

Some of these methods are considered rigorously scientific and others less so. Krippendorff (2008) explained that while scientists create knowledge through observation, designers seek to make sense and change things; both can be found in the work of Gramazio and Kohler Research. He proclaimed that science for design should be treated as a scientific activity that questions scientific findings, creates possibilities, vigorously examines their methods, creates variability, and participates as stakeholders in the scientific networks.

> "The history of design is full of examples where scientists claimed impossibilities that designers managed to circumvent or prove wrong. Scientists once assured us that it was impossible for humans to fly and now we do. Engineers calculated that the steel wheels of locomotives on steel tracks would not have enough traction to pull a train, and they were wrong. In the 1950s, IBM researchers are reputed to have concluded that the world would need no more than five computers. This did not discourage Steve Wozniak and Steve Jobs, working in a California garage, to develop the first personal computer. In effect, designers need to question prevailing ontological beliefs. Being afraid of undermining common convictions makes for timid designs. Proposing what everyone knows or already uses is not design at all."
>
> (Krippendorff, 2008)

The quote very well points to the fact that designers are eager to tackle the "known". While researchers are developing models that can be tested, designers have to implement things that have utility and that work. But can design qualify as a science?

The relation of research and design has been articulated in various ways (Gaver, 2012; Krogh et al., 2015). Faste and Faste (2012) propose research as a part of the design practice, pointing to the importance of design delivering knowledge. They developed four categories of design research: design through research, design of research, research on design, and research through design (Figure 3-2). Within these categories, design serves on different stages in generating knowledge.

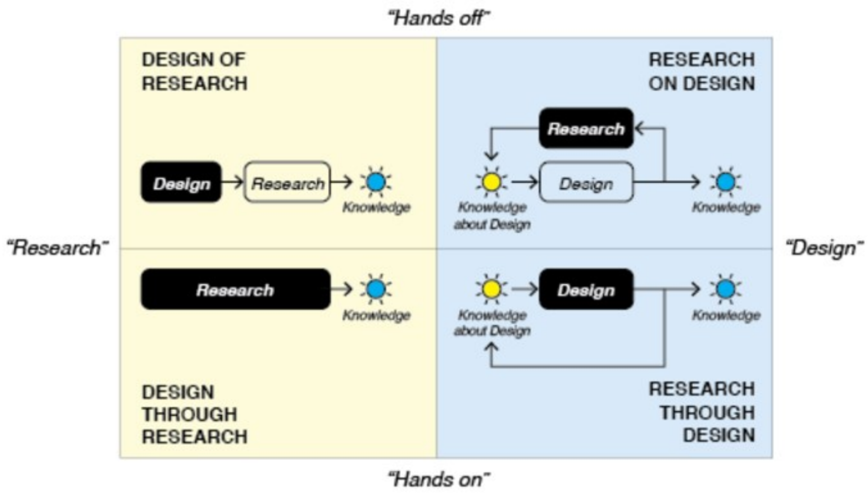


Figure 3-2 Four categories of design research: (1) design through research, wherein researchers perform activities that would conventionally be considered "research" – regardless of their awareness that their activities are "design"; (2) design of research, the activities routinely performed by researchers to plan and evaluate their experimental designs; (3) research on design, wherein researchers study design practice at work, thereby revealing relevant process knowledge; and (4) research through design, wherein designers design things "as usual" but consider their results research because, in addition to shaping tangible outcomes, they have learned something new about their practice. (Faste & Faste, 2012)

The case study design in this research, within these categories, is situated between research on design and research through design. Phases of revealing relevant process knowledge were shifting with steps focusing on reflection for designing for reassembly. Different artifacts were created during the research, yet the focus is not on their qualities as an object but instead on their production of knowledge. During the fabrication, data like photographs, drawing, algorithms, and notes were collected. Moreover, these objects served as proofs of concept and to yield new research question.

Therefore, prototypes and demonstrations are the vehicles for the investigation of Design for Reassembly in this dissertation. It focuses on the case study method to conduct explanatory studies for theory building on design for reassembly. The case study method in architectural research is a well-known research format to explore a phenomenon in its embedded context (Groat & Wang, 2004). In the following sections, a brief introduction of the case study method in architecture is presented. The case study method is explained in more detail and appropriated for the dissertation's technology-driven inquiry of robotic assembly demonstrations. Applying this method for the technology-driven research in the field of computational design in architecture is the inquiry of this dissertation.

3.1. The Case Study Method

Many different approaches and a large body of literature about the case study as a research method exist. The use and the topic in which a case study is used vary depending on the field. It is used in many different areas like sociology, psychology, political science, business, and community planning. Although the different disciplines may implement the method differently or follow discipline-specific protocols, they agree on certain characteristics (Hatch, 2002). The case study was defined as a qualitative research method (Yin, 2014). It follows a strategic procedure for collecting, organizing, and interpreting contextual information and generate insights into phenomena that cannot be measured quantitatively. Qualitative methods enable researchers to generate comprehensive descriptions of processes, mechanisms, or settings. Its goals are developing a deep understanding of a phenomenon and generating research questions and hypotheses that can be further tested in quantitative research. The case study attempts to raise questions that cannot be answered affront and thus needs a qualitative investigation into the topic (Creswell, 2007).

The purpose of choosing the case study as a research method should be exploring, describing, and explaining phenomena (Yin, 2014). It is a flexible method allowing researchers to react to changing circumstances and gathered information. Researchers use the term case study to describe a method that is not an observational study, a survey, an experiment and is not statistical (Merriam & Tisdell, 2009). Hence, this method will never deliver statistical significance conclusions. On the contrary, various evidence such as figures, statements, and documents are linked together to derive relevant and robust conclusions (Runeson & Höst, 2009). Furthermore, the case study is a well-documented and systematic examination of the process, decision-making, and outcomes of a project undertaken to inform future practice, policy, theory, and education (Francis, 2001).

Experiments, in contrast, would emphasize causal relationships between clearly quantifiable variables. The purpose of experiments is to test a hypothesis, a statement that can be either falsified or verified. The case study is more structuring and analytical; it is variable and the course of it may even change during the research. While the experiment aims at validating or falsifying, the case study seeks to open up the discussion and raise new questions for future research (Evans et al., 2014, pp. 85–88).

3.1.1. Technology Case Study in Computational Architectural Research

In architectural research, the case study method was described by Groat and Wang (2004) as the study of a phenomenon embedded in its context, focusing on real-world settings. One of the most significant current research utilizing the case study method in the field of digital design and fabrication is the NEST project (Next Evolution in Sustainable Building Technology). It was initiated by Empa and Eawag in collaboration with partners from the public sector, industry, and academia, such as the Swiss National Centre of Competence in Research (NCCR) and ETH Zurich. Gramazio Kohler Architects designed the building as a research platform from 2010 to 2016. The central backbone of the building consists of concrete slabs and basic infrastructure for installing different research demonstrators (Figure 3-3).

Figure 3-3 The NEST building as a platform gave space for the digitally fabricated DFAB house (photo: Roman Keller, 2019).

Several research projects found their place on the different platforms. A particularly interesting project in NEST is the DFAB house (*DFAB HOUSE – Building with Robots and 3D Printers*, n.d.). The house placed on the NEST platform was designed, planned, and built using predominantly digital processes. The building served as a case study, investigating some of the latest digital fabrication technologies (Graser et al., 2020). These investigations included on-site robotic fabrication (Dörfler, 2018; Hack, 2018), robotic prefabrication (Adel Ahmadian, 2020), 3D printed slabs (Meibodi et al., 2018), and robotic slip casting (Lloret Fritschi, 2016). As such, the building is a compound of several research projects circling around digital fabrication, yielding one collaborative demonstrator (Figure 3-4).

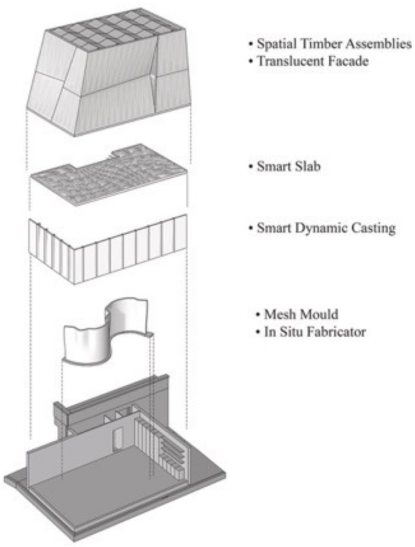


Figure 3-4 Explosion diagram highlighting the different digital fabrication approaches (Graser et al., 2020)

Similarly, Menges institute, the ICD Stuttgart, developed its research on computational design and fabrication through yearly research pavilions serving as demonstrators (Figure 3-5) (*Projects | Institute for Computational Design and Construction | University of Stuttgart*, n.d.). Although these projects are rarely referred to as case studies, they share many qualities that qualify them. These qualities include their extensive documentation in photographs and videos and their comprehensive reporting in the form of conference and journal papers (e.g., Menges & Knippers, 2014). As such, these reporting documents allow for reflection and discussion with peers.

Figure 3-5 Three examples of the research pavilions from the ICD Stuttgart (*Projects | Institute for Computational Design and Construction | University of Stuttgart*, n.d.)

Both research institutes generate knowledge through physical demonstrators. Their investigations were driven by research questions towards the utility of robotics in architectural contexts. The demonstrations reach from prototypes and pavilions up to complete building. While the experiment is in their repertoire, the case study became the dominant method for their endeavors. Architectural researchers in digital design and fabrication have appropriated the case study strategy for their technology-driven investigations, studying topics in their natural context or in situations with variables that exceed a conventional experiment; the case study method delivers results that other methods cannot render.

In this dissertation, the terminology of the *Technology Case Study* (TCS) is introduced to address the technological focus of the investigation. Thereby, it shifts the focus from the more sociologically colored term case study. The investigations in other case study driven dissertations on digital design or fabrication technique were often highly influenced by an emerging technology. Existing examples of this approach in architectural research can be found in design as the study's context (Kilian, 2006; Tessmann, 2008). In the field of digital fabrication and robotics research in architecture, the PhDs by Tobias Bonwetsch (Bonwetsch, 2015a), Norman Hack (Hack, 2018), and Kathrin Dörfler (Dörfler, 2018) are excellent examples of the technology case study (Figure 3-6).

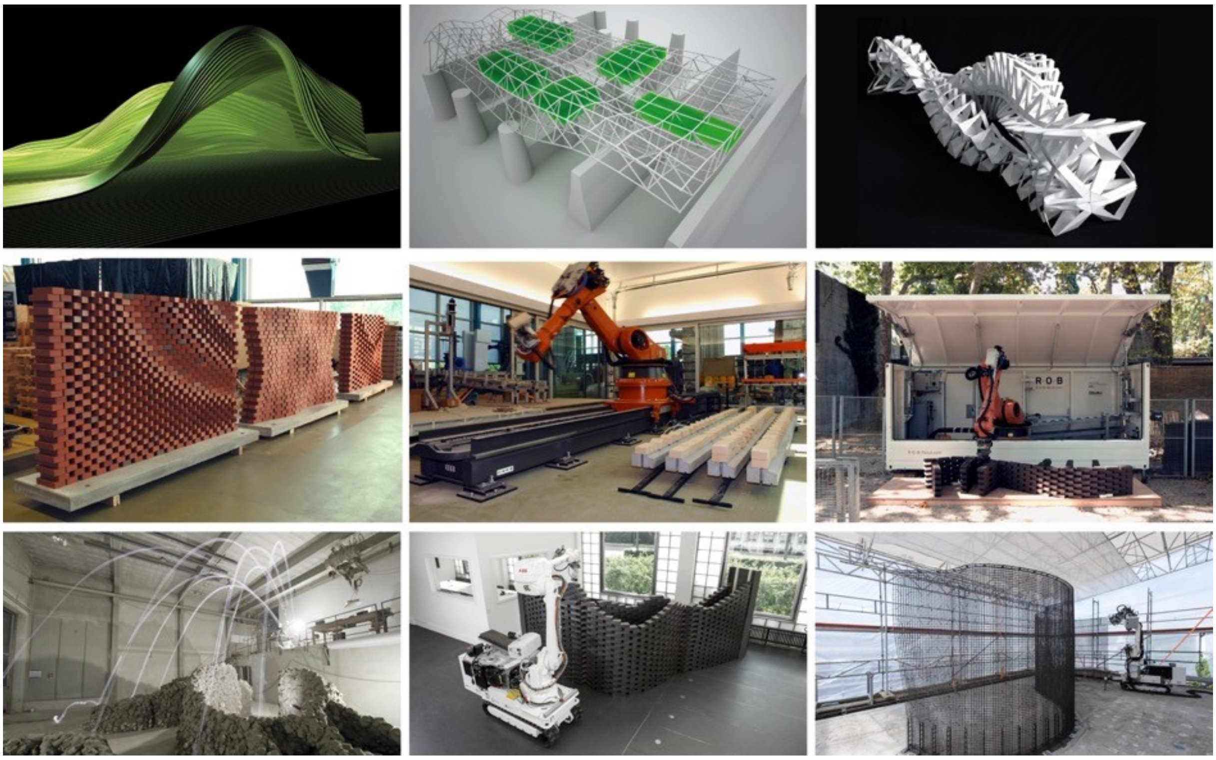


Figure 3-6 Three different series of case studies in computational design-driven dissertations: Oliver Tessmann (Tessmann, 2008) (top row and from left to right): Surface Structure, Space frames, and Sizing; Tobias Bonwetsch (2015a) (middle row): The Programmed Wall, Gantenbein Winery - Robotically assembled non-standard brick façade, and ROB Unit – Structural Oscillations; Kathrin Dörfler (2018) (bottom row): Stationary in situ loam aggregation, Mobil in situ brickwork assembly, and Mobile in situ rebar assembly.

Following these examples, the method was adapted for this dissertation. The intention was to observe the interaction of computational design tools and digital fabrication technologies in the context of design for reassembly. The term case study already suggests its two main characteristics. There should be a case to investigate, which could be a subject, a process, or circumstance. For this research, the cases were design concepts for robotic reassembly.

Additionally, the term study implies the sort of investigation, description, and explanation of how a case is conducted through observation and documentation and the collection and analysis of data. Here the following questions were addressed. Which tools are necessary for designers? Which qualities in tectonic systems and technologies are needed? How are the tools implemented and connected? These questions point to the fact that such means and concepts do not exist. Defining the necessary parts of these concepts and elaborating on their connectivity is challenging. Therefore, the case study method was utilized as an exploratory tool following a rigorous procedure–defined in the case study protocol. The case study`s specific steps for this dissertation are explained in detail in the following sections.

3.1.2. Case Study Protocol

The case study's value as a scientific method relies on the continuous comparison of data and theory. Therefore, a straightforward and curiosity-driven procedure must be stated, implemented, and followed to build theories. The case study protocol describes how the case study has to be planned, conducted, and analyzed. The scientific value of a case study depends highly on its protocol. Rigorous process steps suggested for conducting case studies must be followed while appropriating the case study method for the specific case needs.

The structure for conducting case studies is described along with different steps like case study design, data collection, analysis, and interpretation. These might differ from field to field and from researcher to researcher. Nevertheless, it is crucial to plan those steps and follow a defined protocol (Table 3). It prevents the researcher from missing steps, like collecting data during the study, and introduces rigor to the research questions. The more systematic these steps are planned and executed, the more relevant the study can become.

Table 3 Nine steps to standardize the case study based on Nnaemeka (2015)

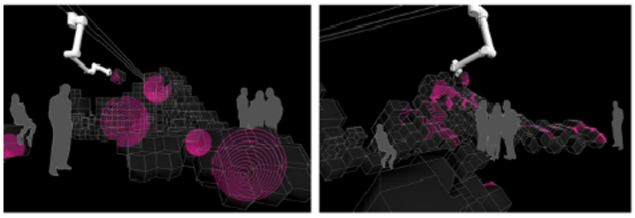
Stage 1. Preliminaries		
Step 1. Aim of the Case Study	Step 2. Identify the Case	STEP 3. Review of Literature
• State the aim of the case study. • State the reason of embarking on the case study.	• Select technologies for investigation. • Define the scope and case boundaries. • Seek design task. • Request site/case specific archival facility and operational data.	• Conduct literature review. • List the books consulted. • Validate the case. • State the yardstick of appraisal.
Stage 2. Approach Preparation		
Step 4. Plan the Case Study	Step 5. Develop Standardized Framework	Step 6. Develop Facility Documentation Methodology
• Create a timeline.	• Identify design attributes. • Identify expected outcomes	• Identify process and logistics for data collection effects • Script possible narrative for the later fabrication procedure • Store drawings, algorithms, etc. in versioned manner. • Setup photographs, videos, 3D scans, etc. for observation.
Stage 3. Data Collection, Analysis and Interpretation		
Step 7. Collect Data	Step 8. Analyze Data	Step 9. Interpret Data and Present Results
• Create design algorithms and drawings from step 6. • Conduct fabrication with data collection via observation from step 6. • Organize data.	• Analyze data from case based on standardized framework. • Develop diagrams to visually study design concepts. • Develop data tables from quantitative data comparison.	• Compare Findings to the benchmarks or standards in literature (if available) • Compare findings to other studies that used similar methodology • Develop design and technology guidelines • Write the lessons learned and other necessary detail.

The case studies in this dissertation were conducted following the suggestions by Runeson and Höst (2009):

1. Case study design: objectives are defined, and the case study is planned.
2. Preparation for data collection: procedures and protocols for data collection are defined.
3. Collecting evidence: execution with data collection on the studied case.
4. Analysis of collected data.
5. Interpretation and reporting of the case study.

The case studies format was set in the Digital Design Unit (DDU) research-driven teaching environment at TU Darmstadt. A collection of four case studies was conducted: continuous robotic reassembly, discretization for dry joined elements, incremental weight balancing of dry joined elements, and tactile robotic assembly. Therefore, different teaching formats were used to produce prototypes and demonstrators. These produced artifacts became cases to be studied. The data collection was done through diagrams, drawings, photographs, and filming. Throughout the case studies, the collected data were documented and analyzed. Finally, the findings were written down in reports in the results chapter of this dissertation. The following sections describe the different steps in more detail.

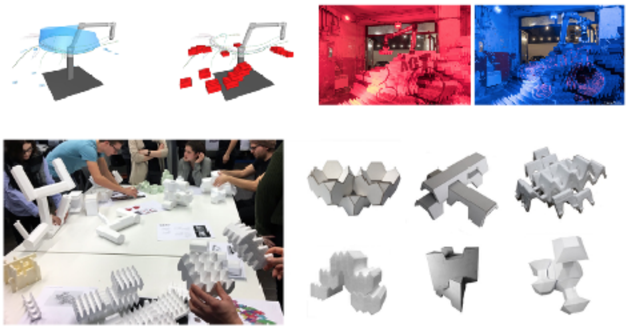
Table 4 The summarized protocol of the first case study



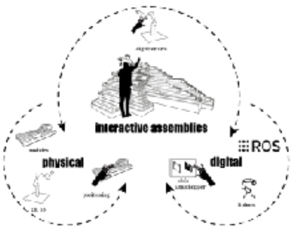
1. Case study design
Objectives are defined, and the case study is planned.
Installation at Frankfurt Lightfestival Luminale 2018 consisting of modules and a robot.
Setup during Wintersemester 2017/18

- Element development (drawings and photographs)
- Robotic programming (code and diagrams)
- Robot endeffector (drawings and photographs)
- Spatial qualities (photographs and videos)

2. Protocoll for data collection
Preparation for data collection: procedures and protocols for data collection are defined.



3. Collecting evidence
Trought the study algorithms, drawings, 3D-models, and photographs are collected



4. Analysis
The collected data finally is reviewed and analysed. This was done using diagrams.

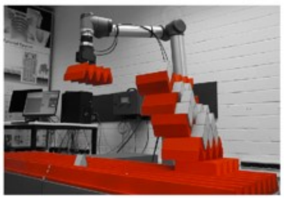
5. Reporting
Finally, the data is gathered into a report. The case study is described and the results are interpreted and discussed.

3.2. Design of Case Studies

The preliminary phase in the case study protocol is the case study design. This step includes defining the case study protocol and readjusting it to the needs of the researcher. The focus has to be put on defining the aims, objectives, and research questions in the design phase. It includes a review of the relevant literature, identification of technologies, and the planning of the study. Although case study research can never be planned entirely afront, and there will be many unforeseen events, it is beneficial to follow a protocol. It is recommended to document the whole procedure as it is developing in a diary or log document.

The studies in this dissertation were set out to be exploratory and cumulative; each study intended to get an in-depth understanding of the research topic from different perspectives. The goal was to open the field for ideas of digitally-driven reassembly by generalizing and creating examples. Each case study focuses on a particular topic in the context of design and reassembly. The topics include algorithms for redesign, dry-fitted stacking bonds, dry-fitted cantilevering through weight distribution, and sequential interlocking blocks (Table 5).

Table 5 The overview of the four conducted case studies

Continous Reassembly	Volumetric Discretization	Incremental Balancing	Tactile Robotic Assembly
			

In the following sections, the different case study design steps are explained in more depth. The steps include: defining the aims, objectives, research question, a literature review, a technology review, and the planning of the studies.

3.2.1. Aim of the Case Study

The case for the study is expected to be typical, critical, revelatory, or unique in some respect, while at the same time, it must be available (Benbasat et al., 1987). The possible choice of cases is generally vast; almost anything can be investigated in a case study, for example, an individual, a group of people, a process, a product, a policy, a role in the organization, an event, or a technology. When designing the case study, the motivation and the aim has to be clearly stated. This statement can be derived from a problem statement and should lead to a research question and objectives.

The collection of the case studies in this dissertation aimed to present prototypical ideas around the topic of design for reassembly. Questions like: “What are possible approaches for reassembly in architecture?” and “How to implement computational tools for reassembly for the built environment?” were driving the design of the studies. The single studies followed these overall aims. Some of them were individual projects conducted in the form of seminars or workshops with students. Additionally, there are collaborative cases with researchers from other disciplines like the Intelligent Autonomous System (IAS) from computer sciences. Each of them illuminates another aspect of design for reassembly. For each study, specific problems and aims were stated to initialize the context. From these statements, a collection of readings was collected and reviewed.

3.2.2. Defintion of Context

To further narrow the case study and relate it to the current context, the relevant texts must be collected. This process of context formation before conducting a case study is a crucial part of the case studies research procedure, as it involves defining the relevant precedents and concepts (Eisenhardt, 1989). The body of references generates the foundation for the case study and reveals current gaps in the body of knowledge. Such reviews also give space for discussion with peers. Thus, the literature review informs studies further and helps to develop the research question.

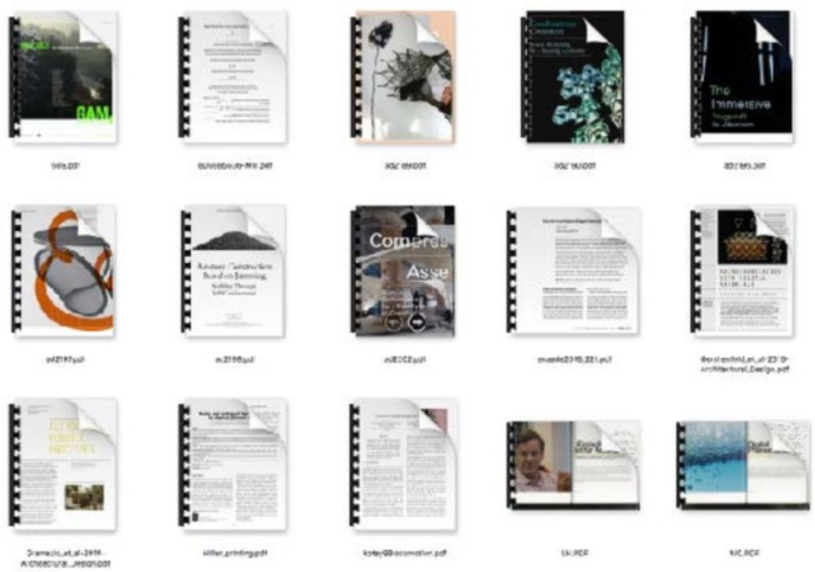


Figure 3-7 The collection of texts that establish the starting context for the first case study

For the studies in this research, the relevant literature was collected as reading lists (see references in the chapters of each case study). These reading lists were not final and had to be adapted throughout each investigation. Based on this review, the aims of each study were realigned. The readings were discussed with the students in the didactic setting of the seminars, workshops, and design studios. By doing so, the students were able to get a deeper understanding of the current state of the art as well as to get familiar with the existing vocabulary and terminology. Students are still in the process of developing their beliefs, making them vulnerable, specifically studying topics without many precedents. They can actively participate in formulating novel theories. Considering their feedback can reveal unclear points in the idea or show a mismatch in its communication. The students become an active part of the discussion. Additionally, such reading lists can be reviewed and complemented by suggestions of peers to guide the study further.

3.2.3. Planning of the Study

Case studies have to be planned by defining the scope and with an appropriate time plan. In the phase of planning, the research becomes concrete. Peers and colleagues should be involved as active critics reviewing the protocol to guarantee its rigor. It is at this stage that the protocol is to be further defined and filled. Because of its evolving nature, the protocol should be treated as a log or diary to inform the final report. Within the planning phase, the timeline is laid out. Experiments and prototypes must be planned, and specific tasks have to be assigned. Finally, the criteria for the case study are detailed.

The settings for the presented case studies are interwoven with teaching. The German university model focuses on doctorate studies that are highly involved in education. While this might sometimes seem like a burden, it also is a great opportunity. It allows doctorate candidates to explore their early ideas with students.

This role of teaching in the pursue of research is well illustrated by the Integrative Technology and Architectural Design Research (ITECH) Program run by the Institute of Building Structures and Structural Design (ITKE) and the Institute for Computational Design and Construction (ICD) at the University of Stuttgart. It is tailored to "prepare students for a future model of architectural and engineering practice with an intellectual as well as technical approach to computational design, simulation and fabrication." (Knippers et al., 2018). Additionally, their research-driven seminars and master thesis dissertations are often embedded into current research projects. Researcher Lauren Vasey (2020) remarked on the vital role of teaching to pursue risky research directions as follows.

> "[In]Stuttgart, there was emphasis on research through interdisciplinary design and teaching. Teaching became the venue by which we could benefit from iterations and take risks. If you trace the lineage of almost all of the significant research projects [at the ICD Stuttgart], they were almost all first pursued in teaching."

Her observation points to the fact that students, depending on their competencies, can contribute to research. Not every student is capable of complicated software implementations; nevertheless, testing and evaluating tools' accessibility is fully within their reach. Over the semester, they develop competencies as peers with an understanding of the topic. So, especially in research projects that intend to open a field, spreading knowledge and competencies is crucial to generate impact and consensus in the long run.

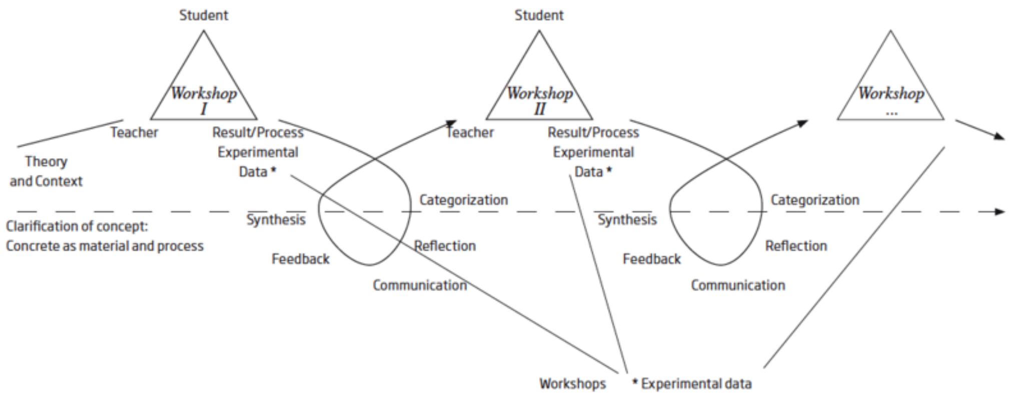


Figure 3-8 The Diagram "Qualitative methodology - research through design" by Manelius shows how teaching workshops are interwoven into research practice (A.-M. Manelius, 2012)

The PhD by Anne-Mette Manelius is an excellent example of such a methodology. In her dissertation, she uses a continuous flow between experiments, reflection, documentation, and follow-up experiments (A.-M. Manelius, 2012). She conducted several workshops with students to collect experimental data (Figure 3-8). The workshops' format involves teachers and students in which the teacher provides theory and context for the topic. In her diagram, this concept is noted by the Didactic Triangle representing the pedagogical relationship between teacher, student, and content (Kansanen, 2003). Additionally, she adds a second layer to the teaching that focuses on clarifying concepts and building knowledge. This layer consists of categorization, reflection, communication, feedback, and synthesis. These activities enable her to build up knowledge while testing it in the next didactic loop with her students.

The presented studies in this dissertation were generated within the didactic setup at the Faculty of Architecture at TU Darmstadt in workshops, seminars, and design studios. Within those teaching formats, the students became active participants in the development of prototypical processes and demonstrators. Accordingly, the case studies had been planned in line with the semester time frames of those formats. Therefore, the planning included a strict timeline for the development and teaching of relevant knowledge and skills to the students. The timeline was further constrained by planned exhibitions of prototypes and demonstrators that served as vehicles for the data collection.

3.3. Identification of Technologies

If one considers science a social construct, we understand that its methods and standards are not meant as limitations but rather as tools to gather knowledge. In 1994, Gibbons et al. pointed out that the creation of knowledge was changing its modus from an institutionalized to a more flexible, socially distributed system. Science shifted from a theoretical towards a technological orientation (Gibbons et al., 1994). The term technology, in general, points towards techniques, methods, and machines for which the appropriate skills are still under development. Technology shifted from being a field of study to the object of study, embracing the industrial and material means of production (Schatzberg, 2006).

A critical understanding of the status and available implementations should be applied within the current pace of technological innovations. Technology and innovation management is a rapidly developing object of study, dealing with technology integration into existing and emerging enterprises (Gershon, 2020). Researchers should understand how well a technology is developed to apply or improve it. Similar to the literature review for a case study, the technologies that are under investigation have to be reviewed. Besides additional reading of literature, the researcher has to interact with the technologies. In the domain of digital technologies, the researcher has to acquire this knowledge through interactions with mediums like machinery, code, and software. The researcher should critically reflect on the technology of choice before starting its implementation.

3.3.1. Technology Readiness Level

To judge the technology readiness for its implementation, the National Aeronautics and Space Administration (NASA) developed the technology readiness level (TRL). It is a scale with levels from one to nine, indicating at which level the technology at stake has been tested (EARTO, 2014). The TRL ranges from basic principles observed (TRL1), technologies that have been validated in the lab, to actual systems proven in an operational environment (TRL9)(Figure 3-9). The NEST project, mentioned above, was stated to enable demonstrations of emerging technologies that have reached TRL of 7 and above (Richner et al., 2017).

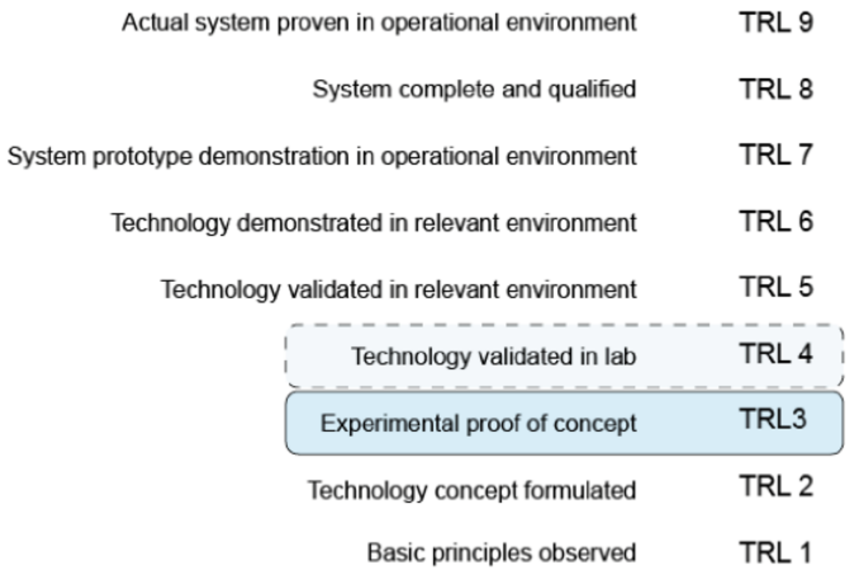


Figure 3-9 The technology readiness level scale: The robotic technologies in this dissertation were situated between TRL3 and TRL4 (blue).

Additionally, the success of technologies relies on their integration into envisioned or planned systems. The integration readiness level (IRL) presents a systematic measurement of the interfacing and compatible interactions for various technologies (Table 6). It highlights the necessity of interfaces for emerging technologies and their interaction. When combined with the TRL, the IRL helps identify technology gaps before its implementation beyond its specific use, allowing researchers to precisely measure readiness seen from different aspects.

Table 6 Integration Readiness Levels (Sauser et al., 2006)

IRL	Definition
7	The integration of technologies has been ***verified and validated*** with sufficient detail to be actionable.
6	The integrating technologies can ***accept, translate, and structure information*** for its intended application.
5	There is sufficient ***control*** between technologies necessary to establish, manage, and terminate the integration.
4	There is sufficient detail in the ***quality and assurance*** of the integration between technologies.
3	There is ***compatibility*** (i.e. common language) between technologies to orderly and efficiently integrate and interact.
2	There is some level of specificity to characterize the ***interaction*** (i.e. ability to influence) between technologies through their interface.
1	An ***interface*** (i.e. physical connection) between technologies has been identified with sufficient detail to allow characterization of the relationship.

3.3.2. Accessible Robots

In this dissertation, the relevant technologies were computational design tools, six-axis collaborative robots, sensors, and interfaces connecting the separate entities. When all of these technologies are at play, one can speak of a system, which can be evaluated against its integration: an automatic assembly system and a computational model. The presented case studies were implemented using available technologies, including the design software Rhino 3D and the scripting environment Grasshopper with its rich ecosystem of add-ons. Different sorts of computer-aided fabrication methods ranging from 3D printers, laser-cutters to hotwire-cutters were used for fabrication. As the six-axis robot is the core technology in this dissertation, it will be explained in more detail.

The six-axis robot is a very generic machine. It can carry out tasks that a 3-axis milling machine could do, can be used to assemble things when equipped with a gripper, or use many other tools like 3D printing nozzles, heat guns, and vacuum suckers, etc. as end-effectors. Thereby, the robot arm becomes specialized for a task.

The availability of a technology set the research scope for this dissertation. Prototyping and demonstrations were carried out in the robot lab setup at the Digital Design Unit (DDU). It consists of two Universal Robots UR10 (Figure 3-10). It is a collaborative robot that allows for fast sketching of small-scale experiments. Humans can share the workspace with the robots and interfere with smaller problems, like miss-alignment of parts, during robotic actions. This approach speeds up investigation compared to a large industrial and fenced robot. The operator can sit close to the robot in action, enabling collaboration and maneuvering around particular limitations (Figure 3-11). With the Grasshopper plugin Robots by Vicente Soler the robots can be simulated and operated from Rhino/Grasshopper via scripting.

Figure 3-10 The robot setup at the Digital Design Unit with two collaborative Universal Robot 10 robots unfenced

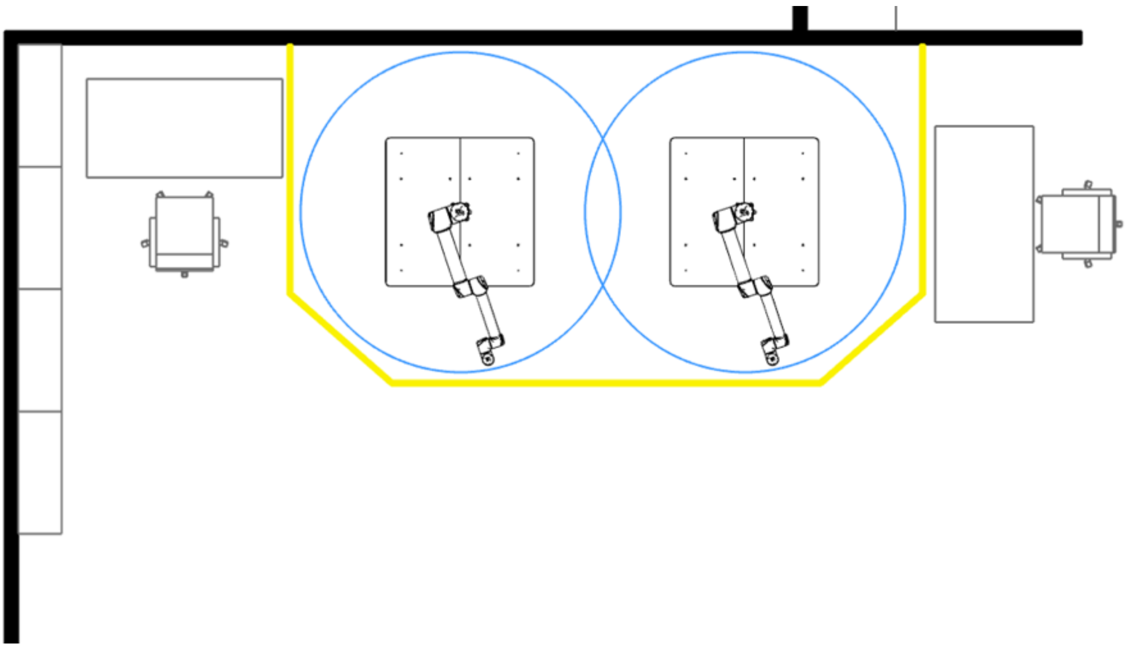


Figure 3-11 Top view of the two Universal Robot 10 robots with their working radii of 1.3m in blue and the high attention area for humans marked by yellow tape and the operating desks next to them

3.4. Data Collection

The case study method must give clear advice on how to acquire research data. The data collection protocol's importance is highlighted as a separate step in the overall case study protocol. Due to the data's relevance, the researcher has to pay attention to keep the data collection in mind at all stages of the study, as this data will later transform into evidence. In case study research, data collection depends on observation tools. In some cases, collecting data is only possible at the end of the study. In the case of technology-driven studies focusing on fabrication and demonstration, the replication of these processes would often be time-consuming or impossible. Photographs and videos have to be planned and set up. Additionally, other process data should be monitored and might even call for specific measurement systems, like precision throughout a demonstration or the execution time.

3.4.1. Prototypes and Artifacts

Researchers acquire data through all sorts of methods. Different scientific fields like engineering and chemistry use models, experiments, and diagrams as active parts in their research thinking. Architecture, as well, is a practice of contemplation through making. Prototypes, demonstrators, mockups, and entire buildings add to architectural investigations' vast body (Thomsen et al., 2011). As material instances that depend on many different variables, these formats might be harder to evaluate quantitatively. However, at the same time, they offer far more explorative qualities through their creative potential. Creating the artifacts becomes significant for testing, reflection, refinement, and development of theories and models. Scrivener (2000) describes two different approaches to research through artifacts. He names problem-solving in technology research projects and creative-production research projects (Table 7). On the one hand, technology research projects focus on problem solving, usefulness, and the knowledge that is created is more important than the artifact itself. On the other hand, creative-production research is intended to raise issues and concerns. These artifacts focus on concerns and experiences while showing the importance of being specific about a desired outcome.

Table 7 Norms of technology research projects (left) and norms of creative-production research projects (right) redrawn from Scrivener (2000).

Technology Research Projects	Creative-Production Research Projects
Artifact is produced	Artifacts are produced
Artifact is new or improved	Artifacts are original in a cultural context
Artifact is the solution to a known problem	Artifacts are responses to issues, concerns, and interests
Artifact demonstrates a solution to a problem	Artifacts manifest these issues, concerns, and interests
The problem recognized as such by others	The issues, concerns, and interests reflect cultural preoccupations
Artifact (solution) is useful	Artifacts contribute to human experience
Knowledge reified in artifacts can be described	Artifacts are more important than any knowledge embodied in them
This knowledge is widely applicable and widely transferable	
Knowledge reified in the artifact is more important than the artifact	

When carried out well and documented correctly, these artifacts can be analyzed during and after their production. The production of prototypes and demonstrators enables analyzing the processes along with their becoming. Furthermore, they are great vehicles to produce knowledge when data are collected purposefully. The development of knowledge through prototypes and demonstrators is a well-known practice in architecture. Moreover, research institutes like the ICD, MIT, and Gramazio and Kohler Research have shown excellent results.

Prototyping in design research is an attempt to verify certain functionality while ignoring certain complexities of production (Camburn et al., 2017). Prototypes are a valuable tool for the exploration and testing of ideas. The prototype is a tool to learn and prove how something behaves. These proof-of-principle artifacts do not have to work fully or be too reliable. Researchers use them to verify the necessary functionalities and critical aspects of their interest. Demonstrators are often believed to be final products to illustrate something; they are also vehicles for full explorations. Furthermore, demonstrations communicate concepts and ideas embedded. On the other hand, when we want to know how people react towards an invention, we build demonstrators to prove viability and illustrating potential applications. It requires a certain level of abstraction to produce prototypes that can make a valid argument for the later demonstrator, a skill well taught throughout architectural studies. Figure 3-12 illustrates the dependencies between the different investigation methods and how the scope and the time for the investigation increase.

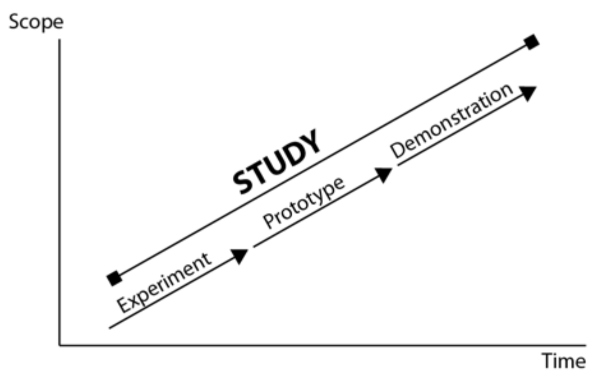


Figure 3-12 The relationship of scope and time for different types of research investigations

The produced artifacts for this dissertation had to be utilized to generate research data. How can data relevant for the research be derived from these processes, and how can their production be documented:

1. One needs to translate the prototypical processes into data.
2. The researcher has to organize the data.
3. The data has to be translated into evidence and interpreted into a report.

Therefore, the protocol for data collection should give guidance.

3.4.2. Protocol for Data Collection

The focus of case study research on qualitative data does not mean that quantitative data like measurements have to be excluded. There are certain synergies between those types of data that allow research to draw concise conclusions. As Mintzberg (1979) described the relationship of the two types of data for theory building as follows:

> “[...]while systematic data create the foundation for our theories, it is the anecdotal data that enable us to do the building. Theory building seems to require rich description, the richness that comes from anecdote. We uncover all kinds of relationships in our hard data, but it is only through the use of this soft data that we are able to explain them.”

The protocol for data collection differs from field to field and from study to study depending on the available sources and methods. In a technology-driven architectural study the data collection protocol includes the following steps.

1. **Defining artifact (prototype or demonstrator) to be produced**
2. **Implement tools for production (e.g., drawings, algorithms, fabrication)**
3. **Collect and store implementation results in the form of files and drawings**
4. **Setting up/scripting documentation for recording prototype or demonstrator defining actions to be captured, camera perspectives, and background design (photographs, videos, 3D scans, etc.)**
5. **Produce prototype or demonstrator**
6. **Take notes during production**

The note-taking procedure can include text, drawings, and photographs. These data can be divided into descriptive (methodology) and reflective (theoretical) (Table 8). It is crucial to minimize filtering during the note-taking as it might exclude important impressions. Questions like “What am I learning?” can guide the researcher. Moreover, anecdotes and informal observations might reveal novel insights and ideas.

Table 8 Research notes during case study

Descriptive	Reflective
(Portrait of technology, setting, fabrication description, etc.)	(Personal reflections, insight, ideas, confusion, hunches, initial interpretation)
…	…

In this research, the artifacts are in the form of demonstrators or small prototypes (Figure 3-13). Photographs and videos were used to capture the overall processes. In some cases, they are inclined towards the descriptive aspects of these processes and, in others, toward the reflective aspects. Moreover, produced drawings, digital models, and algorithms in the form of scripts are stored in a versioned way for later review, allowing the researcher to go back to earlier stages of a design or an implementation.

Figure 3-13 Prototypes models of 3D printed connectors (two left). Small scale demonstrator showing the application of connectors to build an arch (right).

The produced artifacts are the physical remnants of developed processes. As material instances, they highlight the inherent focus of this research, merging the digital and the physical. At the same time, they are byproducts of the processes and methods that were implemented. As they can only be presented in this written dissertation through photographs, they might not always communicate the whole story. Therefore, videos will be provided via weblinks.

3.4.3. Collecting and Analyzing the Evidence

The acquired data have to be accumulated for reflection and publication. If a research project's goal is theory forming, it is crucial to generalize found principles and categorize findings. As the prototypes and their production are rather specific objects, it is necessary to discover the underlying principles on abstract levels. Therefore, the available data have to organized appropriately. Diagrams and tables are suitable documentation and analysis methods (Nielsen, 2011) at this stage of research. While tables are great tools to organize, categorize, and cluster data, diagrams are great vehicles to visualize models and relations on a theoretical level. The collection of diagrams includes flow diagrams used to explain processes, Venn and Euler diagrams explaining logical relations between concepts. Additionally, videos, time-lapse, and photographs enable to capture the production of the artifacts and illuminate their physical appearance from a holistic and a detailed perspective (Figure 3-14). Together with the notes, these representations enable the accumulation of insights for theory building and the future construction of hypotheses. During the analysis, notes and data should be collapsed into interrelating themes.

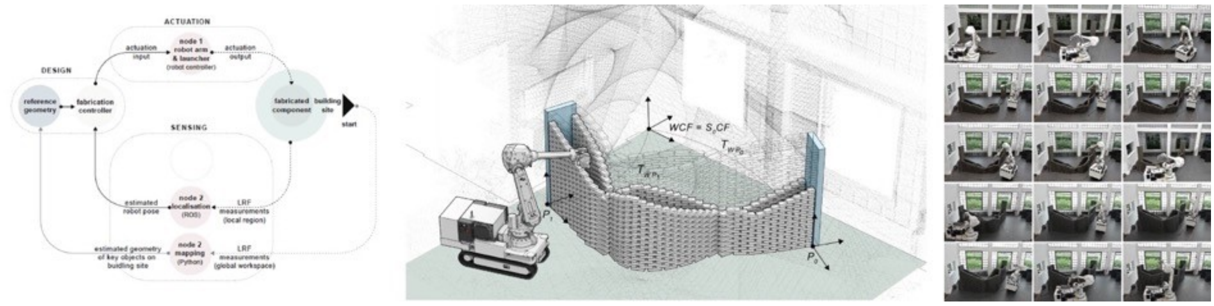


Figure 3-14 Data example in the form of diagram (left), drawing (middle), and photo time-lapse (right) from a case study in Kathrin Dörfler's PhD (2018)

3.5. Reporting and Reflection

There are different approaches towards reporting of a case study method, some around more conventional architecture practice (case study houses), others focusing on scientific-engineering methods and models (Frei Otto). The practice-oriented Case Study Houses Project was commissioned by the Arts & Architecture magazine (Entenza, 1945). In their attempt to create precedents for the ongoing discussion about how a house has to be built post-war, well-known architects were asked to find answers and foster a discussion on the topic at hand. The projects built between 1945 until 1966 were documented in the magazine, serving to challenge the house's contemporary notion. Within the announcement, one can trace the mere complexity of architectural projects that is so hard to capture in scientific encapsulated experiments. Nevertheless, the desire to find answers drove this project and impacted how the residential house was conceived. One of the most frequently published examples of the project is the Case Study House No 8 by Ray and Charles Eames (**Error! Reference source not found.**).

Figure 3-15 The 13 pages presenting the Eames House published in the Arts & Architecture magazine.

The house was published in the magazine Arts & architecture. In its first publication in 1949, the Eames house is presented as an investigation of several contradicting qualities that would be hard to study in an isolated manner. Those qualities include using "materials and techniques standard in the building industry but not standard to residential architecture" (Charles, 1949). The designer couple was living in this house and reported their experiences.

Additionally, the Eames documented the house in the movie 'House: After 5 Years of Living' (Eames & Eames, 1989), a film that presented the house as a container for living. Although less rigorously scientific, documents like this help to study built projects and their effects to create knowledge.

Within the domain of computational design one of the most comprehensive case studies is the Deichmanske Library Media Stations (Figure 3-16), a collaboration of the AHO Oslo School of Architecture, HFG Offenbach and Ocean Research Network (Menges, 2008). A whole book of 171 pages is dedicated to the collaborative study including written discourse and documentation in the form of drawings, photographs, and diagrams. Thus, it renders a good example for documentation and reporting.

Figure 3-16 The Media Station, designed in a collaboration of AHO -Oslo School of Architecture HFG Offenbach and OCEAN (Menges, 2008)

Answering "how" and "why" questions is the primary purpose of case studies. A well-written report helps other researchers to follow the chain of evidence. One of the most common reporting styles is the linear-analytic approach – the standard research report structure (Yin, 2014). It communicates the problem, related work, methods, analysis, and conclusions linearly:

1. Introduction (context, problem)
2. Literature review (background)
3. Methods
4. Analysis
5. Conclusion (implications, limitations, future work)

In her PhD. '*Strategies for Robotic In situ Fabrication'* Kathrin Dörfler reports three case studies that she conducted in chronological order. Each case study follows a linear-analytic approach, well known from conventional journal articles and conference papers in the field (Figure 3-17).

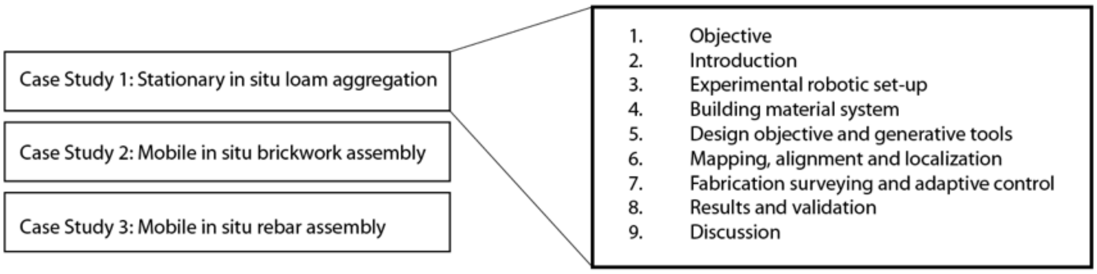


Figure 3-17 Case studies and their reporting structure in Kathrin Dörfler's PhD (2018)

During report writing, the findings are compared with conflicting and similar research. Enfolding the existing literature through the perspective of the gathered insights enables the researcher to build internal validity, raise the theoretical level, sharpen constructed definitions, and develop generalizability (Eisenhardt, 1989). Due to the limited number of cases in fields like architecture, relating studies to existing ones is a crucial and often underrated step in qualitative research. In comparison with earlier studies, during the analysis, the researcher relates underlying similarities. Different phenomena are associated with each other, and gaps in the body of knowledge are identified, enriching the report's conceptual level.

Research in software engineering presents very detailed guidelines for the reporting of case studies. Jedlitschka and Pfahl (2005) gave a clear description of the different sections of the linear reporting structure, which was adapted for this research (

Table 9).

Table 9 Adapted case study reporting structure based on Jedlitschka and Pfahl (2005) by Robson (2002)

Case Study Reporting Structure

Section headings	Subjects
Title	
Authorship	
(Structured) abstract	
Introduction	Context Research questions Research objectives Problem statement
Background	Earlier studies Theory
Case study design/Method	Case and method selection Description of technologies and tools Design and fabrication procedure(s) Validation procedure(s) Data collection procedure(s)
Results	Case and method description covering execution, analysis, and interpretation issues. Subsections may be structured, e.g., according to the findings, each linking observations to conclusions Evaluation and Discussion
Discussion	Summary of conclusions Relation to existing evidence Impact/Implications Limitations Future work
Acknowledgments	
References	
Appendices	

Besides communicating the case studies, these reports force researchers to reflect on their work. As several case studies were planned to become part of this dissertation, this reflection process continually improved this research. The gathered findings inform the next case study, leading to a constant improvement of the theory building methods. The circular iteration of the studies enabled modifying the theory and the case study design (Figure 3-18). It allows this research to draw cross-references and comparisons between the isolated case studies. The recurrent questions aim to develop testable hypotheses by identifying the salient factors and informing predictions about how different problems are related. When to stop such iterative circles is a relevant question that can only be answered with the idea of saturation. Once the improvements of a theory become minimal, the iterations should be stopped (Eisenhardt, 1989).

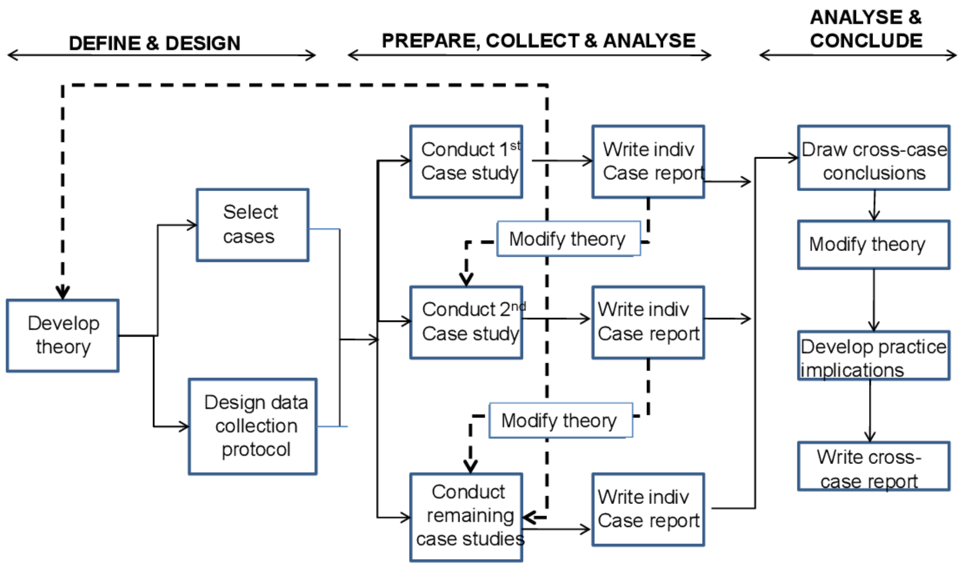


Figure 3-18 The case study method's application to develop and modify theory (adapted from Yin (2014)

Finally, the case study reports were intended to produce knowledge and examples for other researchers. To build theories, criticize, and learn from them. As Flybjerg (2006) argued: "[…] scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and that a discipline without exemplars is an ineffective one."

Conclusion

In this chapter, the case study method was introduced within the field of architecture and tailored for a technology-driven approach. Although the method is broadly used in the discipline for inquiries of digital design and fabrication, its guidelines are rarely articulated.

The hereinbefore defined protocol for conducting case study-driven research aims at technology-oriented questions, focusing on the production and documentation of physical demonstrations. The special considerations for design-driven research were illuminated, clarifying the difference between experiment and case study. The importance of physical prototyping and demonstrations was discussed in regards to the protocol for data collection. Technology readiness (technology readiness level) was introduced, giving further guidance on technological choices. The involvement of didactic methods and the exchanges with students for testing and forming ideas in an academic environment was illuminated for their relevance in case studies. Finally, the reporting concept was laid out, considering the sequential planed case studies in this research highlighting their reflection phases.

The case study method was chosen to investigate various aspects of technology-driven research. Emerging technologies like computational design and robotic automation require building novel theories for architectural production, identifying gaps in knowledge. While prototypes allow first tests of an idea, final demonstrators serve as proofs and communication and documentation devices. The collected case studies produce results as the basis for the discussion of design for reassembly. Those case studies consist of small-scale to medium-scale prototypes and demonstrators. Most of them built under lab conditions. Some of them exhibited as vehicles for a public discussion of the topic, fostering dialog. The next chapter presents the four case studies with their corresponding prototypes and demonstrators.

4. The Case Studies

This research seeks to build an understanding of the physical editability of building elements through robots. Physical demonstrations are the main vehicle for this investigation. They focused on constant reassembly, volumetric formations, cantilevering through incremental weight distribution, and combinatorial interlocking for tactile robotic assembly (Figure 4-1).

How to manipulate reconfigurable building elements through a robot? What are the problems for Discrete Design for robotic reassembly? How are design tools, building elements, and robotic assembly integrated? Can one formally describe the assembly and reassembly tasks into an algorithm that allows both designing and generating instructions for the robot? Such questions are the baseline for the collection of the four case studies presented in this chapter. Two modular systems were developed and coupled with algorithms that enable robotic assembly in a detachable manner utilizing self-aligning building elements with dry joined connections.

This chapter describes the four case studies that have been conducted during the scope of this thesis. The separate studies were done incrementally such that the reflections of the previous studies informed the following study. All studies were set in the academic environment of TU Darmstadt. The first three studies were based on the same initial building kit and offline programming for the construction. The fourth study investigated interlocking building blocks and their combinatorics, utilizing robot learning and tactile sensing for assembly. The studies are all reported following the linear-analytical order of introduction, background, method, results, and discussion. A comprehensive discussion and comparison of the different case studies follow in the final chapter of the thesis.

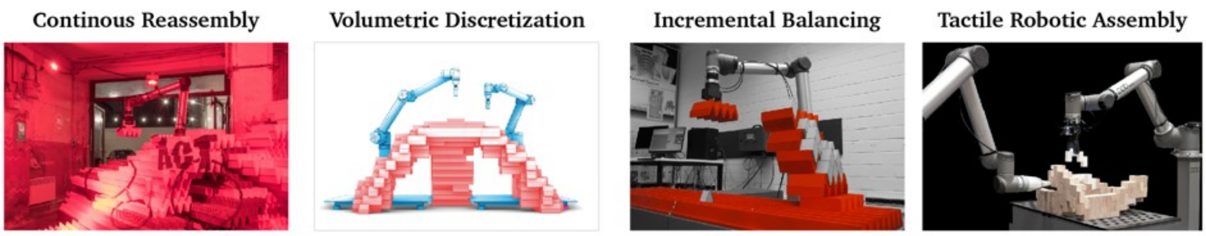


Figure 4-1 Overview of the three case studies that cope with the same modular elements

4.1. Continuous Reassembly

Digital design tools and fabrication expose architects at the same time to variability and precision. The integration of these digital properties into spatial reconfiguration is still an open question. Changeable architecture has seen growing interest by designers following the concept of Discrete Design (Sanchez, 2019). Robots offer the possibility to merge the digital editing from the design environment into the physical by recomposing the arrangement of discrete units.

The project Olzweg by R&Sie(n) is a speculative and poetic proposal of such an approach. The project is a conceptual proposal made for an architectural competition in Orleans, France. The team designed a robot that would become part of the later building complex (François Roche et al., 2006). The robot would constantly reposition elements made out of recycled glass (Figure 4-2). Here is a sales pitch for the robot:

> "Rent this extremely efficient packing, ordering, classifying, numerating and XYZ-positioning machine, for an endlessness less stacking and staggering. The Packer is only available for long-term rent. The machine works to extend existing construction, by testing the possibility of wrapping, smearing, and invading a previous situation to develop a surrounding maze with multiple uncertain trajectories and 'parcours'. The morphological trap it creates is both a jail and a protection apparatus. This dual strategy avoids the occupant perceiving their own madness and protects others from their own pathologies.
>
> Participants require a personal agreement and discharge to play this game as a 'voluntary prisoner', lost in the permanent entropy of packing. In any case you could use, if necessary, RFIDs on PDAs to rediscover positioning – but at your own risk.
>
> Its first use and development was for the 'Olzweg' experiment."
>
> (Francois Roche et al., 2016)

Unfortunately, the team won the competition, but the city of Orleans was too sceptical about the costs of this project, which would always be in flux. This might have been due to the expenses of this proposal or to the many technical challenges that one can expect, as well as legal issues.

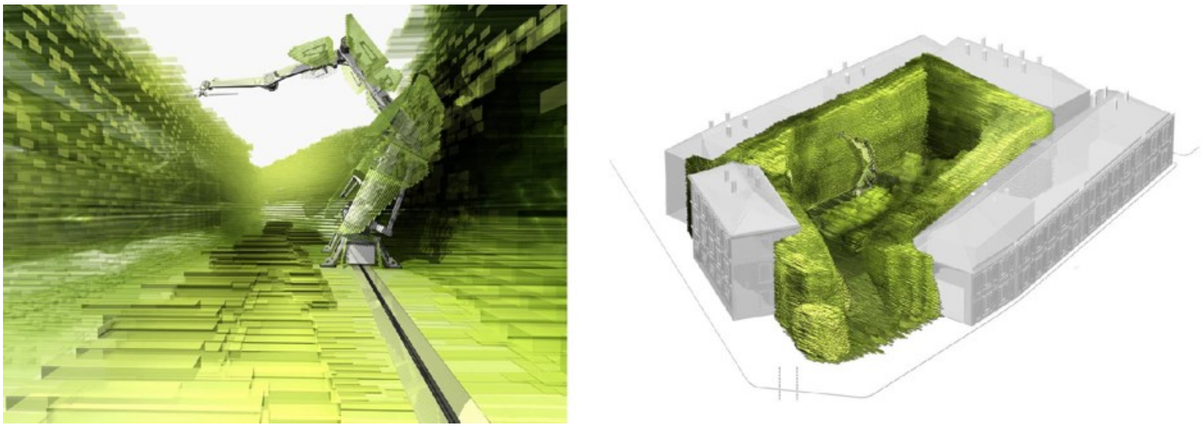


Figure 4-2 The robot moving in-between bricks made from recycled glass on a linear axis (left). The overall complex is covered from inside with this continually changing layer (right) (Francois Roche et al., 2016)

.

Currently, the logistics of building elements in construction are considered a one-time problem; once they are in their final place, they are fixed. The question of automated reassembly of building elements is still to be answered by architects, also from a design perspective. Besides the already complex linear assembly sequence, a reassembly task comes with the extra overhead of logistics. The designer, additionally, has to define a temporary position for each element that has to be repositioned. First, the structure has to be assembled. Second, the elements have to be repositioned into a stack or parking position while not interfering with the disassembly and the later assembly process. Finally, the elements are put into their new location.

This case study seeks to understand how the module positions of an assembly can be changed continuously. What are the mentally exhausting tasks for a designer, and can these be formalized into code? What are the logistic challenges of the elements? The study aims to identify the necessary process steps for continuous reassembly. The objectives were the implementation of a computational design tool in combination with a robot control strategy for reassembly.

Moreover, the installation seeks to also embed the change of the meaning of an assembly, represented by written words that would be altered in the reassembly process. Therefore, a Universal Robot UR 10 had to become an integral part of the installation to continuously reassemble the module aggregation, causing an anamorphic painting that would be spread over several modules to change their shape and meaning (Figure 4-19).

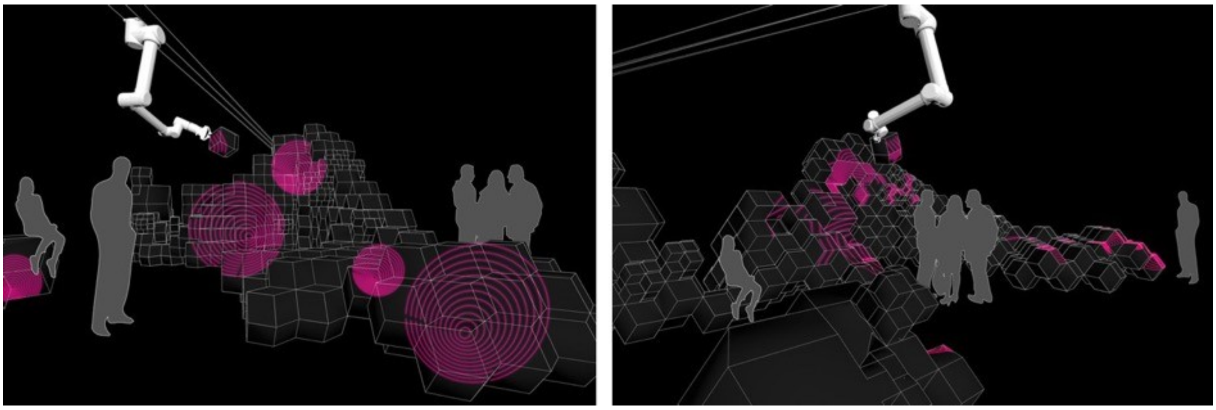


Figure 4-3 Example of an anamorphic effect: on the left, the graphic effect on the spatially distributed elements as seen from the designated viewpoint, and on the right, the scattered graphic as seen from an unrelated position.

The setting for the investigation was a seminar during the winter semester 2017/18 with 18 participants – 11 master and seven bachelor students. The goal of the seminar was to present an installation at the Luminale light festival 2018 in Frankfurt, Germany. Therefore, a design tool and a robotic process had to be implemented to manage the logistics of the reassembly. The installation was done in a final workshop during the last two weeks of the seminar before the opening of the light festival. The format of an installation allowed to speculate on the tectonic, spatial, and aesthetic effects of a design that is subject to constant change.

4.1.1. Background

The background for this case study can be defined by the three topics of robotic reassembly, logistics of elements, and anamorphosis.

Robotic Reassembly

Architecture is not per se the field that deals with how things can be changed automatically. Nevertheless, the emergence of robotic technologies started to shift the attention of architects towards variable systems(Steenson, 2014). One of the earliest examples of a machine altering the physical aggregation of an occupied space was done by the Architecture Machine Group lead by Nicholas Negroponte. Their project SEEK "featured a Plexiglas pen filled with four hundred silvered wooden blocks, a robotic arm that tried to stack and order the blocks, and a horde of gerbils that inhabited the pen. The gerbils made chaos out of the blocks, and SEEK tried to keep track of them"(*Nicholas Negroponte, a Heavy Guy | WIRED*, n.d.). The project made a strong contribution to the debate of such new technologies for the interaction between inhabitants and their architectural environment (van Ameijde, 2019).

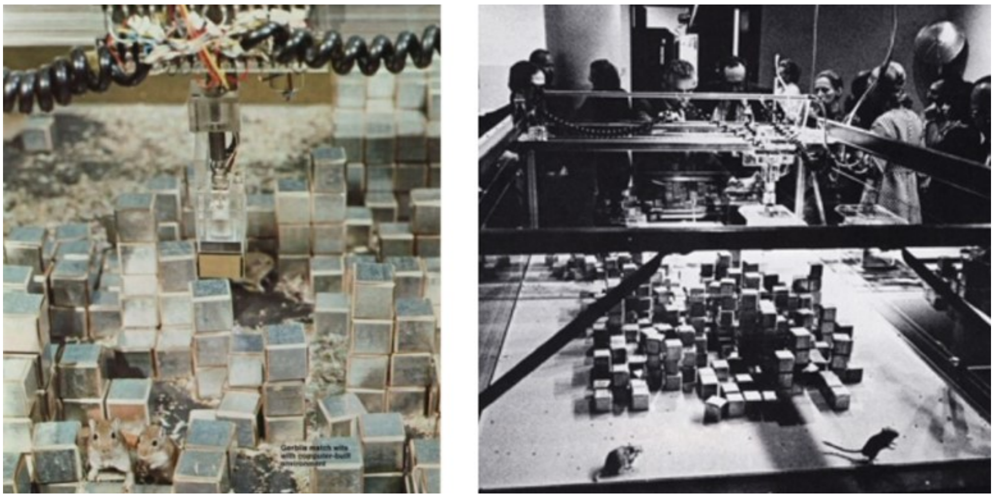


Figure 4-4 Architecture Machine Group, SEEK, 1970 (Software - Information Technology: Its New Meaning for Art, 1970)

A more contemporary example of the editable physical system was presented by Gramazio Kohler Research at ETH Zurich in 2011. The Endless Wall is a robotically stacked wall made from bricks that can be rearranged (Helm, 2014, pp. 142–150). The goal geometry for the rearrangement is given as user input. Within a defined area between two black curves around a robot arm, users can draw a curve that serves as the design input for the next iteration of the circular brick wall. The robot takes bricks out of the existing wall and places them to build the extension of the wall onto the drawn curve (Gramazio Kohler Research, n.d.). The gesture of drawing the curve generates the instruction for the new wall. The operator can make design decisions at the site, while the existing wall serves as the material stack.

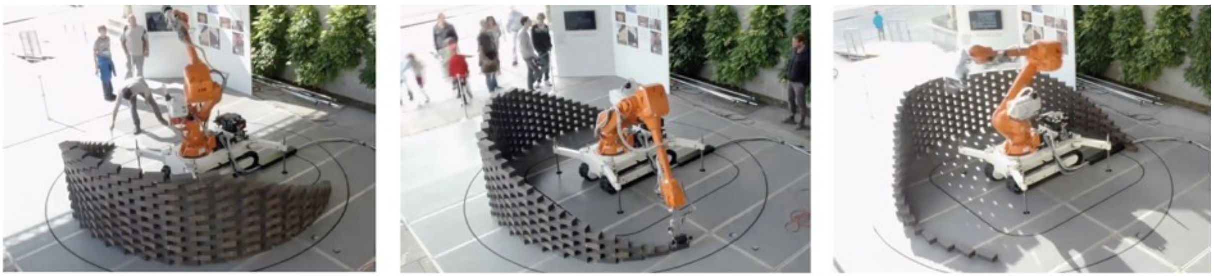


Figure 4-5 Stills from the movie Scientifica 2011 by Gramazio Kohler Research, ETH Zurich, showing three different aggregations of the same bricks.

The stacking figurations in these two examples are limited due to the planar interfaces of the blocks or bricks. The elements came without error correction mechanisms which would result in an accumulation of pick and place tolerances. To circumvent these errors, the systems were equipped with sensing capabilities.

Building elements designed for robotic assembly can be found in the example of self-aligning dricks (Latteur et al., 2015b). The name is a combination of drones and bricks. These elements need to address the tolerances of the flying drone. The blocks come with inclined surfaces that guide the elements into place when dropped off from the drone. This self-calibration mechanisms and fixation in place through their load were explored for various geometries (Figure 4-6).

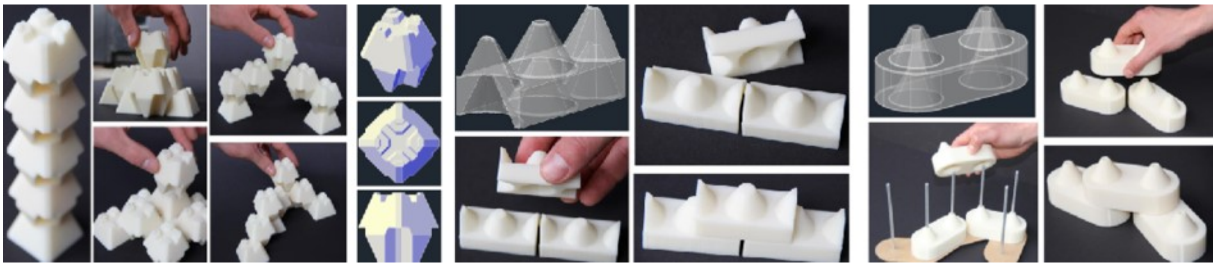


Figure 4-6 Different drick designs of self-aligning building elements (Latteur et al., 2015b)

Logistics of Elements

Construction logistics are divided into two domains: supply logistics (external) and on-site logistics (internal) (Holm & Schaufelberger, 2019). Commonly, on-site or in-situ logistics deal with building materials and elements that have already been delivered. To further minimize supply logistics, it was proposed to treat the existing building as an on-site marketplace or a material bank (American Institute of Architects, 2016; Copeland & Bilec, 2020).

An approach to automation of the construction process was conceptualized as a Computer-Integrated Construction concept (Warszawski & Sacks, 1995). Here, an integrated information management system tracks the tasks and building components in a project model. Temporary inventory management keeps track of the current as-built status. Each element is tracked at its current location and updated in the digital model.

Anamorphosis

Anamorphosis is a geometrical projection technique that creates an image on a surface that appears distorted from all but a small set of viewpoints. It derives from the Greek prefix ana meaning “up,” “against,” “back,” “re-” and the word morphe meaning "to form again." Examples of the technique can be found in renaissance paintings like The Ambassadors by Hans Holbein the Younger (1533), applied to architectural surfaces in the Gallery of the Monastery of Trinità dei Monti in Rome by Jean Francois Nicéron (1640), and as an architectural effect in the apse of the church of Santa Maria in San Satiro in Milan created by Donato Bramante (1483) (Figure 4-7).

Figure 4-7 The Ambassadors by Hans Holbein the Younger (top left), the Gallery of the Monastery of Trinità dei Monti in Rome by Jean Francois Nicéron (top right), and the apse of the church of Santa Maria in San Satiro in Milan created by Donato Bramante (bottom) (Di Paola et al., 2015)

In recent years, such optical illusions have been generated through computational methods and digital techniques. These enabled designers to apply anamorphic paintings to complex architectural surfaces (Di Paola et al., 2015; Hosseini et al., 2017) to generate distorted 3D objects that inherit anamorphic qualities (Hansford & Collins, 2007), or create robot instructions for the fabrication of an anamorphic sculpture (Jovanović et al., 2017).

4.1.2. Method and Case study design

The investigation was set within the academic structure of a seminar during the winter semester 2018/19 at the Faculty of Architecture at TU Darmstadt at the Digital Design Unit. All students were introduced to modular design and trained in robot programming for assembly tasks. Rhino 3D and Grasshopper were chosen as design and fabrication software; together, they ensure a strong linkage between the design and fabrication procedures. During the seminar, the students specialized in different topics related to our installation – aggregation, module fabrication, robotic programming, gripper design, exhibition design, and documentation.

In our context of the seminar and the light festival Luminal, the case study was designed to investigate the following questions. What are the common problems in implementing computational tools for reassembly of a modular system? How can these tools be used to aid in changing the configurations and meanings of an installation?

Module Design

Modular building elements are not commonly designed for robotic assembly. From a list of existing studies (Goessens et al., 2018; J. D. Hiller et al., 2011; Mainka et al., 2013), specific properties like coupling, alignment, and orientation were extracted. Since the robot was not equipped with any sensor, the element design had to be robust against minor placement tolerances and should have self-calibrating properties. Additional constraints were given by the EPS material and machine limitations of the hotwire cutter. Different design variations were tested for their self-alignment and aggregation potential (Figure 4-8).

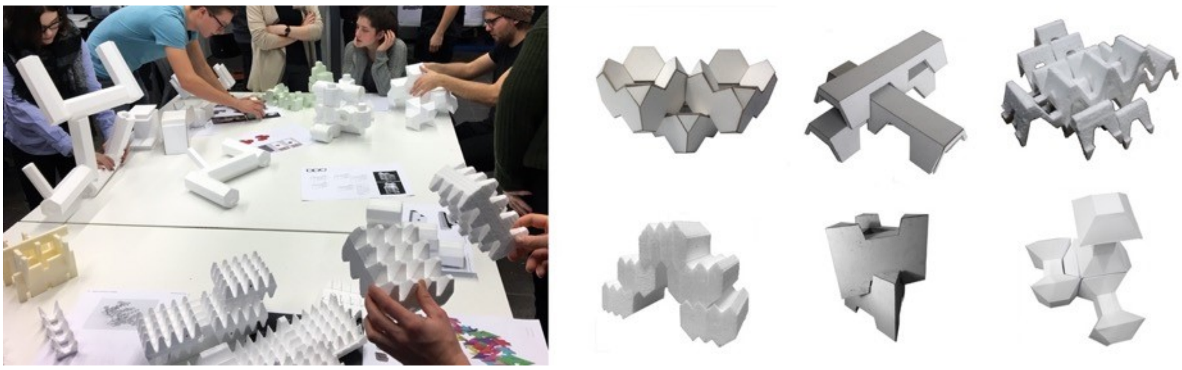


Figure 4-8 Students exchanging their module concepts (left) and examples of small modular assemblies (right).

The final design consisted of a zig-zag contour, enabling vertical stacking of the elements (Figure 4-9). The module design emphasises the joint as an inherent property of the module as opposed to an added joint onto a preexisting geometry. The exact angles of the zigzag geometry was a negotiation between the numbers of the teeth, material friction, and the self-calibrating properties (Latteur et al., 2015a). On the one hand, if the angle is not steep enough, the modules will not slide into place. On the other hand, if the angle is too steep, there might be too much friction. Various lengths and numbers of teeth were fabricated, forming the overall building kit (Figure 4-10).

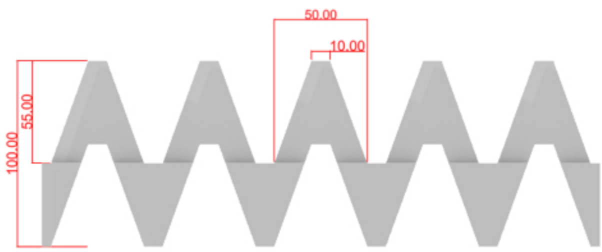


Figure 4-9 The section dimensions of the corrugated geometry

Figure 4-10 The different types of foam modules. In total, 400 corrugated modules were produced.

The material for the elements was chosen by accessibility. Eight polystyrene blocks of 50 x 50 x 200 cm were available, which were previously used as benches at an exhibition in Frankfurt, Germany. The polystyrene type had a feasible density of 150 kPa, allowing an acceptable cutting speed for our CNC hotwire-cutter and providing enough strength for the module design. The polystyrene blocks were divided into two pieces, each one meter long to fit into the CUT 20005 hotwire-cutter (Figure 4-11). It took two hours of machine time to cut the one-meter-long polystyrene blocks following the defined contour. These initial modules were further subdivision into smaller modules (Figure 4-12).

Figure 4-11 Our CUT 2000S hotwire-cutter with one of the initial polystyrene blocks (left) and the cutting of the zigzag geometry (right)

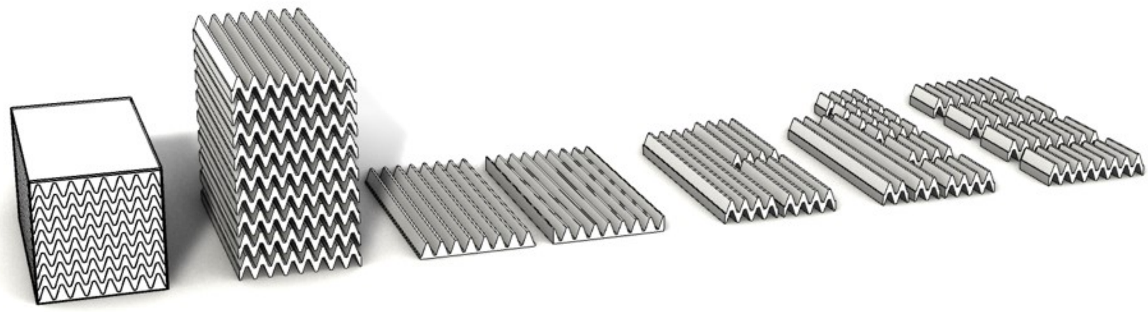


Figure 4-12 The extraction and subdivision of the modules based on the foam block size of 50 x 50 x 100 cm

Additional modules were cast in concrete. This change of material provided the possibility to design porous modules, allowing us to change the directionality. A small module was developed to increase the self-calibration in the other direction once it was placed on a conventional module. The flat-top modules served as a bar counter. Finally, the heavier modules permitted building cantilevering structures by serving as counterweights (Figure 4-13).

Figure 4-13 The collection of concrete elements serving as counterweights in the installation. The smallest block on the left side served as a position fixing device.

The heavy concrete elements served as counterweights to stabilize the installation and as a surface within the wet area of the bar furniture installed across the robotic installation. Their formworks were printed using Ultimaker 2 3D printers with polylactide (PLA) filament. The screed mixture contained Sopro screed and glass fibers. The 3D printed formwork was prepared with a silicone spray enabling the smooth separation of part and formwork (Figure 4-14).

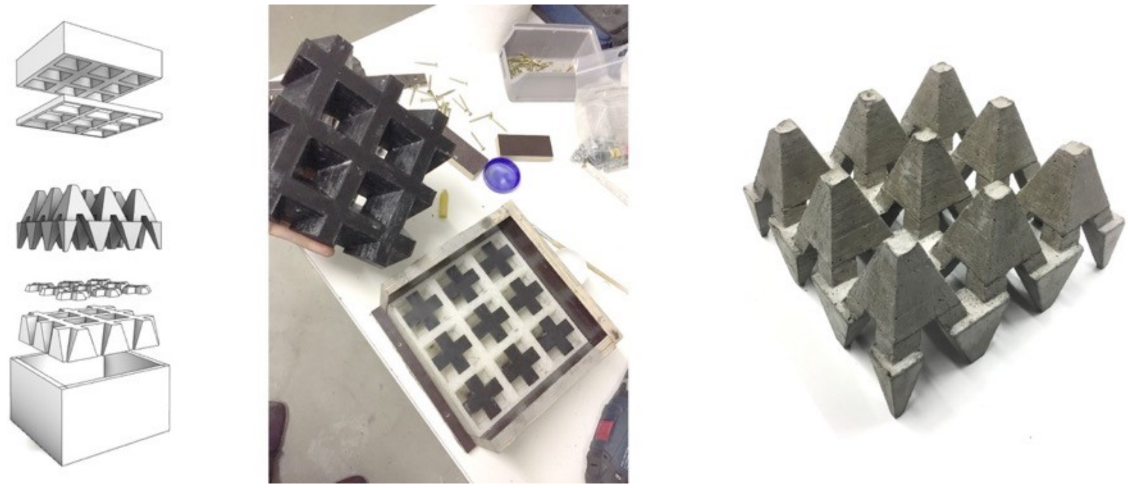


Figure 4-14 Formwork production of one concrete element using 3D printed parts

The module geometry allowed the transport of the modules in a packed way, saving transport space. The polystyrene modules were painted with red color (Figure 4-15) to merge with the anamorphic graphic –painted in neon orange – once the light would switch to red.

Figure 4-15 Painting the elements

One important feature of the modules is the different degrees of freedom. Along two axes, the module can only be coupled with each other following a predefined grid. Along the Y-axis, the modules can move in continuous space. Thereby, the modules combine the discrete with the continuous domains of assembly (Retsin, 2016), resulting in elements that can be characterized as 2.5D discrete. This property also has to be accounted for in the design tool, restricting the designer while offering an infinite space of shifting and combining modules. In total, 15 different types of modules were designed, and 400 pieces were fabricated; all of them can be coupled with each other by vertical stacking. The modules were tested against the fabrication systems and robotic manipulation.

Aggregation

Designing with discrete elements is either a very tedious task or comes with a lot of constraints. In this case study, Rhino 3D was used as the design environment. The design constraints were determined by the sizes of the elements and were implemented into the digital design tool. Therefore, a base grid was set up that followed the module dimensions in the x- and y-axis. Any input curve a designer would define was divided by this base grid, partitioning the curve for the designed modules. For the sake of editability, curves were chosen as design interfacing geometry. Furthermore, the logic of working with separated curves enabled the design of an almost column-like arrangement of the elements, generating depth with the overall installation. This approach is fundamentally different to subdividing a volumetric body based on the element dimensions. Instead, the curves represent different strands that would become stacks of elements.

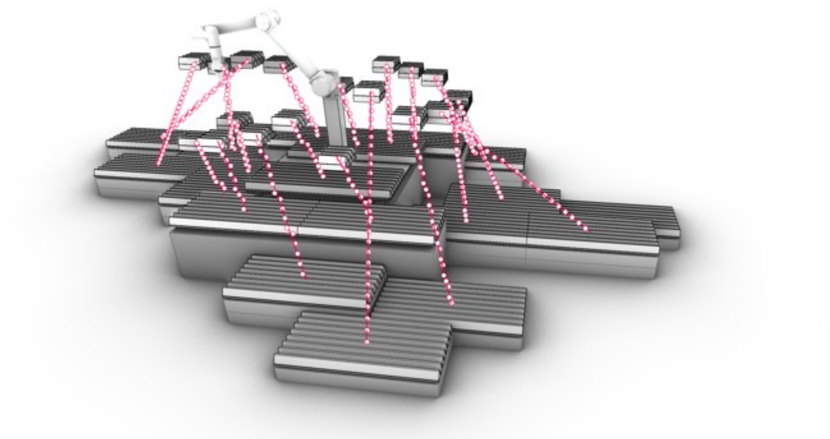


Figure 4-16 The base and the top module define the curves of the different stacks of the modules.

The final design consisted of 12 curves from the base boxes to the designated top reassembly modules. The final design was aggregated manually – future work can further automate the negotiation of the input constraints. At this stage of the research, this step was negligible. The plinths lifted the modular aggregation onto the eye level. From these boxes, the aggregation grew towards the six-axis robot in its center.

Anamorphosis Graphics

The goal of the anamorphic effect was to foster human movement around the installation. Several patterns were projected on already fabricated modules, providing a more realistic setup; as the actual viewpoint was the same as the projector position, it was never be accessible. The digital design tool aggregated the elements along curves. To emphasize the anamorphic effect, we aimed at creating spatial depth from the viewpoints. While a flat surface would also reveal the projected image from other viewpoints, the spatial depth blurs the image into different layers of the projection cone.

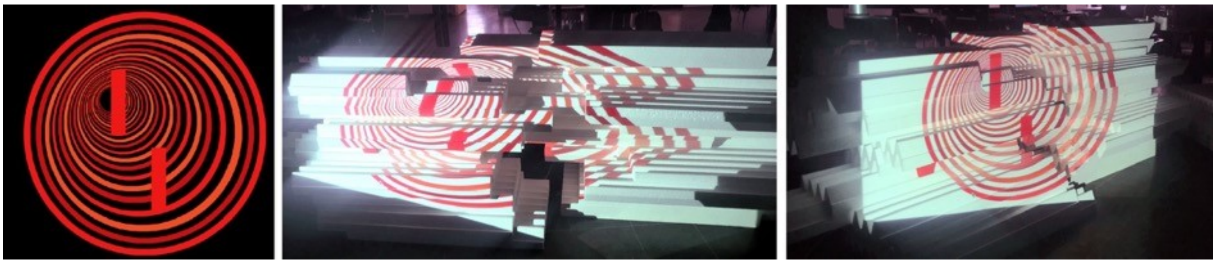


Figure 4-17 The test graphic (left) projected onto unpainted modules seen from a random viewpoint (middle) and the designated viewpoint (right)

In relation to the title of the exhibition "YOU WANT TO SEE, LEARN TO ACT," two graphics were created and mapped onto the aggregation as anamorphosis from two opposing viewpoints (Figure 4-18).

Figure 4-18 The two graphics that were projected onto the modules to create an anamorphic illusion. The first contains the word SEE written in grey and SEEK written in orange outlines (left). The second contains the word ACT written in grey and REACT written in orange outlines (right). The additional graphics were added to obscure and disrupt the words from other viewpoints.

Several methods were used to evaluate the anamorphic effect. The first set of simulations was done using the 3D software interface of Rhino 3D, pivoting around the installation. The viewpoint was defined on the height of 1,4 m, allowing smaller persons to see the anamorphic effect, while taller persons have to bend their knees a little bit. As the mouse operations in the software interface are far from the real experience, further simulations were conducted utilizing a VR headset. In this way, spectators could relate it to body movements.

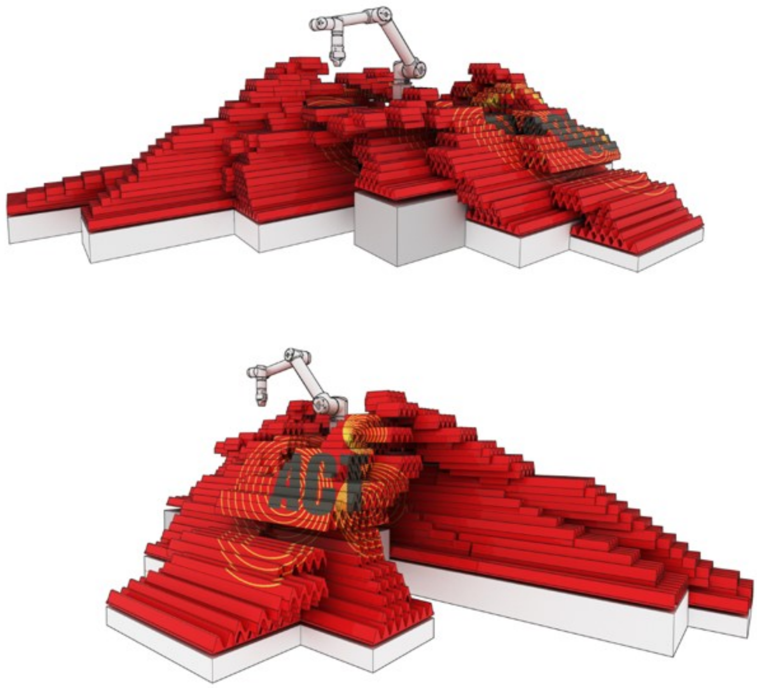


Figure 4-19 Illustration of the anamorphic effect. The text "ACT" is not visible (top) until one reaches the designated viewpoint (bottom).

Robot Programming

The reassembly process for the robot is considered a a pick-and-place task. For its execution, the robot needs an end-effector, a gripper. The robot program for a pick and place process can be divided into the pick, path, and place sequence.

We developed an electric gripper for grasping the parts. The mechanism and fingers matched the module geometry. The weight of the modules to be grasped was 100 g. The acceleration for the lift was set to 180 mm/s. The parts for the gripper were 3D printed from PLA; we covered the fingers with a rubber surface to provide more friction. The coefficient of friction between the foam elements and the rubber surface was 0.4. The following equation describes the calculation of the needed force for the gripper:

$$F = \frac{ma}{\mu n}$$

F	is	the force required to grip the object,
m	is	the mass of the object,
a	is	the acceleration of the object,
μ	is	the coefficient of friction and
n	is	the number of fingers in the gripper.

A Modelcraft Standard servo RS2 with a torque of 31 Ncm was built into the gripper. The gripper was connected to the UR10 robot flange via a customized connector (Figure 4-20). The software interface for opening and closing the fingers was implemented using an Arduino Board and connected to the analog tool output inside the robot controller, allowing gradual steps between opening and closing.

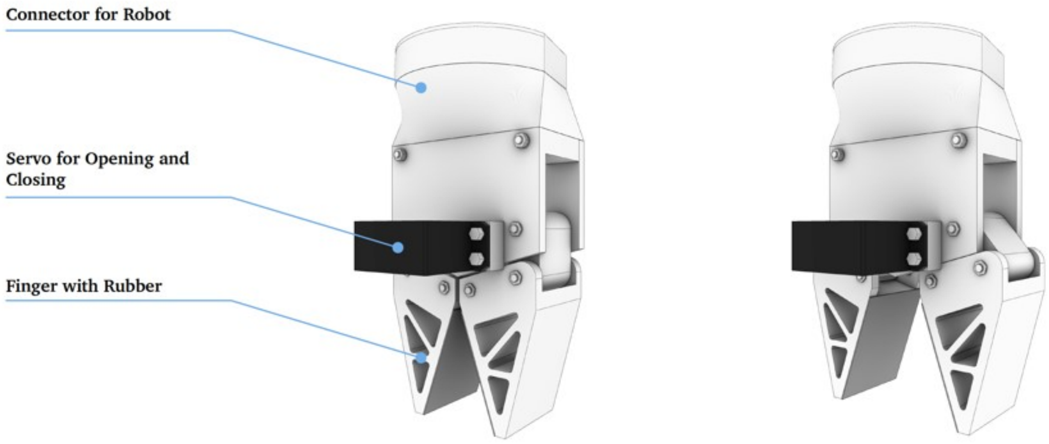


Figure 4-20 The electric parallel gripper in closed (left) and opened (right) position

The installation was preinstalled under controlled lab conditions at TU Darmstadt. To negotiate the precise robot movements and the tolerances caused by the material, the positions of the elements were recorded. Therefore, the industrial robot served as a digitizer arm, a commonly used method to digitalize models (Entous, 1998). To put the robot into compliance mode, the brakes of the robot's joints were released to be manipulated by hand (Figure 4-21). Whenever needed, the exact XYZ position of the tooltip was recorded and transmitted through a WebSocket connection from the robot's controller via ROS to Grasshopper and, subsequently, into the Rhino 3D model. The WebSocket connection was implemented using Bengesht (Tahanzadeh, 2017), Rosbridge (Crick et al., 2017), and the UR ROS Driver (*Universal Robots ROS Driver*, 2018). The captured locations were captured as cartesian coordinates and translated into 3D digital representations of the blocks. As the robot was used as a digitizer arm, it was expected that all parts would be in reach of the robot. Additionally, the Grasshopper plugin Robots was used to simulate the robotic movements, avoiding collisions or unwanted joint movements on any axis.

Figure 4-21 Digitization of new module position in compliance mode: human places a new module (1), human moves robot to the location of the module (2), the new position is saved (3).

Once the aggregation was digitized, the order for the reassembly process was defined. During the procedure, no elements were added or removed from the installation, and the restacking was organized to avoid the visual effect of two stacks. Instead, the parts were evenly distributed in the installation.

The robot program is composed of a pick-up sequence. The robot approaches the part with an open gripper and a 30 cm offset in the Z-coordinate. From the start position of the sequence, we reduced the speed of the robot to approach the pick position. Once the robot reached the pick position, the grasping is sequenced. The robot was programmed to pause the movement for 0,5 seconds, close the gripper, pause 0,5 seconds again to make sure that the part settled in the gripper. With the grasped part in the gripper, the robot has to move up 30 cm, back to the approach position. The pick-up sequence is completed, and the robot proceeds with the path sequence.

The robot has six degrees of freedom that allow almost all possible movements within its workspace. However, there are certain movements that cannot be executed – singularities describe the condition in robot arms of collinear alignment of two or more robot axes causing the robot to lose one or more degrees of freedom, resulting in a physical blockage. To avoid this, a guiding surface was implemented (Figure 4-23). From the approaching positions, the robot was guided towards the guiding surface and to move along this surface inbetween pick-up and placement sequence; thus, avoiding singularities or hitting itself with a picked part.

Finally, the robot approached the place sequence, which started 30 cm above the placement position. At reduced speed, the robot ha to move to the placement position. Once reached, the robot pauses for 0,5 seconds, opens the gripper, waits for 0,5 seconds to release the part, and drives back up to the approach position. After the whole sequence is completed, it starts again with the approach of the next pick-up position by moving along the guiding surface.

The mathematical puzzle Tower of Hanoi serves as an example of the problem of building element logistics during reassembly. In the riddle-like game, one has to move a stack of different sized rings from one pole to another. There are three poles available: the from-pole, the with-pole, and the to-pole (Figure 4-22). The only two rules are that one can only move one ring, and no ring can be covered by a bigger ring.

For our installation, the constraints might be different; nevertheless, the game and our installation share some characteristics. In both cases, one has to deal with varying states of the assembly and with a set of rules or constraints that limit the actions between the different states. With the six-axis robot, only one element at a time could be moved. Instead of the from-pole, one starts from a given assembly to translate it into a second assembly – the to-pole. To accomplish the translation, the elements have to be temporarily stored in the stack position – the with-pole.

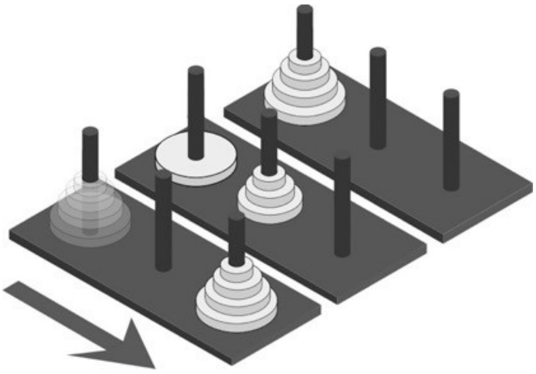


Figure 4-22 The three different poles and different sized rings in the game Tower of Hanoi

All parts of the sequence are parametrized except the pick-up and placement positions, as well as the guiding surface. For robot programming, it does not make any difference whether this sequence is parsed twice or hundreds of times. The only limitation of the process is that it is offline robot programming. In such processes, the robot program is compiled once and sent to the robot for execution without any possibility to interfere with the program. If an error occurs in the middle of the execution, the whole program fails. Due to tolerances of the parts or unforeseen interception of visitors, such errors were expected. To be able to identify the program line in which the robot would be stopped, a robot log was implemented. The log constantly showed the current program step. Thereby, all previous program steps could be cut off and the program restarted.

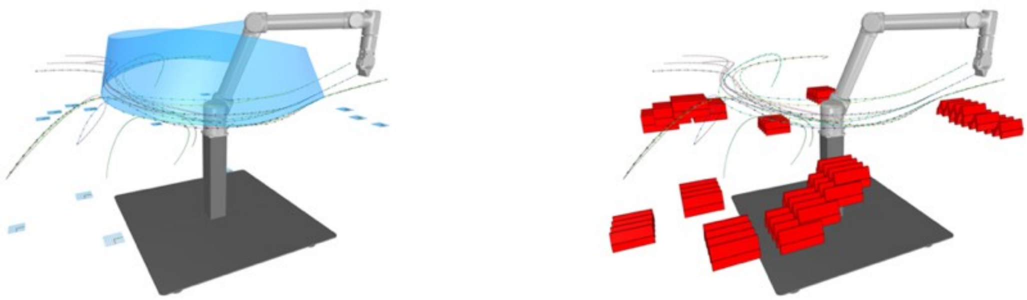


Figure 4-23 The instructions of the elements were notated in the form of planes. The blue surface restricts the movements of the robot (left).

4.1.3. Results

This study was set in a setting in which 18 architecture students were responsible for different topics of reassembly: robotic programming, digital fabrication of elements, design tools, site planning, exhibition design, and documentation. The set deadline by the festival opening limited the time of inventing and implementation.

The exhibition was open for five days in the hours from 18:00 – 22:00, with two students supervising the robotic reassembly. The installation was meant to serve on several levels. It was intended to help answer the research questions and get closer to the objectives. Furthermore, it was intended as an event location during the light festival to get in touch with the community and promote discussion between architecture students, researchers, and spectators. The activities were documented by the students via photography and filming. For purposes of reflection, process diagrams of the robotic reassembly process were created.

The complexity of this project and its interconnected methods called for a considerable load of back and forth between the different steps. Module design, fabrication, aggregation, anamorphosis, and robot programming were always treated as integrated processes. Commonly, a design task would start from its global shape and then be subdivided for assembly – instead, this project started with the subdivided modules and its robotic assembly. This shift from discretizing at the end towards starting from a discrete set gives rise to the following discussion.

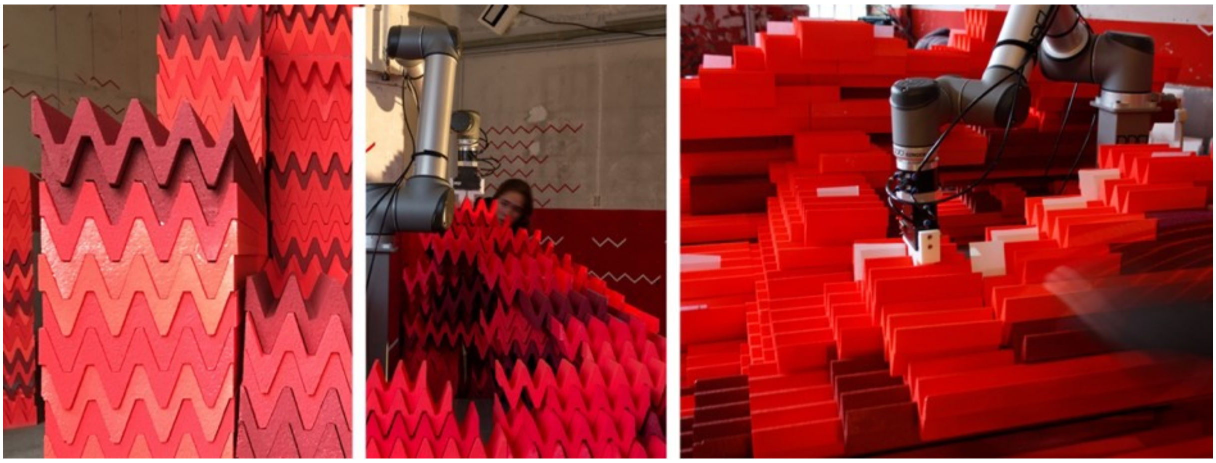


Figure 4-24 The packed blocks (left), the in-situ calibration of the robot (middle), and the reassembly testing (right)

Reassembly Cycles

A typical cycle of repositioning of 20 elements at different positions took 18:27 minutes at a velocity of 150 mm/sec. Errors occurred over the duration of the installation due to the interference of visitors, causing dislocation of the elements. Such events called for the stop of the running program until all elements were put back into place. The program log allowed to rerun the program from the last instruction. The grasping process was always sufficient, and no grasping errors occurred.

The elements were only self-calibrating along one axis; tolerances along the other axis started to multiply after several circles. Once a component was a millimeter off, the error would increase with each following round when moved again. The issue was partially addressed by adding small concrete alignment pieces into the element below. If the placement of an extra alignment piece was not possible, the blocks had to be put back manually after 6-8 cycles. The log for tracking the cycle rendered itself very useful, as the tracking of the repositioned elements was not implemented.

In our assembly, elements were not fixed to one position only; throughout the light festival, the robot kept on reassembling the installation. Spectators watched the robot carrying out its tedious task with ease. The slow rhythm of illuminating the whole space in different colors was mesmerizing in combination with the movement of the elements in space (Figure 4-25). After understanding their role in relation to the installation, people started searching for the correct viewpoint to see the anamorphic effect, watching the de- and recomposition. The installation fueled many discussions between students and spectators about robots in construction.

Figure 4-25 Spectators standing within the installation

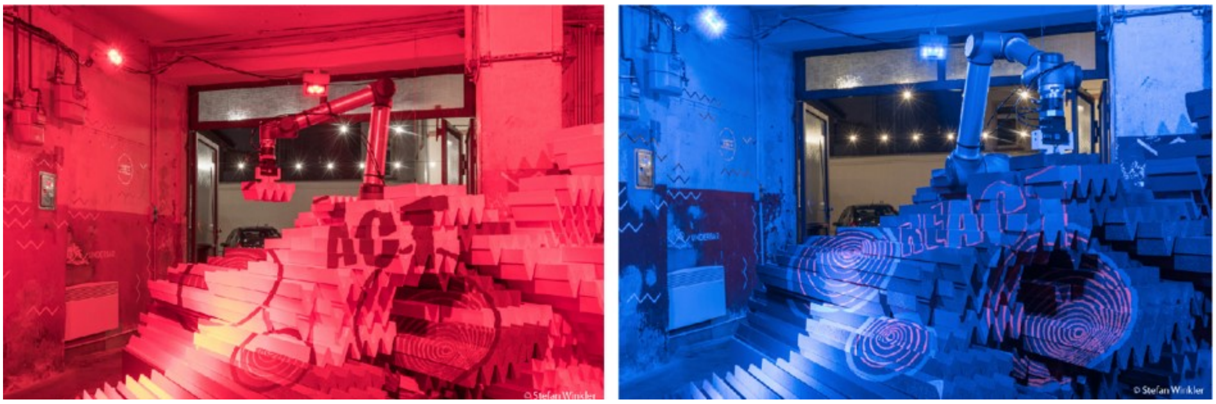


Figure 4-26 The change of light color indicates a warning that a piece is transported, and making the neon orange paint dissappear (left). After a part is placed, the light turns blue, which illuminates the neon orange paint, thus revealing the letters RE and changing the meaning from ACT to REACT (photos: Stefan Winkler).

Temporary Placements

The installation gave insights into the self-logistics within an assembly, the implementation of design and management tools for reassembly, and their spatial impact as a dynamic structure. The self-logistics presents many challenges, as the elements in transition have to be stored elsewhere. This could have huge spatial impacts; currently, obsolete parts have to be parked within a structure, which might lead to aesthetics of spatially non-optimal occupations of these elements.

Figure 4-27 Concrete elements integrated into parts of the foam block aggregation

4.1.4. Discussion

In this case study, the continuous reassembly of structure through the use of design strategies, robotic technologies, and dry joined building blocks was investigated. The task was to aggregate corrugated foam modules into a shape-changing sculpture for a light festival in Frankfurt. The robot became a self-contained machine as well as an integral part of the installation. Spectators experienced the change of an anamorphosis through the robotic reassembly of elements.

Curve based aggregation

The design tool was limited to input curves that assigned specific types of elements to each curve. The tool succesfully aligns the elements with the discrete grid in y-axis and z-axis. At the same time, it allows for continous shifts of the block in the other direction, merging the concept of discrete and continous (Figure 4-28). The continous movement could be set in the design tool to dscrete steps if required. In the physical blocks this could only be achieved by small inlays.

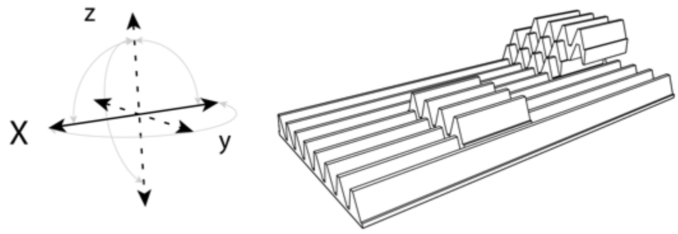


Figure 4-28 The blocks allow continous placement along the x-axis and discrete steps in y-axis and z-axis.

There were no structural considerations implemented into the design environment, which was a limiting factor for design decisions. Recent research has demonstrated a stability assessment method, allowing for the quick evaluation of stability for user-defined loads and supports (Andrea Rossi & Tessmann, 2017a).

Continous Robotic Reassembly

Design for reassembly cannot be understood as a linear sequence of assembly and disassembly. The logistics for reassembly involves considerations for the storing or parking of elements. Therefore, open areas may be designated for such scenarios. The elements for repositioning and their parking position were chosen by hand. The ongoing repositioning of the elements.

The robot became a linkage between the physical elements and their digital representation. By digitizing the element positions, the information flow became bi-directional, as they were captured into the digital model. This di-directionality enabled, on the one hand, translating previously defined positions from the digital model to be translated into robot positions. On the other hand, the stored positions could be retraced from the model through the robot pointing at the already inscribed positions. Thereby, the robot became an integral part of the installation. In the setup, the positions of the elements merged back into the digital model, creating an as-built digital model. The modular parts, together with the robot, became a combined system (N. Gershenfeld et al., 2015).

Dry Joined Blocks

The case study provided an demonstration in which building elements were designed for a reassembly process. The dry-stacking system integrates self-calibrating features into the blocks connection detail. While the mortar-based brick relies on the fixation and error correction of the mortar bed, the blocks present a different tectonic approach. Typically, the bricks are carefully placed and positioned manually to address tolerances of the brick. In robotic bricklaying, these issues are addressed by sorting the bricks for highly precise bricks or via sensors (Bonwetsch, 2015b; Dörfler, 2018). To avoid these complexities, very high precision for the manufactured elements would be required, which can be accomplished with digital fabrication (Mohammad et al., 2008). The developed building blocks in this study self-calibrate to the previously placed block. The elements simplify the robotic assembly as there is no need for gluing or other adhesives, which would cause the robotic process to become more complex. Finally, the elements are hinting at necessary preparations for elements that could be reused.

The concrete blocks offered further modalities within the building kit (Figure 4-27). The perforated blocks would allow for a 90-degree rotation of the continuous orientation of the subsequent placed blocks. In this case study, this rotation property was not utilized in the case of the perforated blocks. The materiality made the blocks more robust, as tested fabrication of the geometry made from foam was too fragile. Furthermore, it provided the blocks the possibility to create cantilevers, serving as counterweights in the aggregation. This modality could be implemented in future research, adding material differentiation to the aggregation tool. Both block types illustrate the possibility of providing specialized modalities by extending the building kit.

Conclusion

The redistribution of elements in a logistically sound system is a complex task. To enforce designers to cope with this sort of problem is time consuming and constraining. Nevertheless, the demonstration proved that a typical design environment could be augmented with tools for reassembly. These tools include a design tool for discrete design based on a kit of building elements, the position capturing of physical elements, and robot simulation and instructions.

Future work may focus on algorithms for identifying reassembly sequences with designated pick-up, parking, and placing locations. The commonly linear process of one-time assembly may be challenged by embedding such features into spatial aggregates. Future architects trained in the domain of design for reassembly might develop exciting concepts based on the insights and technological development listed above.

Commonly, construction is executed linearly, with only limited feedback about the built status. Although it was implemented on a very basic level, similar to online programming, one can envision this to be an automatized procedure in which the robot captures this information on the fly. Such a setup would allow the robot to adapt to a dynamically changing construction site, yielding a live as-built model. The robot would constantly know where elements are placed or stored.

The construction industry may experience a reconceptualization through the use of robots, shifting from labor-intensive processes towards higher degrees of automation. Robot-oriented design of building elements may affect both ends of the involved technologies; robots appropriated for construction tasks and building elements fit for robotic reassembly.

4.2. Volumetric Discretizations

This case study focuses on an integral approach from algorithmic design to a robotic assembly process for volumetric discretization. Existing elements from the previous case study were used and combined with an algorithm that discretizes volumetric bounding geometries based on the existing building kit. A dual robotic setup was applied, extending the workspace.

Dry joined architectural elements require special considerations to overcome their loose coupling. Bottom-up processes with prefabricated elements are still less frequently used in design, causing either the adaptation of the design to meet industrial standards of prefabricated elements or requiring the fabrication of custom-made elements. Design tools like Rhino 3D focus on surface-based modelling. The surfaces often operate on a conventional architectural scale such as walls, doors, and windows and do not address the assembly on the granular level of elements. The design on a smaller hierarchical level – the level of elements like rods, plates or bricks – calls for a reconsideration of the available design tools. The discretization of design is set as a secondary phase when detailed and shop drawings have to be created.

Different approaches have been developed in recent years to enable the usage of modular elements or the discretization of digital models in the early stages of design. However, developed software frameworks for modular design still need adaptation and an understanding of their algorithmic principles. Various approaches for the design of brick walls in combination with robotic assembly strategies have been investigated by Bonwetsch during his dissertation (2015b). Researchers have investigated topology optimization for discrete assemblies (Naboni 2019, Rossi 2018). The robotic assembly of such discrete aggregations has been investigated, linking discrete elements with their consecutive robot assembly instruction (Andrea Rossi & Tessmann, 2017b).

Although research endeavors have begun to investigate discrete design and robotic construction, the extent of these investigations is often limited to one repetitive module or the use of adhesives (Retsin et al., 2019). In contrast, this study considers the usage of an existing dry joined building kit for a design tool to position different building elements inside a bounding geometry. A robotic setup is utilized in which two robots share the workspace during assembly. In the design and assembly approach, three main prerequisites have been addressed: the element-based design without adhesives, the dual robotic assembly, and the monitoring of the actual built situation. Further integrations of robotic assembly simulation or feedback from the as-built status are monitored in the design environment. The study investigates how these methods can be utilized to build a physical demonstrator.

This case study aimed at integrating computational design tools and manufacturing techniques for the design with modular dry joined elements. Two demonstrators were built to identify the necessary process steps and gain an understanding of designing for reassembly. The objectives were to develop tools for discretizing any three-dimensional volume bounding geometry, while considering workspace constraints of the dual-arm robotic setup. The volumetric input geometry can be derived from other form-finding approaches and has to be appropriated to the already existing set of elements from a previous study. Finally, 3D feedback in the form of a point cloud for the as-built status of the assembly was captured. The research reveals difficulties with the integration of computational tools, robotic fabrication, and monitoring system for the structures that could be built without adhesives.

4.2.1. Background

Segmentation vs Discretization

During the first Digital Turn in architecture, as defined by Mario Carpo (2013c), the segmentation of larger continuous geometries often was a secondary step after the initial design. This top-down approach focuses on achieving a very close adaptation of elements with the ultimate form. For complex geometries, the segmentation often results in extra efforts of appropriating elements towards an ultimate form (Figure 4-29), a lot of mass customized elements (Figure 4-30) or can lead to compromises in the ultimate form (Figure 4-31).

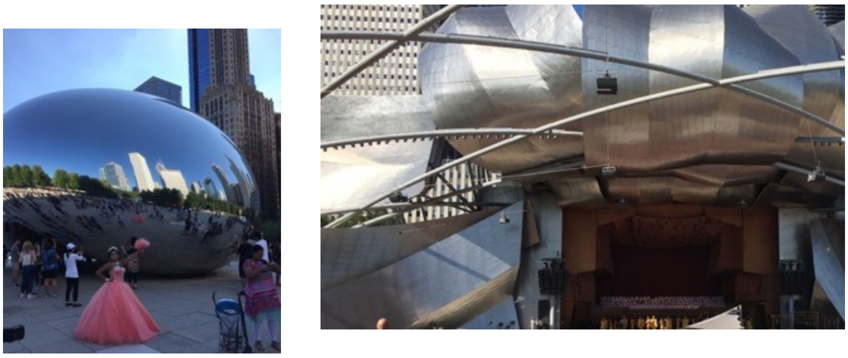


Figure 4-29 Cloud Gate, a sculpture by Anish Kapoor, and the Jay Pritzker Pavilion by Frank Gehry in close proximity in Chicago. While the sculpture creates the illusion of a monolithic object through welded and endlessly polished stainless steel panels, the architectural scale requires segmentation and a much rougher surface treatment. The individual panels are meant to merge into a global sculptural form. (Photos: O. Tessmann)

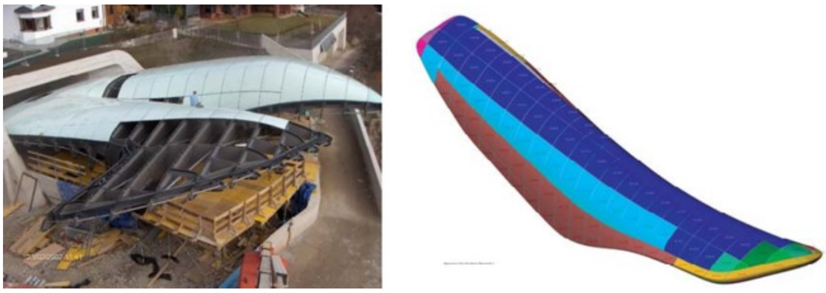


Figure 4-30 Roof of Innsbruck stations by Zaha Hadid Architects. View of one of the stations on-site (left) and of the modelling of the complex envelope with a color coding indicating similarities (Paoletti, 2010).

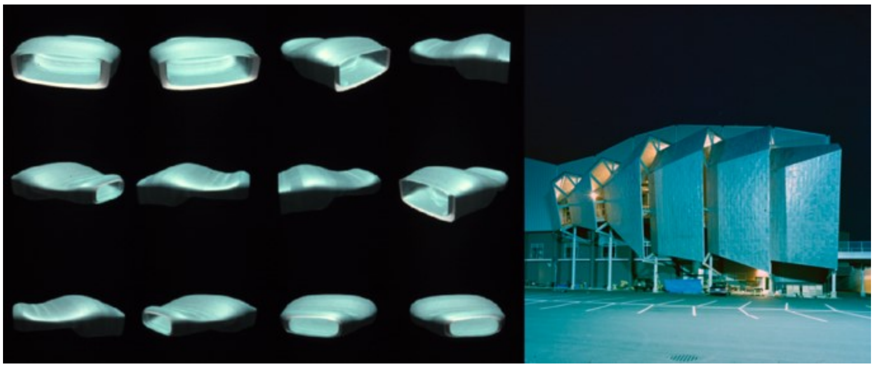


Figure 4-31 The design of the Korean Presbyterian Church from 1995 was a limited partnership of Michael McInturf, Greg Lynn (Hoboken, New Jersey) and Douglas Garofalo (Chicago, Illinois). (*Michael Mcinturf ARCHITECTS - KPC.Ny*, n.d.)

Such approaches offer no possibility for reassembly, and the elements only fit into one very specific position of the segmented geometry. Discretization works the other way around; rules define the combination of a finite set of elements (Sanchez, 2019). Those discrete elements form an aggregation that might be constrained by a predefined three-dimensional hull geometry. However, the elements maintain their discrete characteristic and do not merge into the global form.

Algorithms for discretization have been explored for brick walls at ETH Zurich. Different brick bonds were implemented using the scripting language MEL and python in MAYA as well as the software ROB Creator (Bonwetsch, 2015b). The tool translates surfaces into discrete brick assemblies in sequential order for later robotic stacking. A volumetric modelling tool has been developed, shifting from the traditional boundary surface representations to hierarchical volumetric modeling (Michalatos & Payne, 2016). Recently, researchers have shifted from parametric top-down tools towards more bottom-up approaches with discrete elements (Retsin, 2019b; Sanchez, 2016). These discrete design tools strongly focus on the initial elements as a starting point for design explorations. Although the elements are a crucial design factor, they also need some guiding geometries like curves, surfaces, or volumes and assembly rules. Additionally, other form-finding methods like topology optimization can be used to charge this input information. Nevertheless, the input driver for the actual aggregation has to be translated into the distribution and combination of the elements.

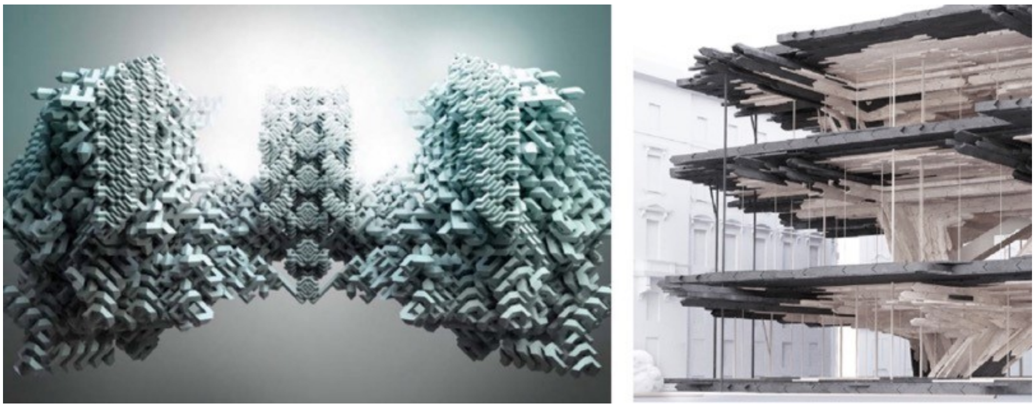


Figure 4-32 Renderings of Polyomino Studio year 2 by Hanze Yu, Kaining Li, Siyu Cui (left) (Sanchez, 2016) and the project KarlsPlatz by Gilles Retsin (Retsin, 2019b)

Dual Robot Arms for Fabrication

Various robot setups have been explored in architectural research, with only a small number of them dealing with the integration of multiple robots (Melenbrink et al., 2020). While humans in construction and fabrication commonly use two or more limbs to fix or assembly building elements (Reinhardt et al., 2018), architectural research on robotics often relies on stationary six-axis robot arms or single robots on mobile platforms or linear axes (Gramazio et al., 2014b). Only in recent years, the usage of two robots for assembly tasks has been investigated. While single robots have a limited workspace, dual robot arm setups have to deal with overlapping workspaces. These overlaps require collision checks between the robots and complicate the robotic path planning.

Gramazio and Kohler Research has shown great research on collaborative robotic assemblies for wooden prefabrication (Apolinarska, 2018) and metal structures (Parascho, 2019). The study Spatial Timber Assemblies at ETH (Figure 2-56) presents an approach for two robots in a sequential assembly process, sharing their workspaces to place and hold wooden beams for manual fixation (Adel et al., 2018). Similarly, robots placed metal pipes in space aligned in such a way that they could be welded together (Figure 4-34).

It has been suggested that the flow of information between a design model and the robotic fabrication should be reciprocal, taking the robotic constraints into account (Parascho, 2019). A robotic planning environment for such complex assemblies is under development at ETH Zurich. It aims at generating collision-free robot paths and the handling of tolerance, verifying input designs on their buildability build-up (Gandia, 2020).

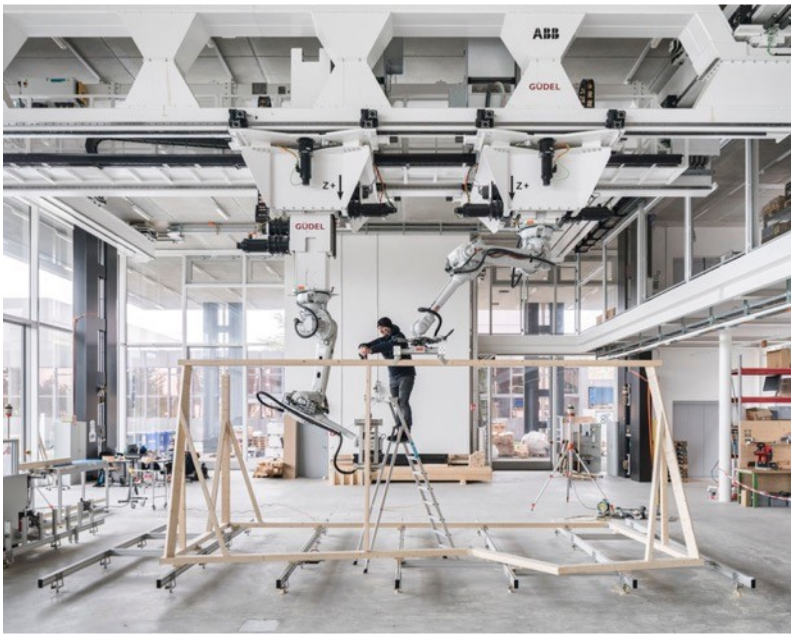


Figure 4-33 In the project Spatial Timber Assemblies, two robots holding wooden beams in place and a human worker fixing the beams. (c) NCCR Digital Fabrication Photo: Roman Keller (Apolinarska, 2018)

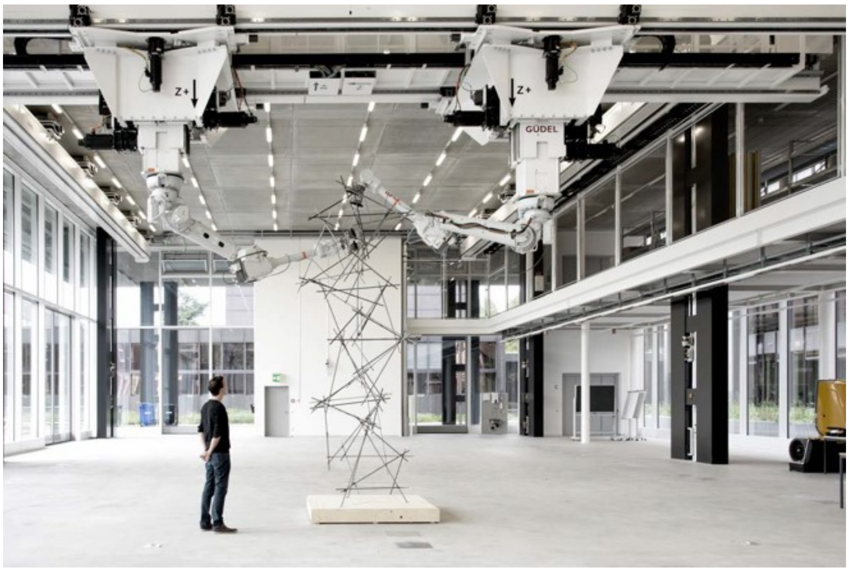


Figure 4-34 Prototype assembled by two robots. Photo: Marco Palma (Parascho, 2019).

The discretization and the robotic assembly were treated as separated steps in the architectural production. Within endeavors dealing with complex design problems, Parascho (2019) suggests identifying several sub-problems. These are form-finding, structural analysis, generation of production data, fabrication, and construction monitoring. All of them require consultation before or during reassembly. Today, it is possible to integrate these sub-problems into the design environment.

The As-Built Modell

In architecture, one can identify different types of models throughout the production: The design model, the as-planned model, and the as-built model, each providing a different level of detail and information (Cho et al., 2013). The design model is used during the design process and containing conceptual relevant information to derive spatial relationships. The planned model translates the design model into buildable information, containing information such as material choices, connection details. While the first two are very conventional models used in architectural offices, the as-built model is mainly used for facility management or in historic preservation. Its usage for deconstruction planning or reassembly has not been addressed (Nahangi et al., 2014). The actually built construction can be digitally fed back into the planned model, creating an as-built model requiring data collection and data refinement. The model is built after construction through capturing procedures. For the data collection of the actual built status, computer vision approaches ranging from laser scanning to image processing can be utilized. For the project Remote Material Deposition, a robotic loam throwing project, a 3D laser scanning approach was implemented, surveying the ongoing fabrication process (Dörfler et al., 2013). The collected data came in the form of a 3D point cloud. These point clouds need further processing to derive the relevant information for the digital model. They can be translated into surface geometries, boundary representation (BRep) or Constructive Solid Geometry (Segura et al., 2013).

4.2.2. Method

The goal of this study was to implement a dual robotic assembly process with an as-built monitoring process for a discrete assembly. A set of modular building elements were integrated into the design algorithm that can volumetrically discretize any hull geometry.

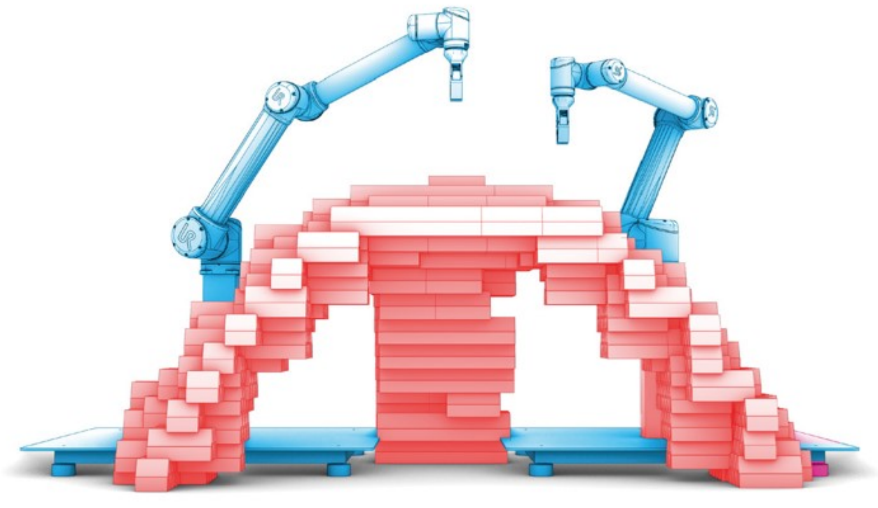


Figure 4-35 The designed volumetric shape before being tested against robotic assembly constraints

The case study design was set in a seminar called 'Robotic Sensing' during the summer semester of 2019. In the seminar, 18 students were introduced to modular design with an already existing modular system (see case study 1). Moreover, the students had to implement sensor interfaces using a Microsoft Kinect depth camera. Finally, in a group workshop, the students were introduced to robot programming in Grasshopper using Robots (Soler, 2019). Based on their gathered knowledge, in a discussion round, the students proposed project ideas to be carried out in a two-week workshop at the end of the semester. The presented project is one of five experiments conducted during the workshop. The project was conducted by a team of two students under the supervision of the author. A small prototype was built to test the feasibility of the overall approach. Based on the gathered insights, a larger demonstrator was assembled to reveal new challenges.

A prerequisite for the study was the reuse of an already existing building kit that was extended by blocks of 48 and 96 mm wide. Based on the dimensions, the modules were clustered into two sets – the length and the width set (Figure 4-36). Thereby, the modules allow for a wide array of lengths in step sizes of 10 or 12 cm and, at the same time, guarantee a minimum dissection. The two sets were to be combined to form a layered cross-bond.

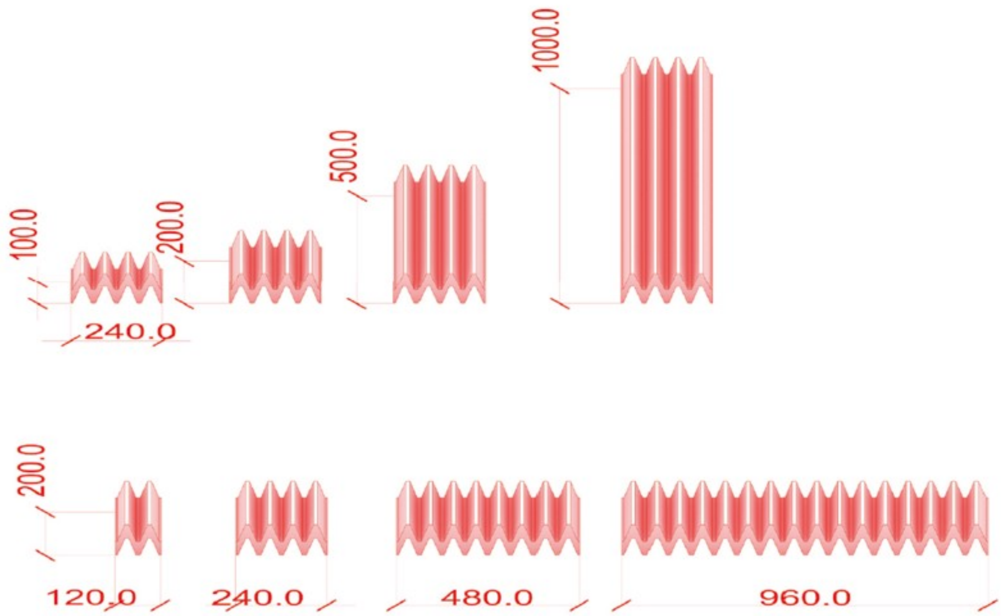


Figure 4-36 The modules are clustered into length-based blocks (top) and width-based blocks (bottom).

Discretization of Bounding Geometries

By combining the two sets on alternating layers, the horizontal overlaps between the layers can be maximized. The layered stacking approach can be compared to volumetric bricklaying (Bailey & Hancock, 1990). Simple stacking of blocks without consideration of bonds between the layers would cause instability. To avoid such unstable stacking, the layers for the blocks were discretized, alternating between the two available sets of modules (Figure 4-37). The elements were used to populate volumetric boundary geometries. For layer-based stacking of discrete elements, the implementation of two operations is crucial; the generation of the slicing of the boundary geometry to generate layers and the mapping of the elements onto the alternating layers. Both procedures depend on the initial building kit and the geometries of the elements. In this approach, the layers were differentiated based on the two types of modules for a cross-layer system (Figure 4-36).

The starting point for the algorithm is a volumetric boundary that was sliced horizontally (Figure 4-37). The geometry is cut with an offset that is based on the block heights. In the case of the used blocks, the layer height was set to six centimeters. The sliced outlines intersect with planes that meet the width of modules, which is 24 cm for the length blocks and 20 cm for the width blocks. The blocks are assigned to the resulting line based on their length, starting with the longest blocks and then sub-sequentially adding additional blocks.

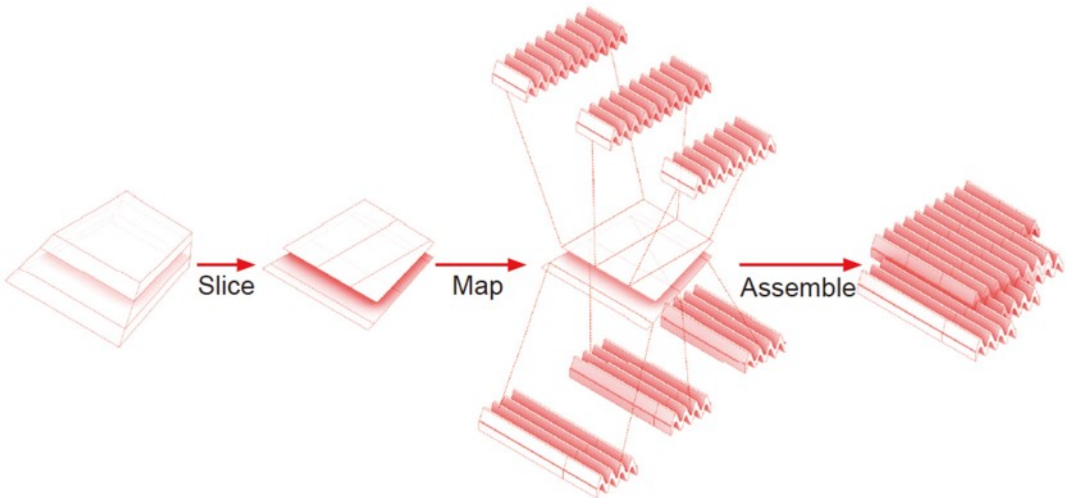


Figure 4-37 The slicing and mapping procedure of the discretization algorithm

Dual Robot Setup

Dual robot setups came with an overhead of programming and communication between the robots, to avoid collision between the robots. The robotic setup for this case study consisted of two UR 10 Robots. As the robots were placed on fixed stands, they were located two meters apart from each other, allowing them to maximize the buildable space. Each robot had to have access to all available modules. Each robot had a feeding area that would be manually fed with the necessary modules.

The case study focused on the assembly with a dual robot system. The stationary robots were placed 2.1 m apart, providing a feasible distance for reaching an overlapping workspace. The robotic simulation was integrated into the design environment. Thereby, the designer was able to alter the design until the workspace constraints were met (Figure 4-38).

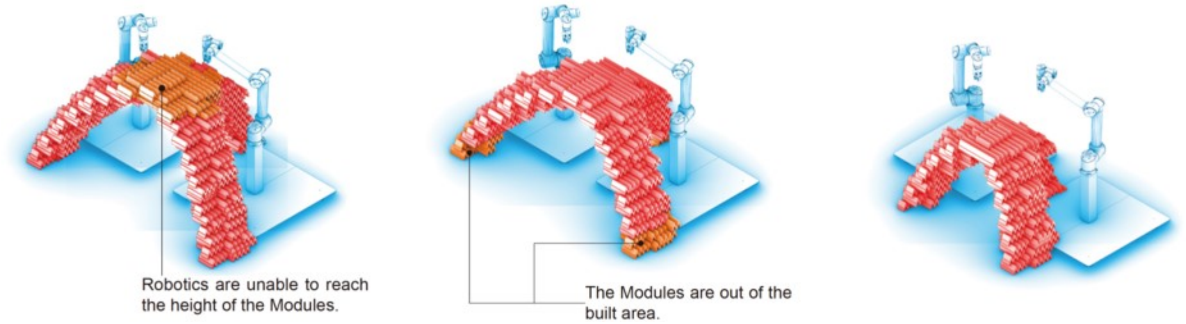


Figure 4-38 Altering the geometry of the assembly constrained by the most distant elements on the bottom and the top of the structure (orange element)

The assembly process consisted of eight module pick-up locations, reachable for the two robot arms. The dual robots were programmed in Grasshopper using the plugin Robots by Vicente Soler (2019). It provided simulation and code generation for all crucial steps in the pick and place procedure.

The robots were equipped with parallel gripper systems with fingers matching the block geometry. To avoid the overhead of a collision check in the program, the robots were programmed to wait for each other to finish the next assembly task; once the first robot finished, the second one started the next placement. A digital output-input connection facilitated the connection between the two collaborative robots and was implemented in the robot programs. The first robot sent a digital output signal to the second robot, indicating the start of the next sequence for the second robot. While carrying out an assembly sequence, the first robot waited for a digital signal from the second robot once it was finished.

As-Built Modell

As the actual built status of the assembly may differ from the precise digital model due to material tolerances, assembly errors, or damages, it was crucial to capture the as-built status of the aggregation. In this study, the focus was put on an image-based approach to generate depth information using a Microsoft Kinect Version 1. This sensor uses structure for light, emitting an infrared light pattern and capturing the deformation of the pattern to calculate the depth of a scene.

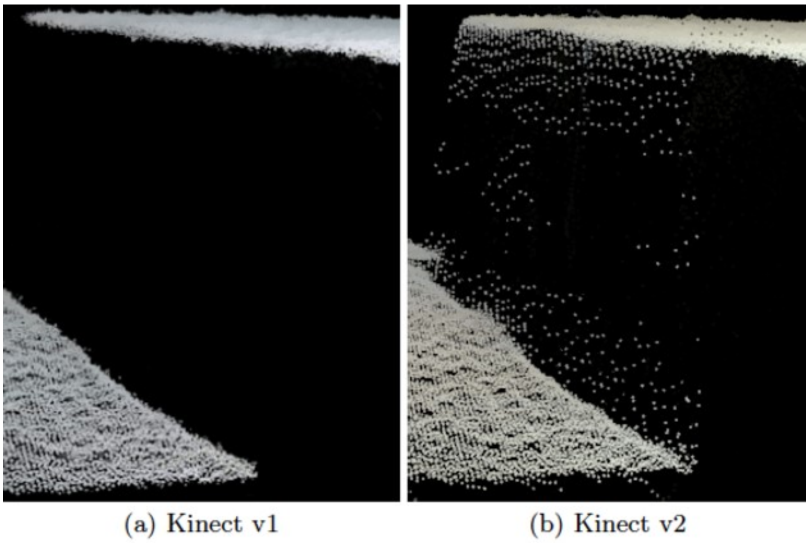


Figure 4-39 The erroneous pixels between the two horizontal points for the Kinect v2 are caused by flying pixels (Wasenmüller & Stricker, 2017).

Tests with the Kinect Version 1 and Kinect Version 2 revealed that the elements come with less noise when using the Kinect 1, due to flying pixel errors with the Kinect 2 (Figure 4-39). Kinect 1 uses structure for light which reduces the flying pixels as opposed to the Time-of-Light sensor used in Kinect 2 (Wasenmüller & Stricker, 2017). The camera observed the whole scene from above, guaranteeing maximum coverage and visibility. The system was used to automatically detect the block type based on the derived outline derived from the point cloud. While most as-built models are derived once the construction is finished, certain information such as the in-between assembly steps get lost. In the presented setup, the overall aggregation was captured at each sub-sequence of the assembly. This process allowed to derive a sequential as-built model (Figure 4-40).

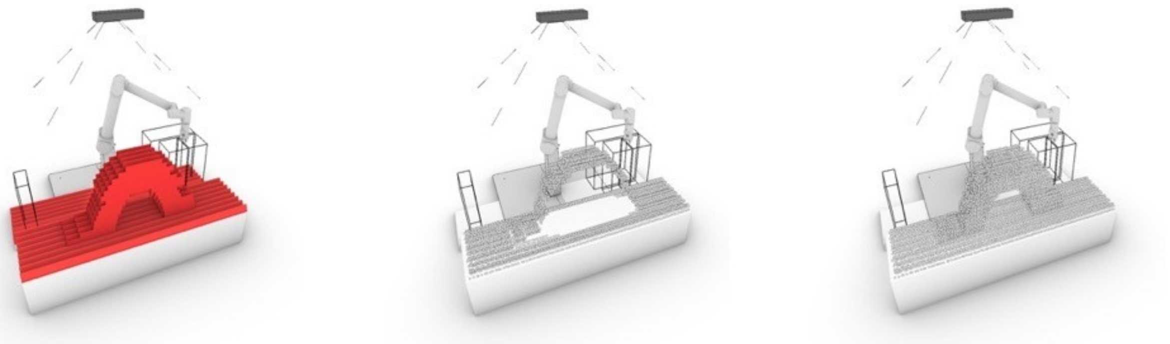


Figure 4-40 The planned model is used as a baseline to capture and segment the point clouds into element base chunks (left). A complete scan captured from the final assembly (middle) and a sequential scan revealing insights about each placed element (right).

In total, two UR 10 robots, eight pick-up locations, one computer, and a depth camera contributed to the physical setup. The software implementation included Firefly (Payne & Johnson, 2015) for capturing the 3D point cloud from the depth camera. The point cloud was then translated into a module representation. Therefore, the point cloud was contoured, generating curves that can be measured against the contour of the respective modules.

4.2.3. Results

The overall process was achieved without avoidable breaks in the digital chain from design to manufacturing and documentation of the as-built status. The design environment was equipped with custom-made tools for discretization, robotic programming as well as a feedback mechanism for the as-built status (Figure 4-41). Due to the integration into one algorithm, the design could be manipulated at different steps. Changing the overall geometry while seeing the robot constraints being updated. Throughout the construction process, the progress was monitored via 3D scanning and converted into an as-built model.

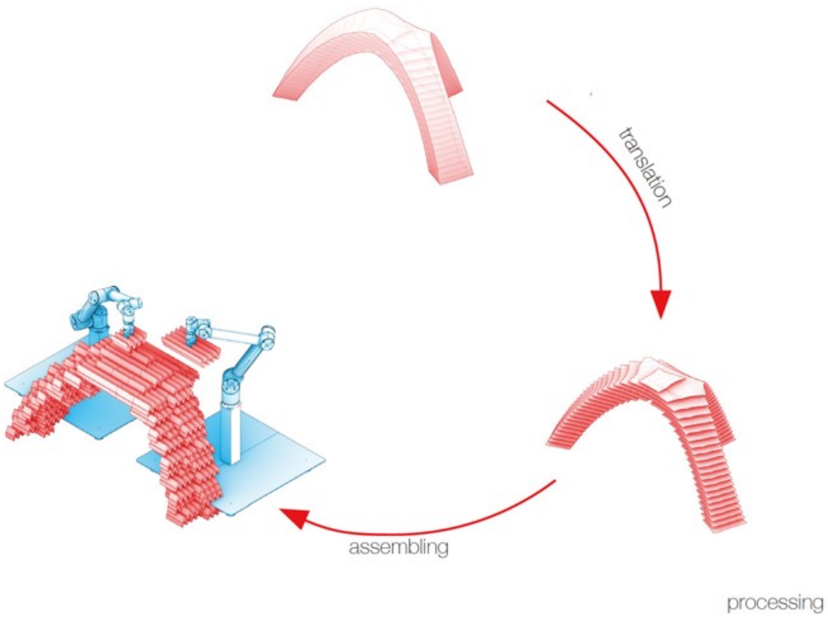


Figure 4-41 The overall process diagram showing the translation of input geometry to a robotic assembly process

Volumetric Aggregations

The design algorithm was capable of discretizing various volumetric bounding geometries. Depending on the length differentiation of the modules, the geometry fitting can be adjusted. The speed of the discretization algorithms enables real-time adjustments of the guiding geometry by the designer, yielding fast design iterations (Figure 4-42). Thereby, when designing, decisions based on the module distribution were made to avoid aggregations that looked unfeasible for self-support or robotic construction. A collision between the modules did not occur.

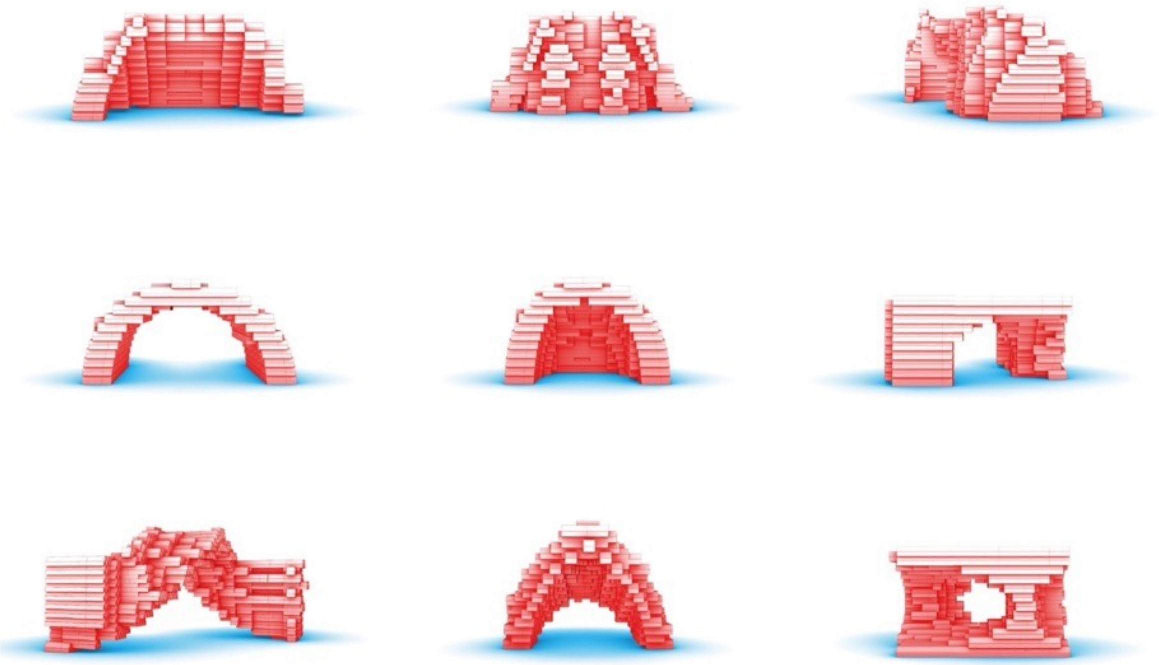


Figure 4-42 Different aggregations based on volumetric bounding geometries (image Jianpeng Chen)

The final design of the hull surface was generated through a mesh relaxation algorithm using the grasshopper plugin Kangaroo by Daniel Piker (Piker, 2017), highlighting the possibility of external tools for generating the bounding geometry (Figure 4-43). The mesh relaxation here is set up as a catenary model generating a tension only model. It is obvious that the translation into the discrete blocks did not account for this approach and is an illustration of possible inputs rather than a literal and meaningful translation of the input geometry. The final design measured 150 x 155 x 90 cm. The algorithm minimized the subdivision of the bounding geometries by first distributing the largest blocks available.

Figure 4-43 The mesh relaxation algorithm (top row) with its bounding volume, sliced and translated into guiding lines (middle row), and the population with the building blocks (bottom row)

Dual Robotic Assembly

Two aggregations were assembled; one small arch assembled by a single robot and a shell-like aggregation in a dual robot process. The arch was assembled from eight different block types and a total of 40 blocks (Figure 4-44). The robotic sequence from approaching a module for pick-up to placement and descending form it took an average of 25 seconds for a single module. Each was assembled and disassembled in about 17 minutes, while the pick-up location was manually fed with blocks.

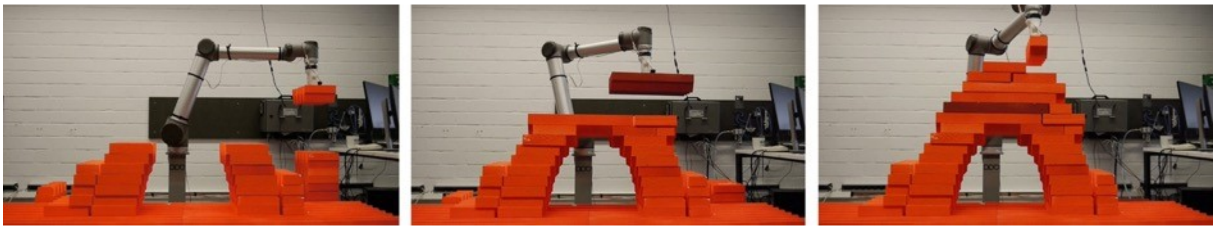


Figure 4-44 The initial prototype assembled from three different types of modules and 38 modules in total

The final aggregation built by the dual robot system was self-supporting and built in roughly 1.5 hours under supervision of two students. The robot programs worked sufficiently, and the communication between the two robots was always synchronized. The pick-up locations were manually refilled by the students. The assembly was finished without any collisions between the robots, the aggregation or carried parts. Minor errors in the grasping mechanisms occurred due to tolerances of the fabricated elements. These errors caused the stop of the assembly and manual readjustments of the elements.

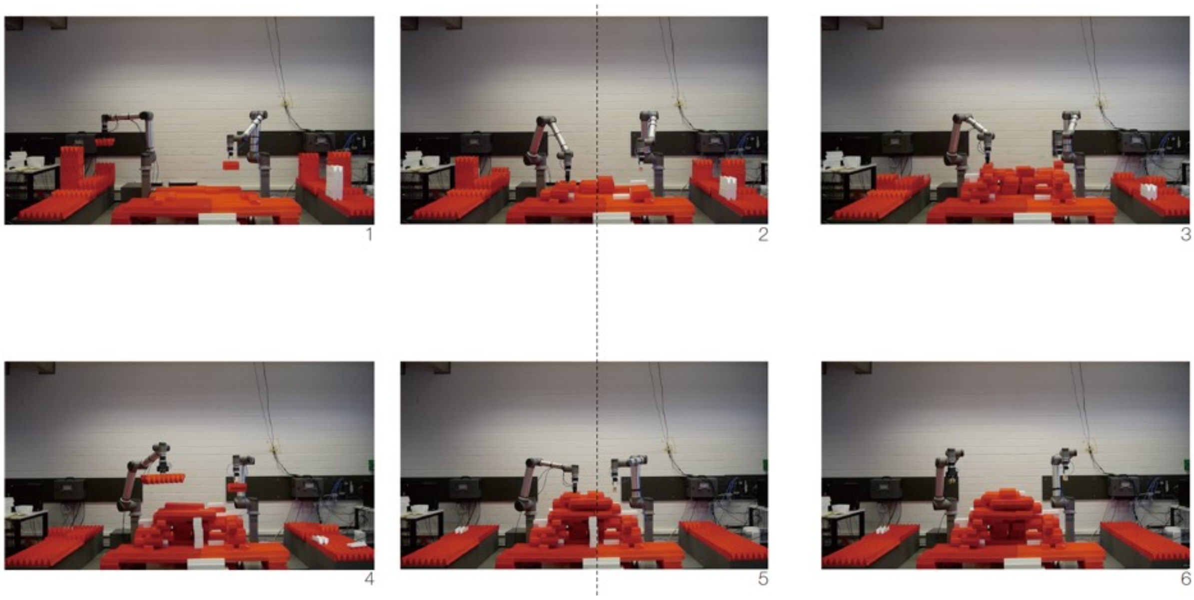


Figure 4-45 Robots sequentially building the structure

These errors started during the grasping of the elements and caused the parts to either slip out of the gripper or causing misalignment (Figure 4-46). In such cases, the program had to be stopped at the step of the error and restarted with manual error correction. At one delicate point during the assembly of the shell-like structure, a support structure was necessary due to a span larger than the longest module. The support was removed after placing the consecutive layer, resulting in a support-free aggregation in the end. In areas of higher force, the parts started to misaligned due to the loads settling. The structure deflected around 5-10 mm from the digital design model.

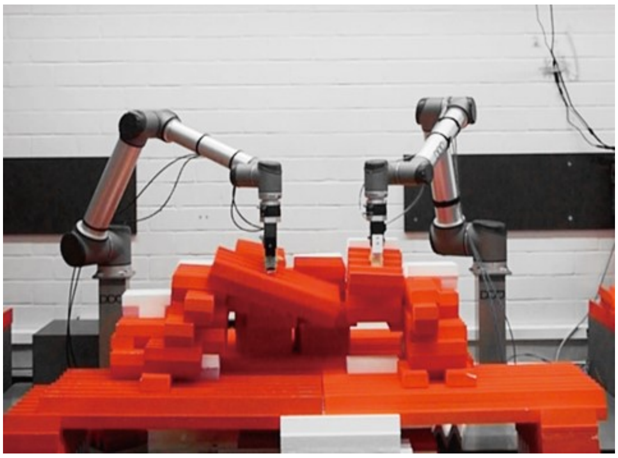


Figure 4-46 The robotic assembly of a part failed due to tolerances in the grasping

Sequential As-Built Model

From the point clouds, the actual distribution of the elements into an as-built model was derived, linking the physical back into the digital. If carried out automatically, the geometric representations at each sub-step of an assembly could be stored into a sequential as-built model with the point cloud information linked to the designated block type (Figure 4-47).

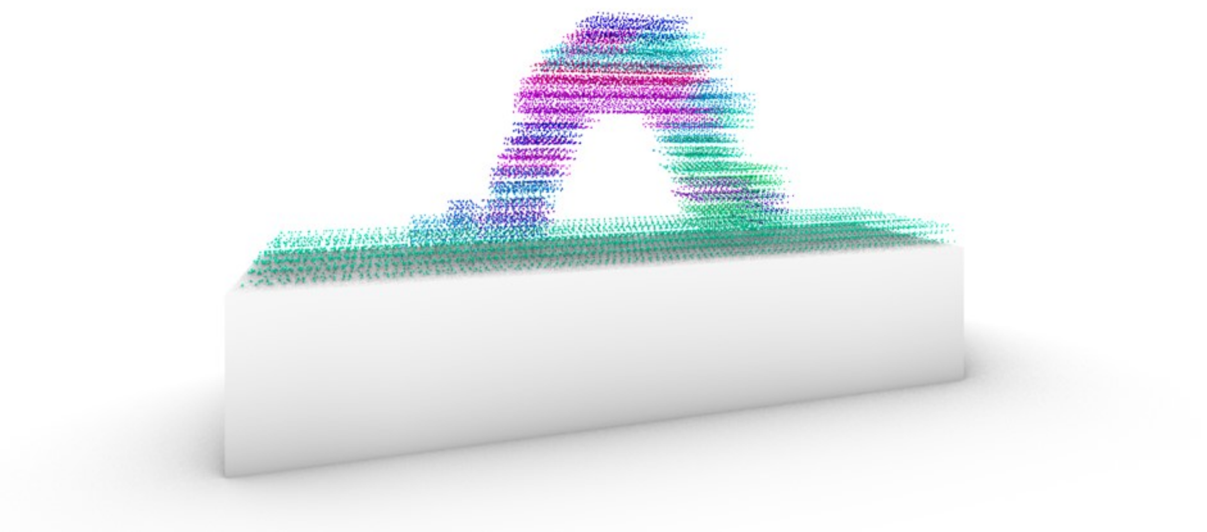


Figure 4-47 All point clouds captured for each placed element separately in one model. The colors indicate the separate point clouds.

4.2.4. Discussion

The case study presents an approach to volumetric discretization based on a building kit and a dual robot setup for assembly. With a given set of blocks, the design tool was able to discretize various volumetric bounding geometries in a layered bond. Through the robotic assembly procedure, insights into manufacturing issues were gathered that have to be addressed when designing with discrete elements and dry-fit connection. The accomplishments of the study can be summarized as follows: First, the development of a cross-layer discretization algorithm for volumetric geometries that is adaptable in regards to different blocks geometries. Second, a dual robot system for assembling with stationary robots that share one workspace while continually executing their tasks. Finally, a sensing system that can derive module positions from a 3D point cloud and map them into a sequential as-built model. The overall results imply that all three approaches for reassembly should be integrated into one software environment. Thereby, design and assembly might not be a one-off linear process but could be continued into the future.

Discretization Based on Availability

The examples of different discretized volumes suggest that the tool can cope with almost any bounding geometry. The mesh relaxation algorithm was not able to provide the necessary information to generate a stable structure. Even though structural optimization was not the focus of this case study, the algorithm could be exchanged by more suitable form generation algorithms due to the modular design algorithm and setup of the design environment. Moreover, the cross layering may also need to be further optimized to distribute the elements without gaps. While other studies have shown attempts to derive such information from topology optimization (Naboni & Kunic, 2018), it has to be noted that the used building blocks are non-convex and have a complicated connection interface. However, the currently available tools for discrete assembly and their optimization or simulation are rather limited or have to be appropriated. The usage of the mesh relaxation can be regarded as not ideal for the available set of modules due to the geometry of the elements and the directionality of forces within a funicular mesh. Tools that can inform the later discretization like topology optimization or weight distribution for discrete assembly might be a more promising field for future investigation.

One major difficulty in the presented study was the focus on a dry joined building kit. The modular blocks with a dry-fit connection came with the burden of excess structural complexity. Thus, appropriate engineering analysis tools were not available to guarantee stability. One option might be the usage of physical simulations fit for non-convex geometries.

The cross-layer approach holds similarities to bricklaying bonds. Previous investigations have proven the feasibility of bricklaying robots for differentiated geometries (Gramazio & Kohler, 2008). These studies already involved design tools for the arrangement of bricks. The present study presents a design tool that can cope with a set of differentiated modules. The modular arrangement follows a similar logic as in volumetric bricklaying. While most bricklaying systems deal with only one type of brick, the system implemented in this case study integrates a set of different block types. Eight different types were investigated, but it is possible to extend the system.

The initial design was placed into the workspace areas of the robots to make sure it could be built. Nevertheless, there were some unforeseen circumstances that go beyond the workspace to workpiece arrangement. For one, the robot's workspace only defines the operational reach of the robot. It does not account for the assembly plan of the blocks, resulting in a shrinkage of the workspace due to further constraints introduced because of the block sizes. It is easier to place parts inside the volume than close to the boundaries of the workspace, as the robot forms a new entity with the blocks, which may limit the reachability and workspace. Additionally, the construction environment changes along the assembly sequence. Several steps of the design adjustment required the designer to infer his knowledge about the robotic constraints by running robot simulation or tests on the real robot setup.

Distributed Assembly

The robot system was set up stationary with two similar six-axis arms. The study shows that communication between two robots that share one workspace is feasible to distribute tasks. The demonstrator provides insights on how to speed up the assembly process and how to extend the workspace in a robotic construction setup. Although the placement of the parts was not happening simultaneously in the workspace, other tasks like pickup and transport were carried out in parallel. The workspace was reduced due to the size of the blocks. The bigger the block, the more limited the workspace was because of collisions with the robot or the environment.

Accuracy problems in the assembly were caused mainly by tolerances of the workspace setup or module tolerances. The 3D scanning setup was not able to negotiate these tolerances, as the scanning system itself only has an accuracy of +- 3 mm. To overcome this limitation, further investigation is needed into either a higher precision in workspace and module or a better sensing system that could compute according to those tolerances. In consideration of the tolerances on conventional building sites, the latter might offer more potential.

The blocks were to be assembled without adhesives using a dry-fit connection. This works well in situations of vertical stacking but creates problems in cantilevering situations. The problem can partially be addressed with support structures or by adapting the geometry to avoid problematic overhangs. One way could be more complex interlocking that requires much more complex assembly skills of the robot. Currently, there is no procedure implemented that would allow us to test the feasibility of a structure. The case study did not focus on the stability of the assembly, as there was no feasible simulation to evaluate the stability. Current simulation tools available to architects do not offer any simulation for such contact-rich behavior of non-convex bodies as used in this study.

Conclusion

This study proved the feasibility of an algorithmic approach that can cope with a set of modules and assign them properly into a volumetric assembly. A dual-arm robot setup was implemented for an assembly task. Through a 3D scanning procedure, the whole process was monitored to generate an as-built model linking the physical assembly with its digital twin. Finally, a demonstrator was built with two stationary robots, illustrating a completely digital process chain.

However, several aspects of building with dry joined elements need further development. Currently, the physical simulation of contact-rich aggregations is not possible within conventional architectural design environments. The implementation of existing physics simulation from other fields might solve this issue. Another way to overcome this limitation might be an analytical approach to calculate contact between parts as well as considering the weight distributions within an aggregation. The robot dual-arm setup is a first step towards more advanced task-sharing scenarios between robots. The whole construction sequence can benefit from strategies in which robots align their tasks in delicate points. For instance, the fixation or support of elements during assembly might help overcome local difficulties within the assembly sequence.

Although a 3D scanning system was used, it was not possible to outfactor the tolerances of the elements and the workspace. Construction elements always come with tolerance. To overcome those tolerances, an adaptable system that uses sensory input could help. Here, the integration of a sensor system as well as a robot control mechanisms that can use the sensor input have to be developed.

Future research into bridging or spanning structures composed of discrete elements without adhesive can make building systems for reassembly more acceptable in architectural design. The strong linkage between the discrete design, robotic assembly, and as-built monitoring illustrates how the different stages of architectural production form an integral process for reusable dry joined elements. Enabling designers to use discrete parts without adhesives is a crucial step towards an approach to architecture that is not static and might enable future generations to reassemble already existing structures.

4.3. Incremental Balancing

One outcome from the first study was the concept of counterweights. Made from concrete, heavier blocks enabled the figuration of cantilevers. Prefabrication has many benefits, such as reducing costs and effort when well implemented. Currently, there are many research activities around the topic of prefabrication and off-site construction (Ginigaddara et al., 2019), including the reduction of falsework and scaffolding as well as the automation of assembly (Razkenari et al., 2020). These literature reviews suggest an intensification of research on DfMA to rethink the current design strategies of elements and on-site assembly.

Research institutes like ICD Stuttgart or the Block Research Group (BRG) have put enormous research into the digital fabrication of prefabricated elements (Block et al., 2017a; Menges & Knippers, 2014). However, the assembly remains relatively conventionally, relying on human labor, scaffolding, and adhesives when used to build cantilevering and arching structures (Figure 4-48).

Figure 4-48 ICD/ITKE Research Buildings, onsite manual assembly of digitally prefabricated components using support structures, Landesgartenschau Exhibition Hall from 2014 (top row), BUGA Wood Pavilion from 2019 (middle row), and BUGA Fibre Pavilion from 2019 (bottom row) (Photos: ©ICD/ITKE University of Stuttgart) (Menges & Knippers, 2014).

These preliminaries turn the reusability or repositioning of elements into complex tasks and hinder automation, for instance, with robotics. The problem of incremental stability throughout the construction process with differentiated weighted modular elements is still unanswered. To overcome these limitations, Jin et al. (2018) proposed further investigations into the mechanism of integrating BIM, Design for Manufacturing and Assembly (DfMA), lean, and sustainability for off-site construction.

For instance, in most cases, cantilevering structures are assembled using adhesives like screws or glue and rely on the usage of scaffolding. For structures that are to be reassembled automatically, these approaches are obstacles that are to be avoided.

From the problem statement, the following research questions can be derived. How to design cantilevering aggregations for robotic assembly using dry joined elements without falsework?

Cantilevering structures are usually realized using falsework, for example. One way of creating such structures can be achieved by exact weight distribution. Keeping the center of mass of the cantilevering module above the physical edges of the underlying module, the cantilevering structure stays stable.

A modular system coupled with a set of algorithms is proposed that enables the construction of detachable modular assemblies. A self-aligning and stackable modular system is developed to allow differentiation in module size and weight. It is shown how static considerations can be incorporated into the design procedure to enable the assembly of cantilevered structures (Heisel et al. 2017). Moreover, a sequential robotic assembly process is implemented, generating self-standing structures without support or extra formwork. The robot can cope with differently sized and different types of modules within one assembly process. Finally, two demonstrations highlight the precise balancing that was achieved using the available modules.

4.3.1. Background/Context

Balancing Discrete Elements

The construction of arching and cantilevering structures is a challenging task. Commonly, these structures are erected using falsework. Architecture historians speculated how Gothic vaults could have been constructed with minimal falsework using stone-weighted ropes to balance the vault during the sequential assembly (Figure 4-49) (Shelby & Fitchen, 1961, p. 192).

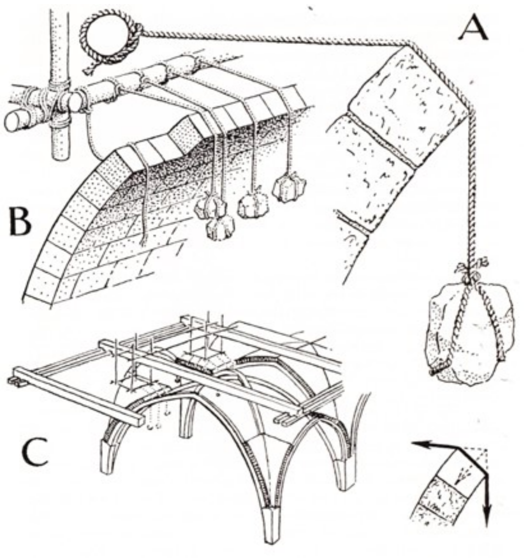


Figure 4-49 The stone-weighted rope device for building web courses without lagging or other falsework as proposed by Shelby and Fitchen (1961, p. 192). A stone spans from a pole over the last-placed stone with a weight stone at the other end, creating a compression force almost perpendicular to the stone interface to the previously placed stone (A). Drawing B shows a series of such ropes used to fix the current assemblage of the vault. Drawing C illustrates the minimal falsework consisting of wooden beams.

Nowadays, such tension-based systems are used for erecting simple arch and vault structures (Figure 4-50). The Arch-Lock system consists of prefabricated concrete elements that can be assembled using anchor points and temporary chains (*Lock-Block Ltd. - Arches*, n.d.). Their dry joined unparalleled geometric fit reduces tolerances and makes the use of mortar obsolete, enabling later disassembly.

Figure 4-50 The Arch-Lock system for tension-based falsework, copyright photographs: Lock-Block Ltd. 2013 (*Lock-Block Ltd. - Arches*, n.d.)

One way to use dry joined elements for more complex designs has been widely investigated at BRG. They have shown great expertise in the construction of compression-only structures (Block et al., 2017a). The elements assembled without adhesives have to be put into equilibrium with special consideration – they have to be balanced – using the 3D thrust-network analysis. However, there are two problems with this research; first, it still uses bespoke elements that can only be used at their designated position, and second, it again relies on falsework during erection. Most famous is the Armadillo Vault, in which the elements are assembled without any adhesive (Figure 4-51) (Block et al., 2017b).

Figure 4-51 The assembly of the dry joined bespoke elements of the Armadillo Vault with its falsework consisting of a plywood waffle structure and standard scaffolding towers (Block et al., 2017b). Image: Anna Maragkoudaki/Block Research Group, ETH Zurich.

The approach to build more complex compression-only structures was also combined with the temporary chain method using an algorithmic approach to replace the commonly used dense formwork (Deuss et al., 2014). Although the feasibility of this approach was only demonstrated in small-scale models, it still shows how assembly necessities can be integrated.

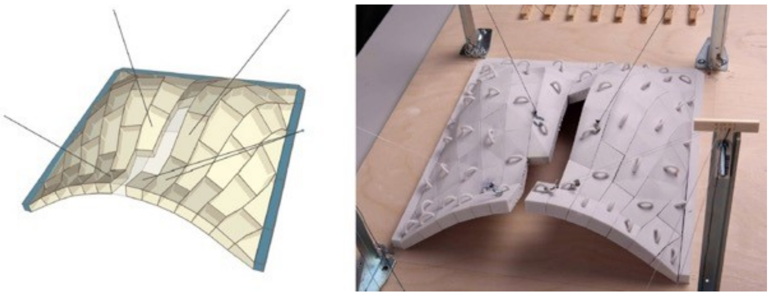


Figure 4-52 Digital and physical model of the algorithmically optimized masonry structure with only four temporary chains (Deuss et al., 2014)

The equilibrium of structures assembled from discrete elements without adhesives was investigated in the field of digital design in architecture through different approaches. It has been shown that most geometries can be discretized using geometrical differentiation to create equilibrium (Frick et al., 2015). Therefore, the compressive and frictional contact forces between elements was used to generate a self-supporting, discrete-element assembly of arbitrary 3D shapes (Figure 4-53).

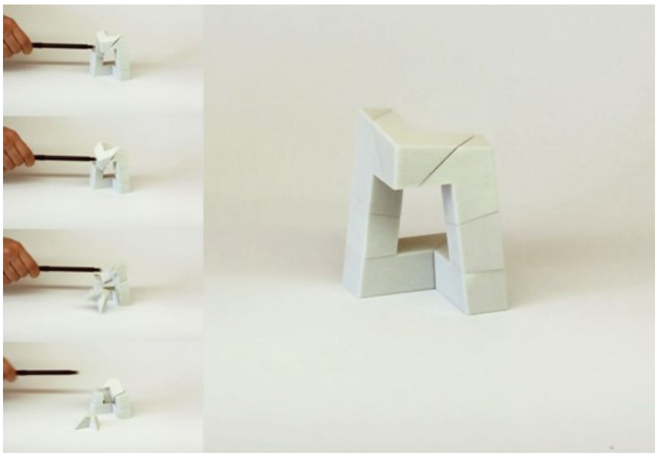


Figure 4-53 The volumetric decompositions of a CCTV model into a self-supporting, discrete-element assembly (Frick et al., 2015)

Additionally, the center of mass of elements can be altered incrementally to build cantilevering structures (Figure 4-54). Thereby, the erection of a column of non-stable form was achieved (Zayas et al., 2017). The practice Matter Design presents different approaches to balancing building elements based on their center of mass (Clifford et al., 2015).

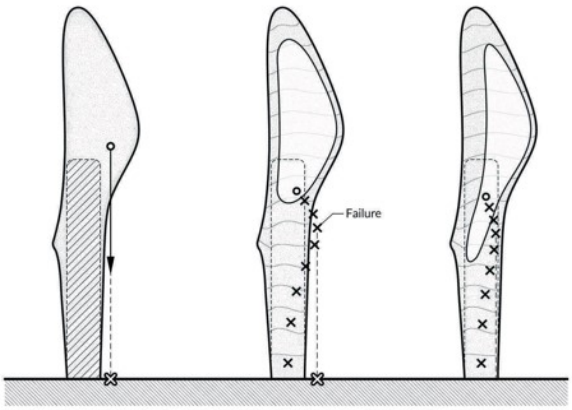


Figure 4-54 The alteration of the center of mass of a column like sculpture for incremental assembly. On the left is the homogenous solid object, in the middle is a hollowed object with the center of mass (circle) for final stability, the object on the right is stable at all incremental assembly steps (Zayas et al., 2017).

However, these approaches all rely on bespoke elements which would prevent their reuse without further preparation or are very limited in their combination (Arch-Lock). These cases are suboptimal for reassembly as the overall system cannot be altered. Once produced, the elements fit into their exact position in the overall structure. The assembly was done manually. Such labor-intensive processes require either very precise framework or the attention of a human worker.

Robotic Assembly of Cantilevers

In recent years, numerous projects dealing with topics of robotic assembly in architecture have been conducted(Gramazio et al., 2014). The majority of them deal with vertical stacking of elements that allow building highly articulated structures. Although these investigations are very impressive and novel, they focus on geometrical differentiation. The assemblies are irreversible due to the use of adhesives or are constrained to wall-like assemblies.

Stacking linear elements of various lengths and spatial orientation were investigated to build cantilevers of certain spans in a human-assisted robotic assembly process (Chiang et al., 2018)Due to the homogeneous materiality of the elements, the geometrical variability became the constraining factor in these aggregations. The elements were made from rectangular boxes with varying diameters and lengths. Thus, the more extending elements enabled to built the cantilevering, with smaller elements as counterweights.

Figure 4-55 Design to Robotic Assembly: An Exploration in Stacking (Chiang et al., 2018)

Another example for building a cantilever made use of a geometrical dry joined. Ariza and Gazit (2015b) used self-load in a demonstration to fix an assembly. A predefined double-curved geometry was subdivided into a diagrid to guarantee stability during assembly (Figure 4-56). Therefore, a geometrical assembly detail was embedded that addressed the problem of material tolerances enabling robotic assembly. Similarly, Ron et al. (Ron et al., 2018) suggest a robotic assembly process for formwork-free walls and arches with bespoke mono-material bricks with topological interlocking.

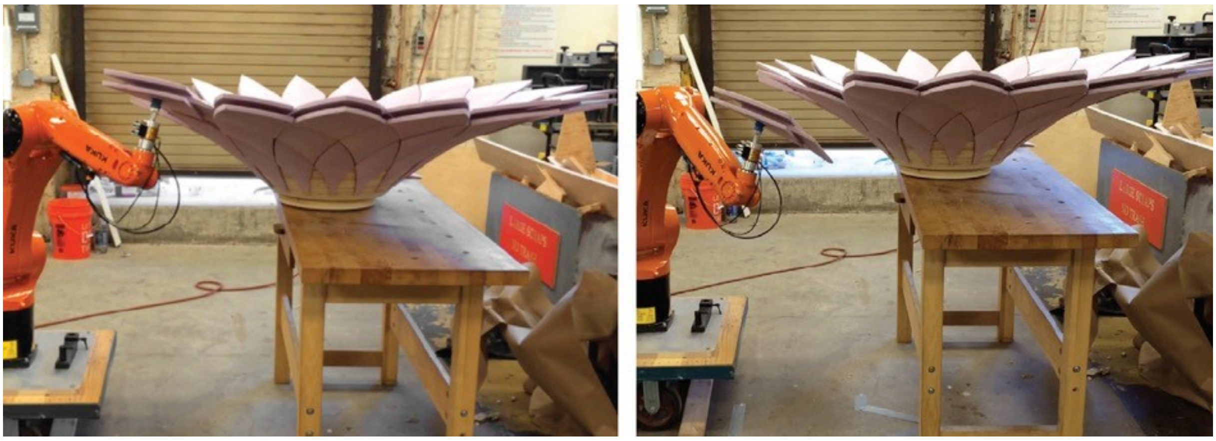


Figure 4-56 Full-scale robotic assembly of the diagrid structure (Ariza & Gazit, 2015b)

Different discrete elements for robotic assembly have been investigated for collaborative assembly (Andrea Rossi & Tessmann, 2017b). Designers can alter the assembly positions during execution while an algorithm constrains the positioning of elements based on a given set of rules. Here the integration of user input, algorithmic constraining, and robotic assembly are all integrated into a single fabrication process.

Two robot arms were used to erect arches in order to reduce falsework (Wu & Kilian, 2018). In this approach, the robot constantly has to carry more weight than that of one element (Figure 2-58), which might lead to the necessaity of several or gigantic machines to keep elements in place. Moreover, all parts have a specific position and serve as geometric containers for the compression forces; the masses of the elements were not addressed.

Figure 4-57 The robotic assembly sequence with constant equilibrium of a compression-only arch (Wu & Kilian, 2018)

The automated assembly of building elements, currently, is asserted in homogeneous ways, meaning that all elements have the same material properties. These homogeneous implementations leave out the possibility of design of complex non-geometrical relationships. Different architectural necessities could benefit from an integration of such differentiation of building elements during construction. The proposed methods rely on bespoke elements that have preassigned positions in an assembly, hindering their reuse in different assemblies. This could be addressed by the usage of prefabricated modular elements. Such elements would be well equipped for automation, and when carried out in detachable manners, offer the possibility of future reuse (G. B. Guy, 2015). Guidelines for designing such detachable components suggest giving up fixation through nails, screws, or adhesives (Geldermans, 2016). However, buildings are commonly constructed out of many different components, and most modular systems use only a small number of different elements due to the exponential growth of possible combinations. These approaches usually rely on a limited set of differentiated elements. Differentiation in materiality or other properties like porosity to vary the weight have not been investigated in depth. The integration of modular building elements and mass differentiation for reusability are something still to be addressed.

4.3.2. Method

The setting for this study was the seminar Robotic Sensing in the Winter Semester 2019 at the Faculty of Architecture at TU Darmstadt. After an introduction to modular building elements and computational tools for discretizing geometries, a group of three students investigated the idea of weight balancing of a modular system throughout a robotic assembly process. The focus was put on cantilevering structures, a basic architectural element.

Weight Modules

An existing modular system was the basis for this investigation, made out of Styrofoam, thus having equal and homogeneous weight distributions and being very lightweight while having enough compressive strength to be carried with a robotic gripper. The modules have a zigzag form that has several advantages. On the one hand, they are self-calibrating along the x-axis as the spikes interlock with the notches. On the other hand, the y-axis of the modular elements is free and allows for continuous movement along the y-axis.

To build cantilevering structures with these modules, special weight modules were developed that fit into the existing modular system (Figure 4-58). Different weights with the same volume were achieved by filling hollow weight modules with sand. This approach allowed for modules of different weight to be incorporated into the existing modular system. Similar to the original modules, they also have a free Y-axis, which allows placing them at exact positions along the Y-axis. To fit the weight modules into the existing modular system, the original modules were flipped so that they do not interlock with but rather stand on top of each other. The weight modules then fit into the interspaces. The spacer module's purpose is to align the modules when they get stacked by the robot.

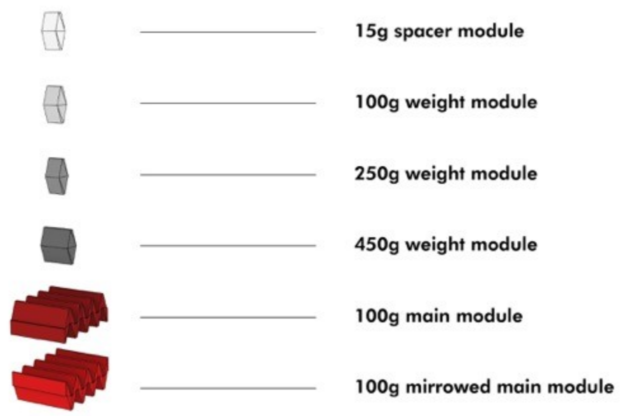


Figure 4-58 Set of modules and their weights.

Fixation of the modules works with compression only and does not require any mortar or adhesive. The disadvantage of these modules, whether they interlock or not, is that they have limited positions in the x-axis defined by the distance between two spikes. The specifications of the modules provide infinite combinatorial possibilities (Figure 4-59). The modules do not have preassigned positions in the assembly. Their exact position is a consideration between their inherent and geometrical properties.

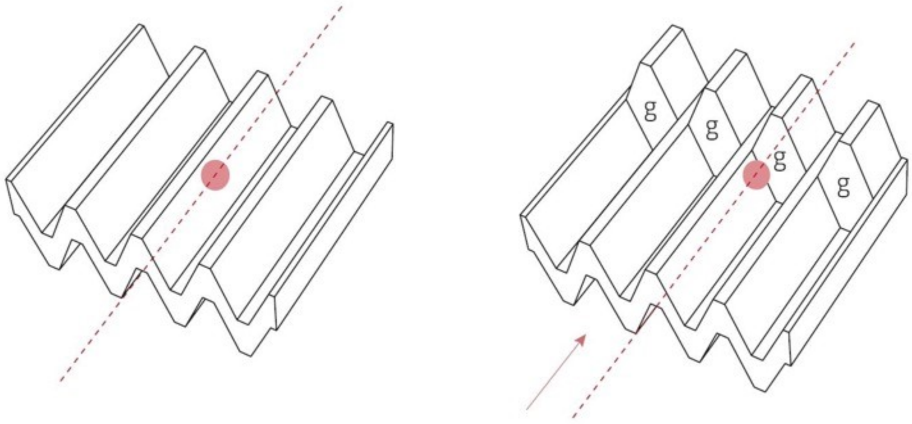


Figure 4-59 Relocation of the center of mass using weight modules.

By adding the smaller weight modules to the aggregation, the center of mass of the primary elements can be shifted (Figure 4-59). The distribution of these modules was algorithmically calculated.

Algorithmic Weight Distribution

A design algorithm that enables discretizing of curb geometries and the distribution of weight in such aggregations allows the design of stable cantilevers. The algorithm developed uses simple NURBS curves as an input to preposition modular units in space (Figure 4-60). The NURBS, in this case, were created manually and represent simple cantilevering forms.

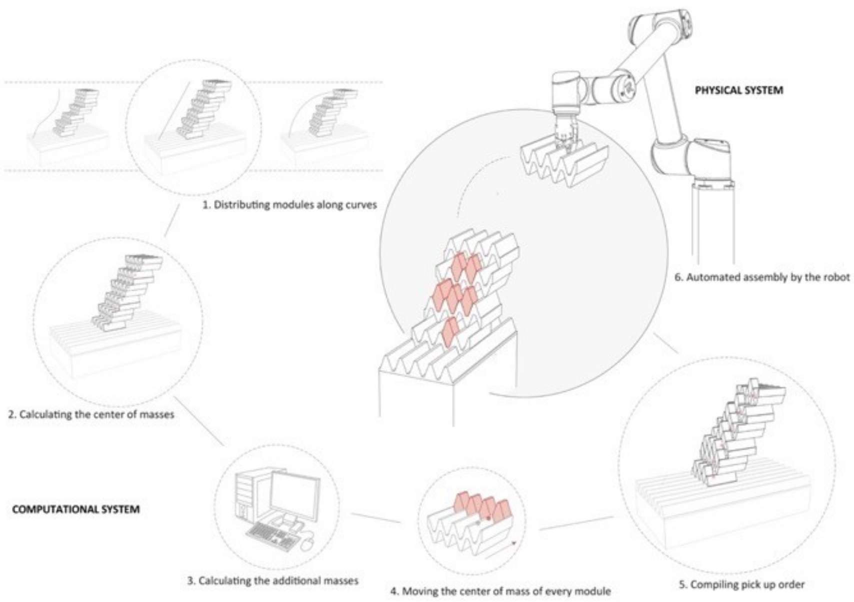


Figure 4-60 Process diagram

To achieve a static equilibrium, the centre of mass of an assembly, when projected along the gravity direction, must stay within the grounding geometry footprint. Normally, the maximum overhang that can be created by stacking modules with the same weight and center of mass at their geometrical center is half the length of a module. By adding extra weight to the cantilevering structure, the center of mass can be moved off-center. As a result, the structure is able to cantilever much further. By stacking several cantilevering modules, the exact distribution of the center of mass for each module becomes more important. Referring to the lever principle, the force needed to create the same moment is proportionally less to the distance to the fulcrum. Therefore, if a weight is placed far away from the fulcrum, it requires much more weight to move the center of mass above the physical edges of the lowest module. An algorithm that calculates the masses was developed to keep the modular aggregation in equilibrium (Figure 4-61).

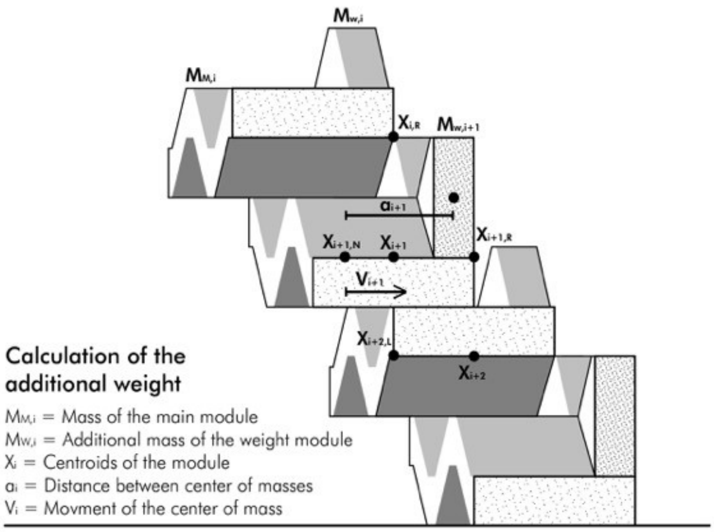


Figure 4-61 Diagram for the calculation of mass distribution.

Additional weights are required to keep the aggregation in equilibriumat all steps. By installing weight to the module on top, the center of mass of the module under it is moved in the direction of the additional weight. This needs to be considered when calculating the additional weights for the modules beneath.

To calculate the additional mass Mw,i+1, several other parameters need to be calculated. At first, various constants need to be defined. The position of the modules is generated by dividing the input curve into segments with equal height and placing the modules along those segments. Next, the weight, as well as the length of the modules, have to be defined.

With these constants, the shift (Vi+1) of the center of mass of module i+1 (Xi+1,N) can be calculated so that it is beyond the physical edges of module i+2 (Xi+2,L). In the calculation, a safety tolerance of 10 mm was added. The constants also serve to calculate the distance between the two centroids (ai+1) Xi+1,N , and Mw,i+1. With these two values, the additional mass (Mw,i+1) can be calculated. Using these calculations, every step can be calculated for every added main module in the assembly.

The digital model contains all exact positions and weights of the elements. Tacking them in the right order and with high precision for exact balancing requires a method to translate such exact measurements into the physical arrangement.

Robotic Programming

The automation of incrementally building the cantilevering structures was done using a Universal Robot 10 (UR10). For each type of module, a different pick-up location was defined (Figure 4-62). The sequence of the pick and place procedure is defined algorithmically. This allows designers to check for collision and reach of the robot already during the design stages.

All of the parameters ensure that the assembly is in equilibrium during all steps of the assembly. The generated assembly sequence leads to the stable construction of the cantilevered construction. The use of the robot guaranteed a high level of accuracy as a slight deviation in the placement of a module would lead to a collapse of the precisely balanced cantilever.

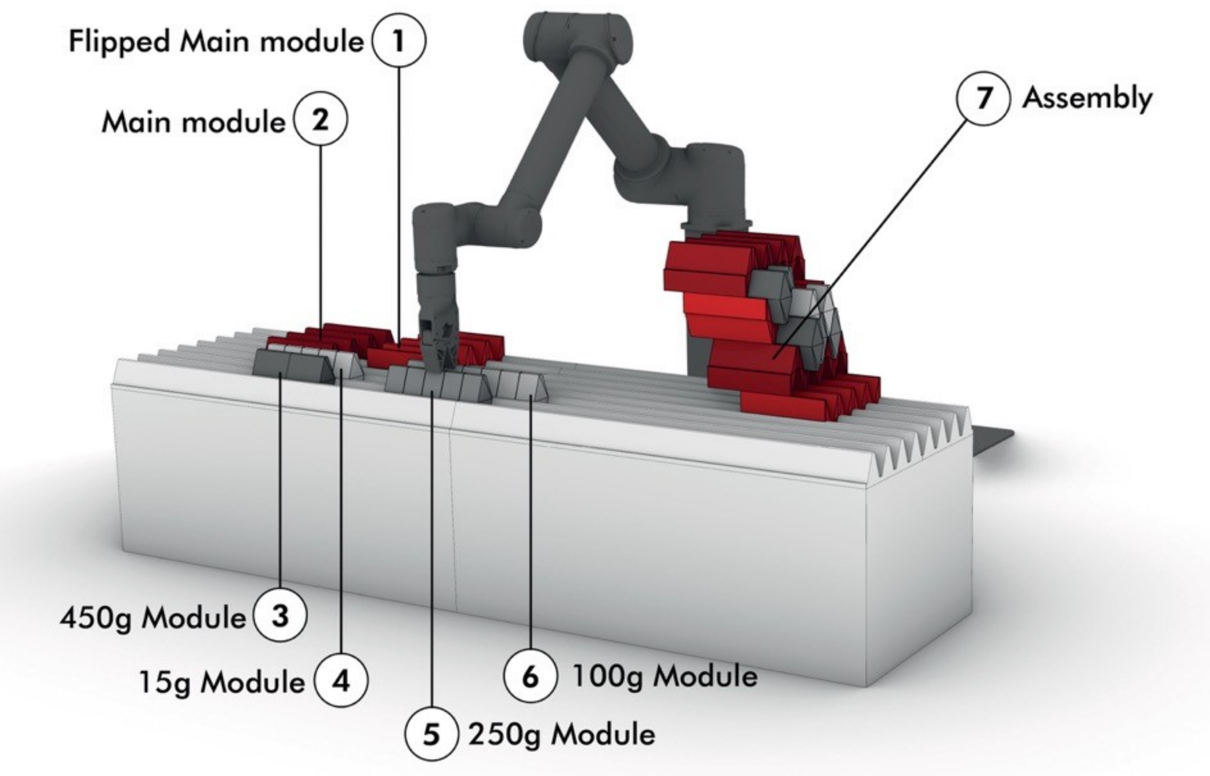


Figure 4-62 Digital simulation with the six designated pick-up locations for the different module types (1-6), the six-axis robot arm, and an unfinished assembly (7)

4.3.3. Results

The successful implementation of the modular system in an algorithmic design tool and a robotic assembly are discussed in the following sections. Based on the results, the study is compared to existing results. This research was focused on the idea of building cantilevers with modular elements that offer the potential to be reassembled. The six extra weight modules extended the existing building kit, enabling an array of combinations shifting the overall center of mass of an assembly (Figure 4-63). The proposed integration of weight modules into the existing modular system from a previous study was successful. The hollow modules filled with sand enable a gradual differentiation of the weights.

Algorithmic Differentiation

The developed algorithm was able to map the modular elements into different geometries by negotiating the modular properties with the robot constraints and availability of modules. Different assemblies were set up, highlighting aspects of the possible re-assembly of modules. The algorithm sufficiently distributed all six module types and was tested on different input curves (Figure 4-63). At this moment, the algorithmic implementation is limited to planar curves and did not address the 3D location of the center of mass.

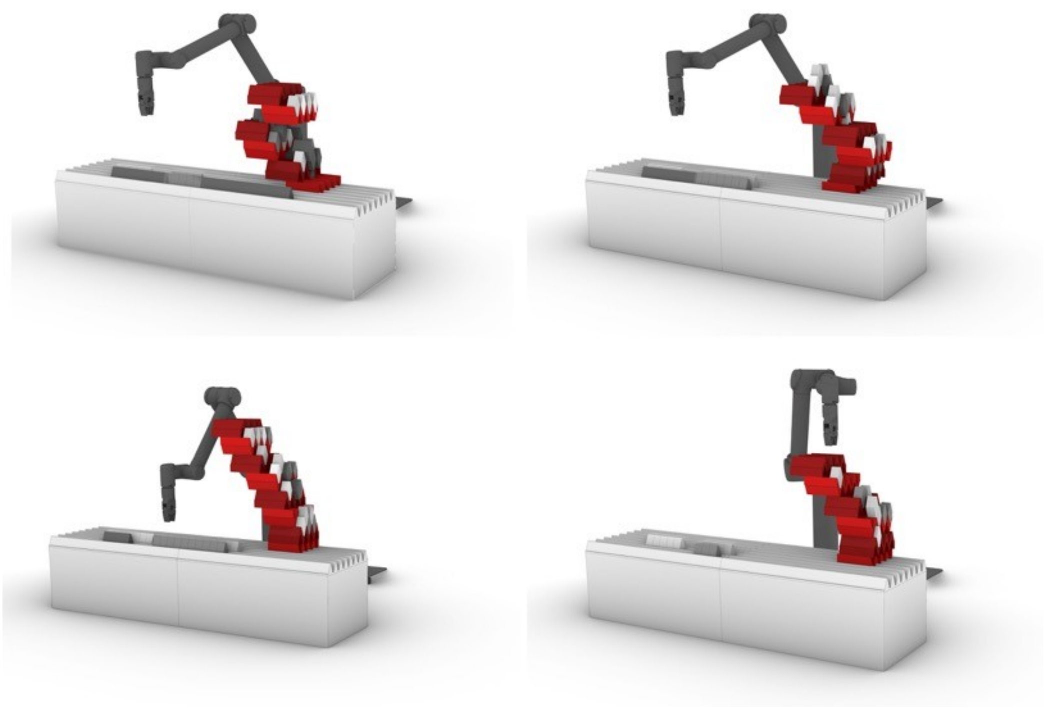


Figure 4-63 Different input curves were tested and translated into modular aggregations.

The design algorithm for discretizing and mass distribution was integrated with the robot simulation. The robotic simulation gave the designer visual guidance of delicate points during the assembly and informing it with constraints like out-of-reach positions of elements for the robot. Thereby, the design space was constraint by the direct integration of the simulation. The robots workspace and payload also limited the scale of the demonstrations.

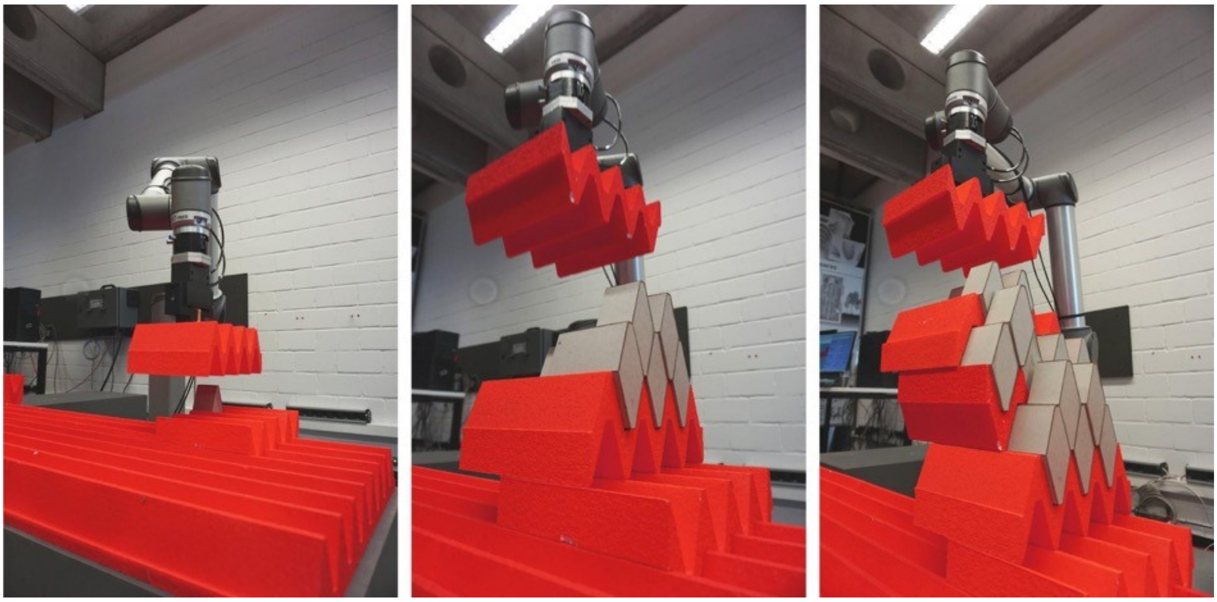


Figure 4-64 The robotic assembly process

Robotic Balanced Masses

The finesse of this approach is highlighted by two robotically assembled demonstrations (Figure 4-64). In the first case, a single weight module was removed, causing the whole structure to collapse (Figure 4-65). In the second case, one extra weight module was added by the robot, stimulating the collapse (Figure 4-66). The two demonstrations highlight the necessity of safety buffers in such constructions.

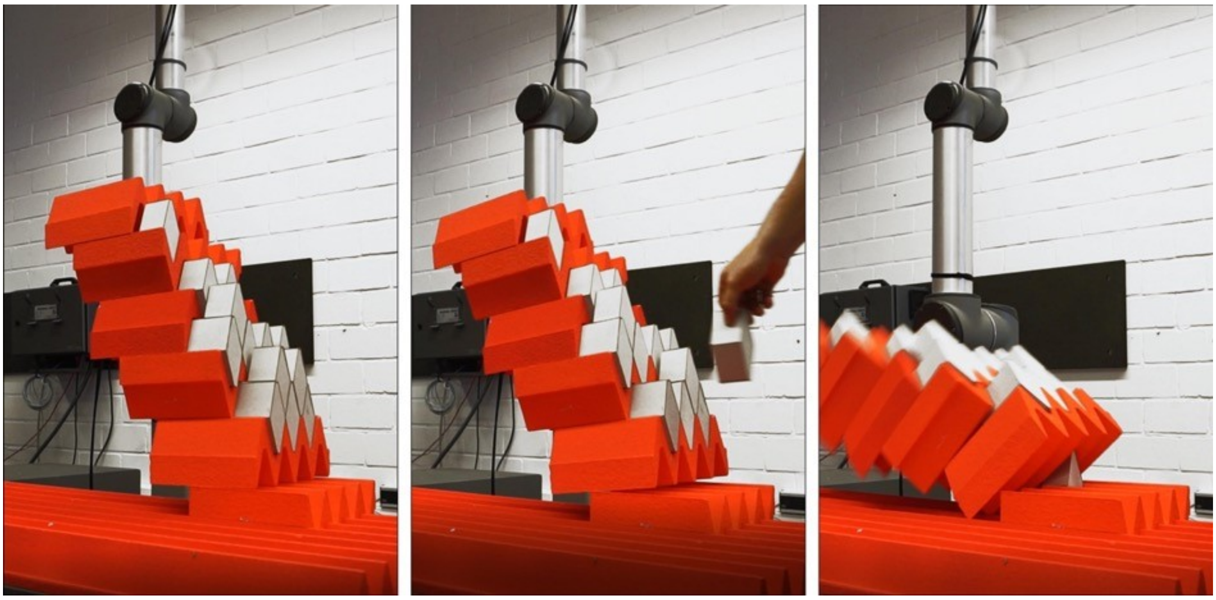


Figure 4-65 Removing weight from the cantilevering structure

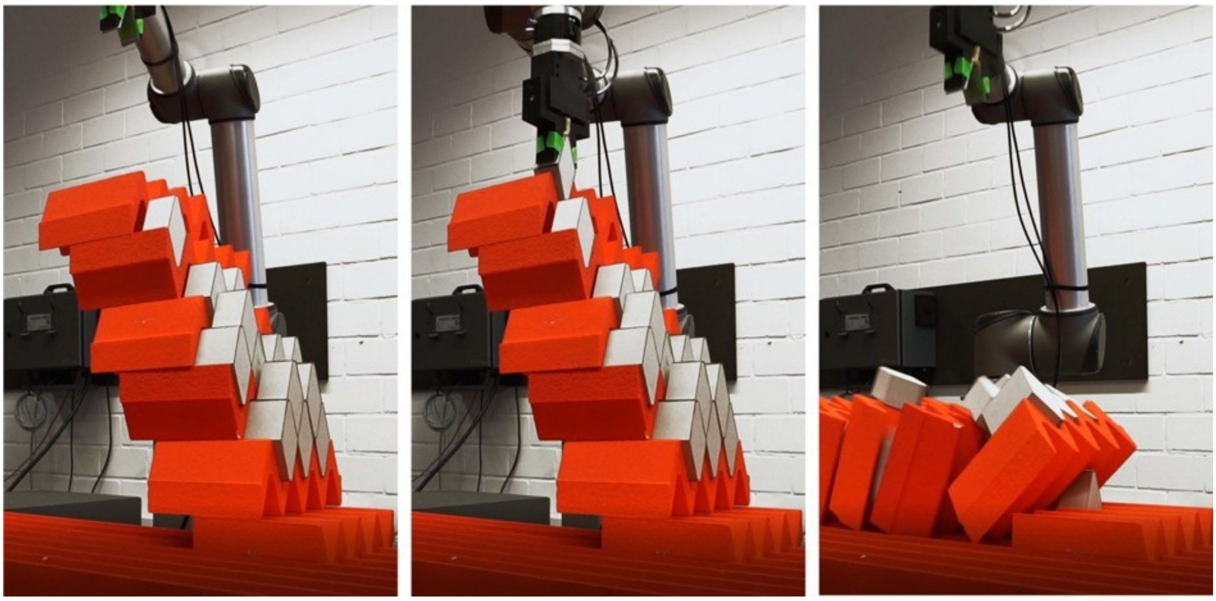


Figure 4-66 Adding weight to the cantilevering structure

The robotic pick and place system worked appropriate, and the designated pick-up location were sufficient for the task. The modular parts and the alignment base that kept all elements in the same grid eliminated tolerances along one axis.

4.3.4. Discussion

A set of modules with differentiated mass was produced and utilized to shift the center of mass in a cantilevering structure. Instead of relying on falsework, the presented approach used mass to balance all steps of the dry joined assembly. Therefore, the automated translation of a design into robot instructions for an assembly process was implemented. The proposal provides the necessary foundation with which to develop future modular systems for the automated discretization of design and fabrication. It puts special considerations onto fast and unfixed connections without any secondary structure.

Light Weight and Heavy Weight

The approach could be used to build temporary structures like bridges or pavilion-like roofs. Moreover, it could be used as a temporary formwork in scenarios in which it is impossible to reach the ground level. The hollow weight modules could be transported to the construction site and be filled with local material to achieve the necessary weights. Spanning structures may be built by gradually starting to build the structure from each side until they meet in the middle to form an arch (Figure 4-67). Considering the weight of constructions like conventional housing and novel lightweight building elements on the construction market (see e.g., Fiber), this study might present ways to consider the weight distribution in our buildings more efficiently.

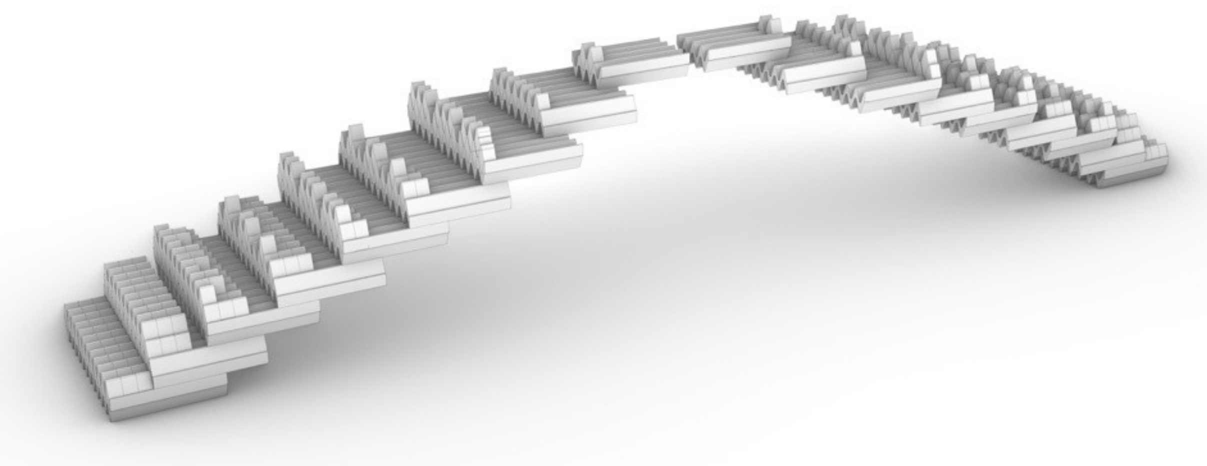


Figure 4-67 Future approach of a bridging structure

In contrast to the existing body of existing studies that use bespoke elements, this research illuminates the differentiation of modular elements for the construction of cantilevers. Approaches like the modular distribution through topology optimization might allow shifting it into more complex assemblies (Rossi and Tessmann 2017).

Latest developments of lightweight, prefabricated elements enable a more differentiated distribution of the weights in a building and might be used temporarily during erection. Architects' and engineers' understanding of masses in a construction can be utilized and inscribed into algorithms to extend possible design solutions for falsework-free construction.

Continous Equilibrium

Although the current algorithm only enables the calculation of one fixed load scenario, it also highlights the possibility to optimize structures and their elements for changing scenarios. Manja van de Worp coined the concept for structures that can transit from one stable state to another as Continuous Equilibrium (Van De Worp, 2019). This could lead to a new way of using mass-produced modules with dry-fit connections and would also open up the discussion of possible reuse of modular building components. Providing architects with a tool to reuse building components and automate the assembly could help to reduce costs and carbon emissions. Additionally, it fosters speculation about safety factors of structures that are only loosely fit.

Conclusion

This incremental balancing provides convincing evidence challenging falsework-driven assembly logics. It highlights how matter can be distributed following the paradigm of mass. This study on weight modules illustrates how such approaches can also be applied to modular assemblages that could be easily reconfigured. Moreover, the preassembly of modules made from modules that have a shifted center of mass, setup as a sub-step in such construction techniques.

On a darker note on the project, one is also reminded of the trust put into machinery and algorithms. What if a machine is accessed and matter manipulated without the proper security factors? The collapses that occurred due to adding an extra part or removing one illustrates the possibility of failure and trust put into machine-controlled environments.

The algorithmic distribution of masses is a very basic one, not accounting for friction or the geometrical interfaces between the elements. It would be possible to get a more accurate calculation with a complex implementation of such parameters. Currently, tools like COMPAS are being implemented with such utilities (Van Mele et al., 2017). The investigation started with an existing modular system that was not designed for mass balancing in the first place. Designing such a system with the mass distribution in mind is something worth exploring as more complex module geometries enable shifting the center of mass, as well.

In future approaches, larger structures could be built made out of one or more cantilevered structures. These could be bridge-like structures that otherwise require formwork. This system can then be scaled up to architectural structures. The combination of the modularity, detachability, and automation of the system allows the simple reuse of the elements. Investigations into distributing material properties in modular assemblies might enable future architects to rethink current modes of production. Informing their decision-making with analytical tools during the design procedure might accelerate this shift.

4.4. Tactile Robotic Assembly

This case study focuses on the usage of a dry joined interlocking module through robotic tactile sensing. While the previous case studies relied on the appropriation of the building elements towards robotic capabilities, this study proposes using an interlocking building block by appropriating the robot for its assembly. The assembly of the elements is achieved by an advanced robot integration, consisting of a visio-tactile sensor and robot learning. The project is an interdisciplinary collaboration between the Digital Design Unit (DDU) and the Intelligent Autonomous Systems Group (IAS), both at TU Darmstadt.

Discrete Design focuses on the building elements as a design driver. Many of the existing examples rely on press-fit connections with error-correcting properties to create sound structures, as discussed in the chapter Background. These connection details have the problem of wearing off, not being robust, or allowing for a limited set of possible engagements.

The idea of sequential interlocking was investigated in 1959 by Konrad Wachsmann for wall panels to be used in housing. The previously placed panels were fixed in place and prevented from any movement once all components were placed. The wall panels were designed to be disassembled or reconfigured according to the user's needs. The reversible connection detail determined the overall grid of the panels. Implementing such an industrial logic benefits economically from mass production and ensures constant and repeatable quality but, at the same time, limits the range of what is buildable. Although the connection seemed to be simple, it still was considered too complicated by most assemblers. Thus, the general Wachsmann connection did not become the universal joint system he was seeking to implement. In contrast, discrete elements can be aggregated in a bottom-up fashion in which the elements, their connections, and combinatorial rules form the basis for open systems. These would offer wide variety due to their combinatorial repertoire and allow for reconfigurations.

Researchers started to develop interlocking assemblies that connect pieces into a steady structure based on the geometric arrangement (Z. Wang et al., 2018). Almost any shape can be discretized into voxelated interlocking pieces (Song et al., 2012). The voxelated approach, in combination with computational tools, help to overcome adhesives for fixation. Instead, the sequence and the geometry fixate the discrete pieces into a steady arrangement. Due to their embedded computational and sequential logic, these approaches offer great potential for automated assembly.

However, the design of complex interlocking assemblies can be a challenging puzzle to solve. While stacking of elements only allows for one direction of movement, sequential interlocking might enable various ways of inserting elements into an assembly. Architectural interlocking systems usually rely on bespoke elements for the unequivocal whole, making them unsuitable for reassembly. Moreover, they often come with tenon joints that weaken the connections' elements and limit their combinatorics.

When designing and constructing with interlocking blocks, one significant difficulty is to draw a connection between their discrete engagements and their effect on the overall structure. Since the geometric transformations are defined relative to the previously placed block, selecting the same engagement may produce a different outcome depending on the previous actions from a global perspective.

Moreover, sequential interlocking often depends on the delicate insertion of the elements, making it hard for robots without sensors to assemble the blocks. The design of almost tolerance-free building elements requires an adaptive assembly procedure. Recent developments in Machine Learning and robotic sensing hold the promise of autonomous assembly for contact-rich building blocks.

This case study seeks to answer if a robot can learn the assembly of a quasi-perfect-fit element. It pushes the idea of robot-oriented design (T.-A. Bock, 1988) away from simplification and error correction within the elements. Instead, it focuses on sensory and learning strategies for robotic assembly, highlighting the combinatorial complexity of the elements.

In this case study, a sequential interlocking system is investigated for its architectural potential and robotic assembly. It seeks to integrate a computational design and robotic assembly approach that relies on discrete, dry-jointed blocks. The blocks are aggregated with the help of digitally augmented combinatorics. Therefore, a design tool is implemented to reduce complex and tedious design tasks. Furthermore, this case study investigates the robotic assembly of interlocking building blocks autonomously. A robotic assembly procedure based on tactile sensing is utilized. Robotic learning, based on a demonstration, is used for the assembly of the perfect fit elements. Since the block's connection involves complex contact dynamics, the usage of reinforcement learning is tested. A controller to autonomously place building blocks is tested in a small-scale demonstration. The study concludes that the precision and repertoire of the approach – albeit not being perfect – validates the approach and gives reason to move on to more complex assembly tasks.

4.4.1. Background

Sequential Interlocking

The serial-produced SL Blocks can be dry joined in various ways and produce interlocking figures that even allow cantilevering. The proposed blocks are based on mathematical research into interlocking octacubes, called SL Blocks (Shih, 2016). The blocks consist of one S-shaped and one L-shaped tetracube attached. The specific arrangement of cubes in the SL Block provides many possible interlocking combinations compared to other octacubes (Chou, 2019). The interlocking is sequential, which results in assemblies in which previously placed elements are prevented from any movement by the subsequent placed blocks. There are six types of engagements defined as geometric transformations between the host pair and the next pair that are to be added.

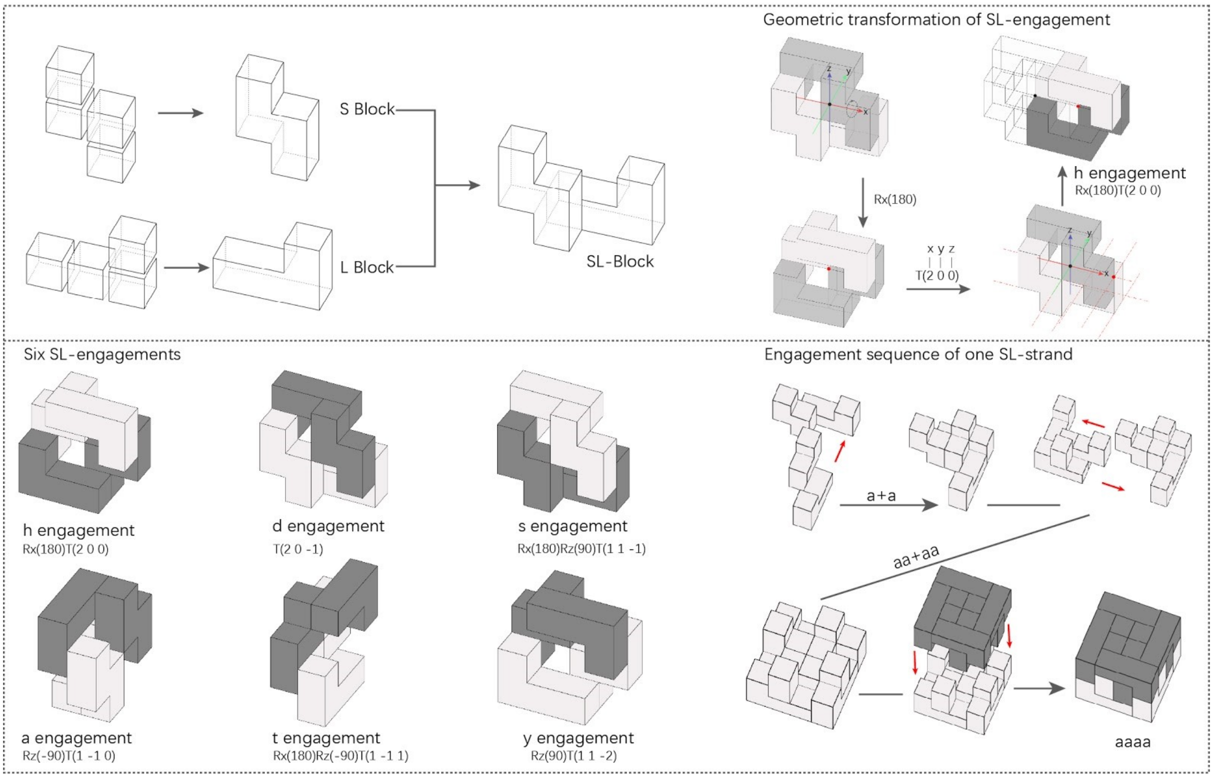


Figure 4-68 The composition of the SL Block (top left) and the six engagements. The string aaaa specifies a string of four engagements lining up to form the configuration (bottom right).

SL Blocks can be combined into various SL strands. These are represented as a sequential concatenation of engagements, which specify the assembly process starting with an initial SL block and adding blocks one by one (Shih et al., 2019). The design with these blocks currently depends on manually defining these notations. Figure 4-69 shows examples of manually defined SL strands with their defining engagement sequence notated in the letter sequence. Flipping the sequence changes the growth direction of the strands, while insertion of engagements into existing sequences can have various effects, as shown in the bottom row.

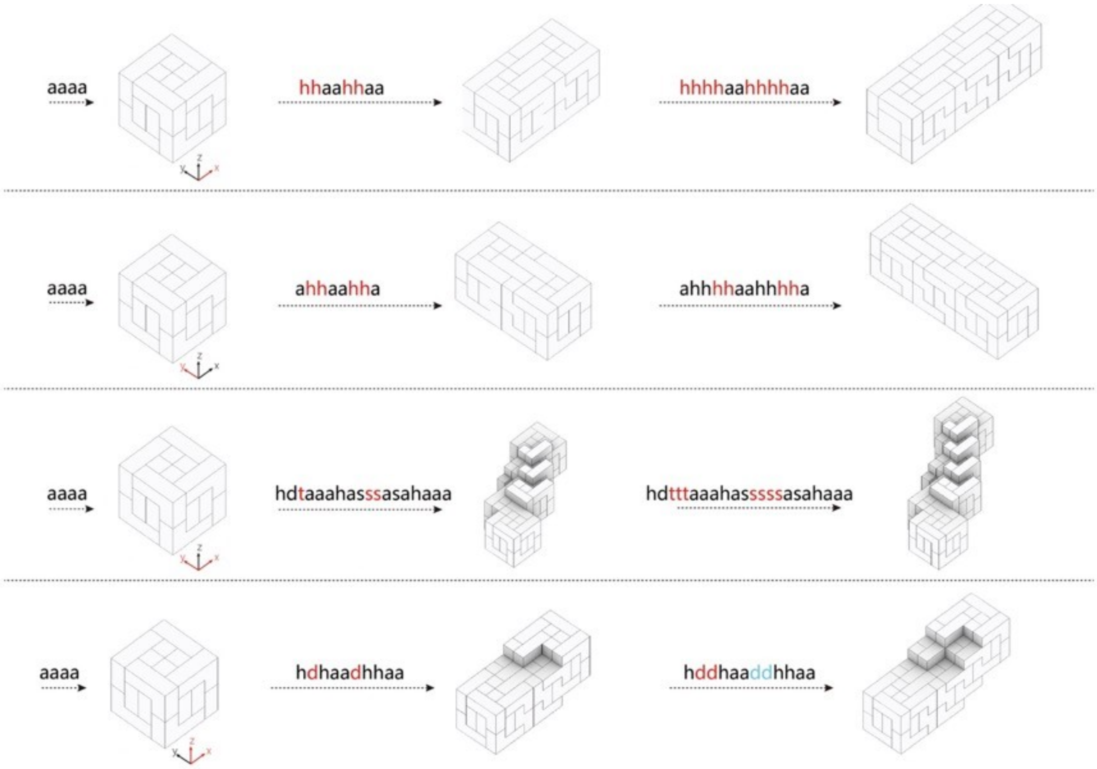


Figure 4-69 Example sequences of SL Block engagements with their denoting string sequence (image: Yuxi Liu)

The SL Blocks do not come with accessory or integral connections; instead, the blocks themselves serve as the connection. The arrangement of the containing voxels provides enough connection interfaces. Element geometry and connection logic are highly integrated. Thus, the geometry provides a robust quasi-perfect fit connection, making the assembly an arduous task, even for humans (Figure 4-70). The robotic assembly of a sequential interlocking system has been investigated for single voxels with integral connectors carved out of the blocks or added to the block (Zhang & Balkcom, 2016). However, to achieve a similar variety in figurations, this system depends on nine different types of voxel blocks. The used integral connection might break easily and not be robust for several circles of reassembly.

Figure 4-70 Manual assemblies of SL Blocks.

Tactile Sensing

For contact-rich assembly tasks, the sense of touch is a crucial skill (Yousef et al., 2011). Construction workers easily coordinate their senses of touch and vision to assembly things (Reinhardt et al., 2018). Implementing the sense of touch for robot manipulation is still a challenging field of research. Various tactile sensors have been investigated (Kappassov et al., 2015). However, most of these systems are expensive, and the sensor readings are hard to analyze. In recent years a sensor technology that provides sufficient data while being inexpensive has been developed. These sensors consist of a camera behind a soft silicone gel with embedded blobs coined as FingerVision (Yamaguchi & Atkeson, 2017). The camera tracks the deformations of the gel through blob detection and derives applied forces between the grasped object and the fingers. Tactile feedback was used, e.g., for tactile exploration of object properties (Lepora et al., 2016), grasping (Bohg et al., 2014), object and tool manipulation (Chebotar et al., 2014; Ramón et al., 2013). The FingerVision sensor was implemented in an earlier study as preparation for this case study. In a small-scale model, the first assembly tests were conducted and resulted in a set of robot skills (Figure 4-71).

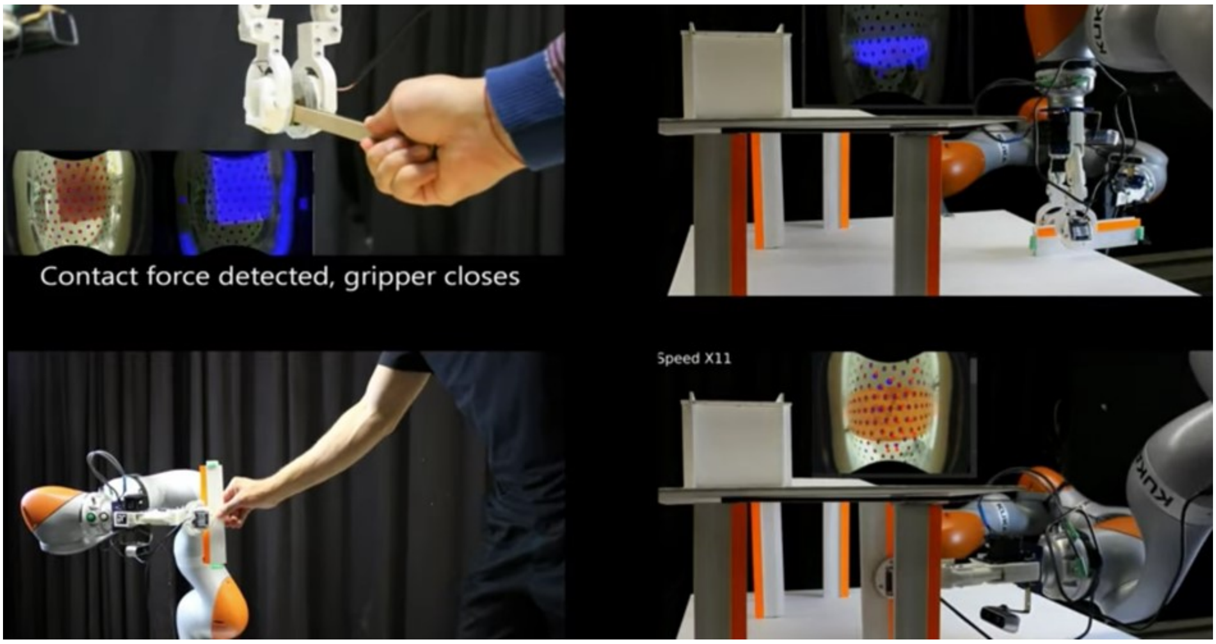


Figure 4-71 Different skills implemented on a collaborative robot using the FingerVision sensor. Handover (top left), inspection (top right), follow mode (bottom left), and insertion (bottom right) (Belousov et al., 2019)

Another visio-tactile sensor is the DIGIT sensor. It is an inexpensive, compact, and high-resolution tactile sensor. DIGIT improves upon past vision-based tactile sensors by miniaturizing the form-factor to be mountable on various grippers, enhancing reliability, and providing a manufacturing manual (Lambeta et al., 2020). Its usage for complex assembly tasks is yet to be demonstrated.

Robot Learning of Assembly

The assembly of SL Blocks can be understood as a more complicated version of the classic peg-in-a-hole task, well known in robotic research (Inoue et al., 2017). The first validation of this approach in the context of architecture was recently considered within the robotic assembly of timber joints (Apolinarska et al., 2021); a joystick-driven assembly was used as a demonstration for robot learning based on a torque sensor.

In contact-rich manipulation tasks, tactile sensors deliver essential information. The data from tactile sensors are typically high-dimensional and hard to interpret; thus, learning is commonly employed to develop controllers that can use such rich feedback signals. The advantage of the learning approach is the system's ability to adapt to changes in the environment, such as part positions in the gripper or incoming sensor reading. Contact between parts, friction, and deviations between planned and actual part locations requires on-the-fly adaptation, a core strength of learning-based solutions.

Utilizing tactile information for robotic manipulation tasks is an area of active research. A neural network model was trained to predict the stability of a planned grasp sensed with the GelSight tactile sensor (Calandra et al., 2018)(Yuan, Zhu, et al., 2017). A reinforcement learning approach was used to stabilize an object with a robot arm based on tactile feedback from a BioTac tactile sensor (Herke Van Hoof et al., 2016). A modified GelSight sensor was used in combination with reinforcement learning to move and rotate small objects such as marbles and dice (Tian et al., 2019).

4.4.2. Method

This case study combines tactile sensing skills for robotic assembly with a modular perfect-fit building block. The distinct aspects had to be integrated into one process in which design with SL Blocks is the base for robot instructions for an adaptable assembly procedure. A visio-tactile sensor was combined with a robot learning approach. The following sections explain the various methods utilized in this case study.

Design Environment for Interlocking Assemblies

The manual design with SL Blocks is a tedious task since the engagement changes at each step, depending on the previously placed block. The possible placement of new blocks is constraint by the existing connection points within the current aggregation. This approach led to a combinatorial problem in which the choice of connection and the engagement of the following placed blocks determines the overall aggregation. Since the geometric transformations are defined relative to the previously placed block, selecting the same engagement may produce a different effect depending on the previous actions from a global perspective.

In Grasshopper, the six engagements of the SL Blocks were inscribed as transformation matrixes and encoded via a string. The designer manually defined a string sequence or selected a predefined sequence (Figure 4-72). This approach already minimized the overhead of manually modeling the engagements and drastically sped up the design process. However, this tool would require altering strings to achieve the desired outcome, which is a complex task, preventing intuitive design.

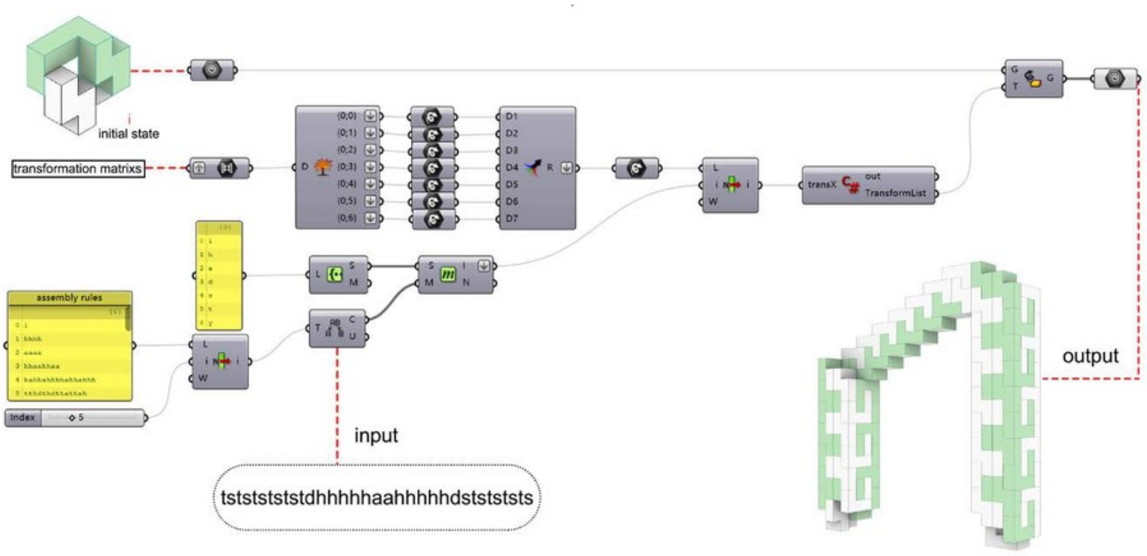


Figure 4-72 The Grasshopper design interface for designing with the manual assignment of string sequences

As opposed to the previously introduced interface, a second approach was investigated. Instead of defining the sequence manually, an algorithm should populate a given curve with SL Blocks, using interlocking engagements. Examples of curves for block-based design have been presented in the previous research (Retsin, 2016; Andrea Rossi & Tessmann, 2017a). However, these did not address such complex and interlocking combinatorics.

There are already several methods available to the architecture and design community through Grasshopper plugins and external programs, such as evolutionary algorithms, direct search, and model-based methods, as surveyed by Wortmann & Nannicini (2017) that could potentially solve such optimization tasks. However, these approaches do not take into account the sequential nature of this assembly problem. They treat the whole assembly sequence as one evaluation point and compute the fitness of the resulting structure only at the end of the assembly process. One approach for iteratively solving problems is reinforcement learning. It can be viewed as an alternative to the existing black-box optimization by presenting the algorithm decisions at every assembly step. To formalize this problem in the language of reinforcement learning, one needs to define action, observation, and reward for the algorithm.

In the reinforcement learning loop (Figure 4-73), the agent (algorithm) takes action (places a block). The environment (Rhino/Grasshopper) returns an observation (e.g., positions of parts relative to the curve) and receives a reward (e.g., a value reflecting how well SL Blocks cover the curve). The agent keeps collecting rewards based on its actions and learns to relate these with the observations, trying to maximize the total sum of expected rewards.

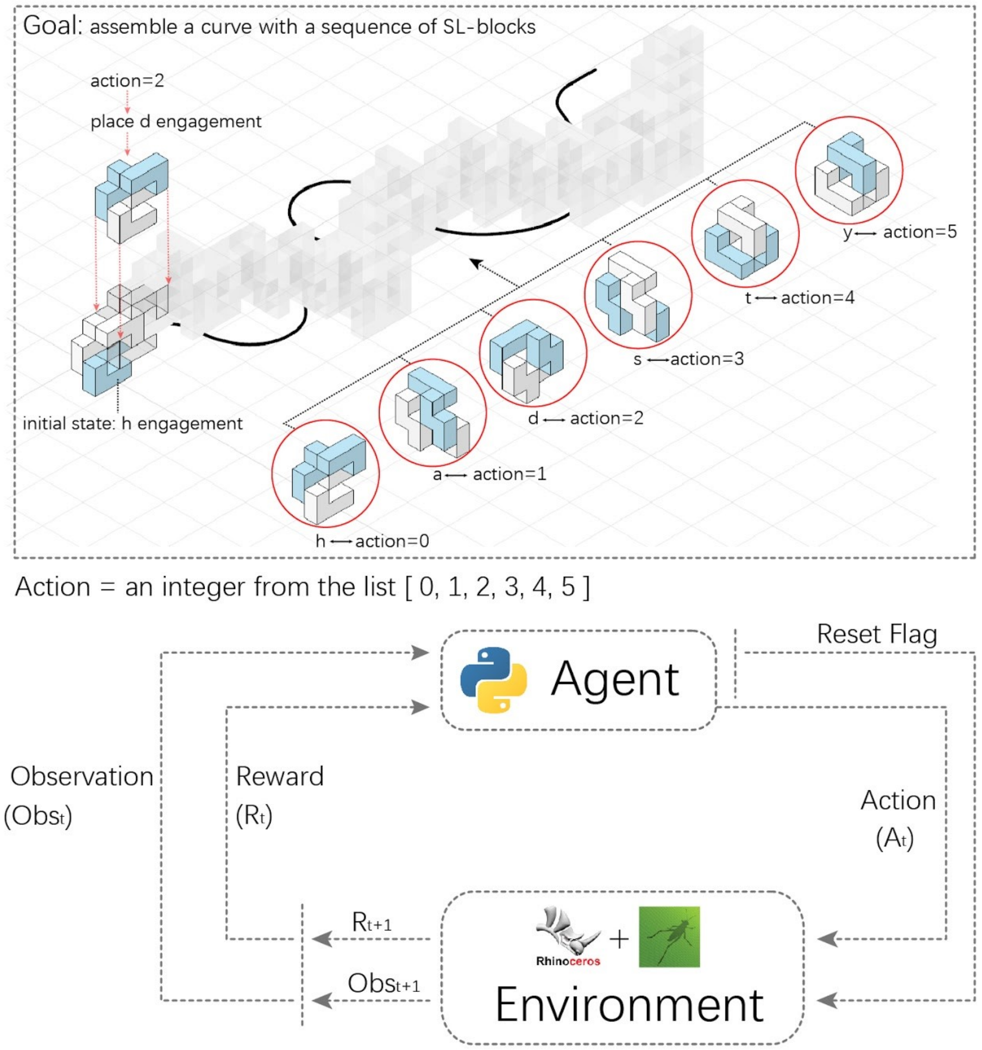


Figure 4-73 Reinforcement Learning Loop with Rhino/Grasshopper as Environment

The actions were defined as integers between zero and five, indicating the six possible engagements of SL Blocks, adding at each step the next block relative to the previously placed. The observation consists of three parts: the list of normalized distance from all 16 voxels of the SL Block to the curve, the sequence of transformations describing the SL engagements (previous actions), and the coordinates of the following three points on the curve (Figure 4-74). These points provide local information about the future direction of the curve. Adding more future points to the observation makes the problem of value estimation easier. However, at the same time, it increases the dimensionality of the observation space and causes the agent to overfit the current curve. On the other hand, providing only one point makes the agent short-sighted, impeding it from accounting for the direction of the curve. In other scenarios, this parameter may be adjusted for improved performance.

The reward function and the reset flag were used to encourage the agent to follow the desired curve. In particular, the reward (defined as one minus the smallest distance of the current block to the curve) is maximized when the structure perfectly follows the curve. If the agent deviates too much from the curve or places a block intersecting a previously placed block, the environment is set back to the initial state by the reset flag; a new learning episode is started.

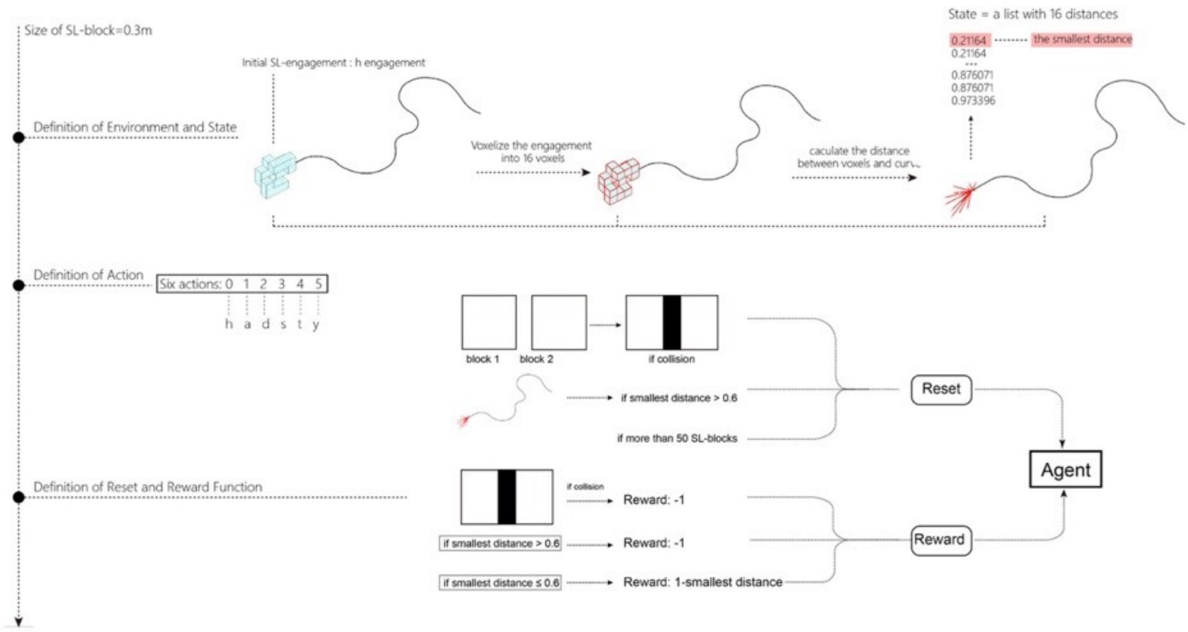


Figure 4-74 Reinforcement learning algorithm explained. The calculation of the distances between all voxels and the design curve, serving as observation. The defined actions of the agent for choosing the engagements. The reward function and the reset flag.

The key idea of reinforcement learning is to cope with a task over a sequence of decisions. To achieve that, all known practical RL algorithms estimate some form of the value function; they learn a function that predicts how good an action is when taken in each state, with goodness measured by the expected future return. In the block to curve mapping task, it is possible to provide a near-optimal solution. Therefore, the distance from the current engagement to a point slightly down the curve provides a reasonable heuristic for evaluating the subsequent actions, pulling the agent as a magnet towards placing the next block along the curve.

The above-described algorithm was implemented using the stable-baselines3 library (Raffin et al., 2019), a standard in the RL community, and connected via a socket-based interface to Grasshopper as an RL environment. In Grasshopper, the designer would define the input curve, tweak the values of the reward function and define the reset flags.

Visio-Tactile Sensing

The contact-rich assembly of the perfect-fit blocks requires sensory feedback for the robot. Therefore, a Robotis RH-P12-RN gripper was equipped with a vision-based tactile sensor called DIGIT (Lambeta et al., 2020) (Figure 4-75). The choice for the Robotis RH-P12-RN gripper derives from the fast-programming interface that enables opening and closing, suitable for tactile manipulation. The DIGIT is a high-dimensional vision-based tactile sensor; its design is based on GelSight (Yuan, Dong, et al., 2017) but is significantly cheaper and easier to produce. The sensor consists of 3D printed pieces, a costume-made PCD chip consisting of a small-scale RGB camera and an RGB-colored LED stripe, an acrylic plate protecting the camera, and an opaquely coated gel pad made from transparent silicone and covered with a reflective coating on the outside (Figure 4-76).

These LEDs are placed inside the casing so that they illuminate the pad from different directions. The RGB camera captures the reflections of the LEDs' light from the gel. If the sensor touches an object, the pad deforms according to the geometry of the object. This deformation changes how the light of the LED reflects from the gel.

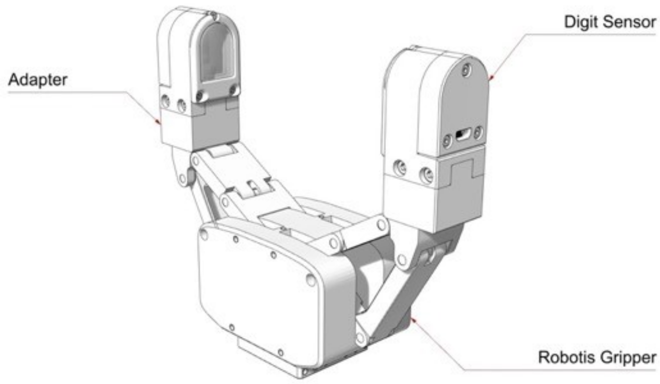


Figure 4-75 Technical drawing of the Robotis RH-P12-RN gripper with the Digit sensor at the fingertips

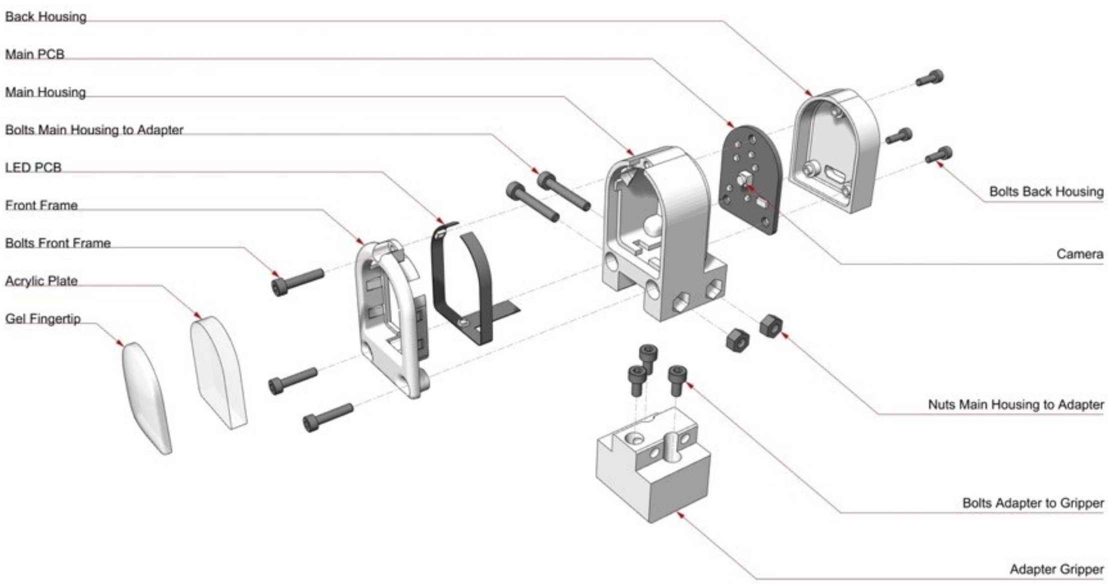


Figure 4-76 The separate pieces of the Digit sensor

The sensor reading provides information about the grasped objects based on the distortion of the colored light within the sensor (Figure 4-77). The sensor reading can provide information about the position of the grasped object between the fingers and enables the detection of collisions based on sudden changes in the gel distortion. Thus, it enables fine-grained manipulation (Tian et al., 2019). The sensor data were captured in ROS to be used for robot learning and as a feedback signal during robotic assembly. The simulation of the gel pad was too challenging, which led to an approach of the sensor input that focused on experiments on the real robot system. The sensor was evaluated during assembly with various materials, including wood, plastic, and Plexiglas.

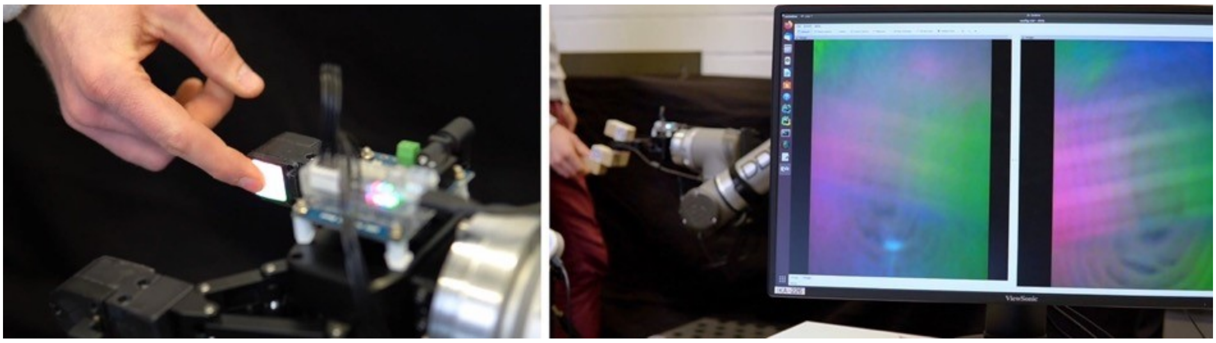


Figure 4-77 The Digit sensor mounted on the robot gripper (left) and the sensor readings visualized (right)

Robot Learning from Demonstrations

The translation of the SL Block strands into robotic instructions was straightforward due to their sequential nature. The instructions included the positions and orientations of the SL Blocks' pick-up locations and their transformations into the placement position. These were derived from the digital aggregation sequence and translated into robot code using Robots by Vicente Soler (2019) and transferred into ROS (*Documentation - ROS Wiki*, n.d.) to allow the robot learning approach to jump in at the tender points when sensory input was crucial.

An interface between the Rhino3D/Grasshopper and the Robot Operating System (ROS) was established to enable data exchange between architectural design and robot control environment. In addition, the dual robot setup at DDU was configured to support IAS research on robot learning algorithms for autonomous assembly tasks. The Robotis RH-P12-RN, a flexible parallel gripper with low-level motor access, was integrated into the overall setup with the DIGIT sensor on one robot – the assembler. The Robotis gripper was chosen for its fast control rates, crucial for object manipulation tasks with feedback. The second robot in the setup was equipped with a Schunk EGH gripper to hand over the blocks from the pick-up location to the assembler.

Instead of pre-programming the whole task into the instruction, certain room was given for feedback-based maneuvers by the robot. A reinforcement learning approach was investigated to train this behavior. To train a reinforcement learning agent, a simulation of the tactile sensor was developed based on the model of light propagation (S. Wang et al., 2020). However, this model did not include soft-body simulation. It was not suitable for contact-rich manipulation tasks that involve deformations of the gel on the sensor, as is the case in the

DIGIT sensor. Instead, a real-robot learning setup was utilized, where the learning is performed on the real robot without employing a simulation environment.

The real-robot learning approach started with the recording of an SL Block assembly from human demonstrations. The block positions were tracked using a tracking system (Optitrack). The real robot was operated in a small step mode to enable slow and accurate movements via keyboard strokes in cartesian space (Figure 4-78), capturing part positions and trajectory. Based on this demonstration, the robot learning approach was implemented for learning tactile manipulation. The reinforcement learning algorithm was defined as follows. The agent is a program that sends commands to the actuators of the robot (Cartesian joint velocity of the end-effector and gripper closure commands) and receives back the state information (e.g., part positions and orientations, robot state, tactile sensor readings), together with the reward signal that evaluates how well the task is solved (e.g., position error between the desired and current part poses). The agent keeps interacting with the environment and adapting itself until it finds a successful policy, a mapping from states to distributions over actions, that yields the highest expected return.

This was combined with a curriculum learning approach, which uses the captured trajectory and adds minor errors that would cause the part to get stuck. The learning algorithm would detect the error based on the sensor feedback from the tactile and DIGIT sensor. The robot learns a policy that would adapt its movements accordingly to get as close as possible to the original trajectory. The idea of curriculum learning was introduced by Bengio et al. (2009) to the machine learning community. The motivation behind it is to imitate the learning process that humans undergo. To master a complex task, humans first need to master the skills that it is composed of. The knowledge and repertoire of skills are acquired in a step-by-step fashion, increasing the complexity of tasks one can tackle with time. Similarly, it has been argued that it may be beneficial for a machine-learning algorithm to start learning on simple problem instances and then gradually arrive at the actual problem to be solved.

Specifically, self-paced reinforcement learning (Klink et al., 2019) was utilized to generate a reverse curriculum for the block stacking task, as it is relatively straightforward to show to the robot how to connect two blocks starting from one initial configuration. However, it would be very tedious to collect such demonstrations for every possible scenario. Instead, the agent should learn to expand its repertoire by itself. To that end, the agent with the capability of the base skill starts to propose tasks to itself and to master them, starting from the given demonstration. In this process, the robot purposely deviates from the provided trajectory, leading to parts jamming, and then tries to correct for that by moving the part to the desired location, guided by the visual and tactile feedback. By trying various versions of this task, a robust robot controller can be learned that masters a variety of the initial conditions. Thus, self-paced curriculum generation helps the agent to learn efficiently without requiring the algorithm designer to provide a fixed curriculum ahead of time.

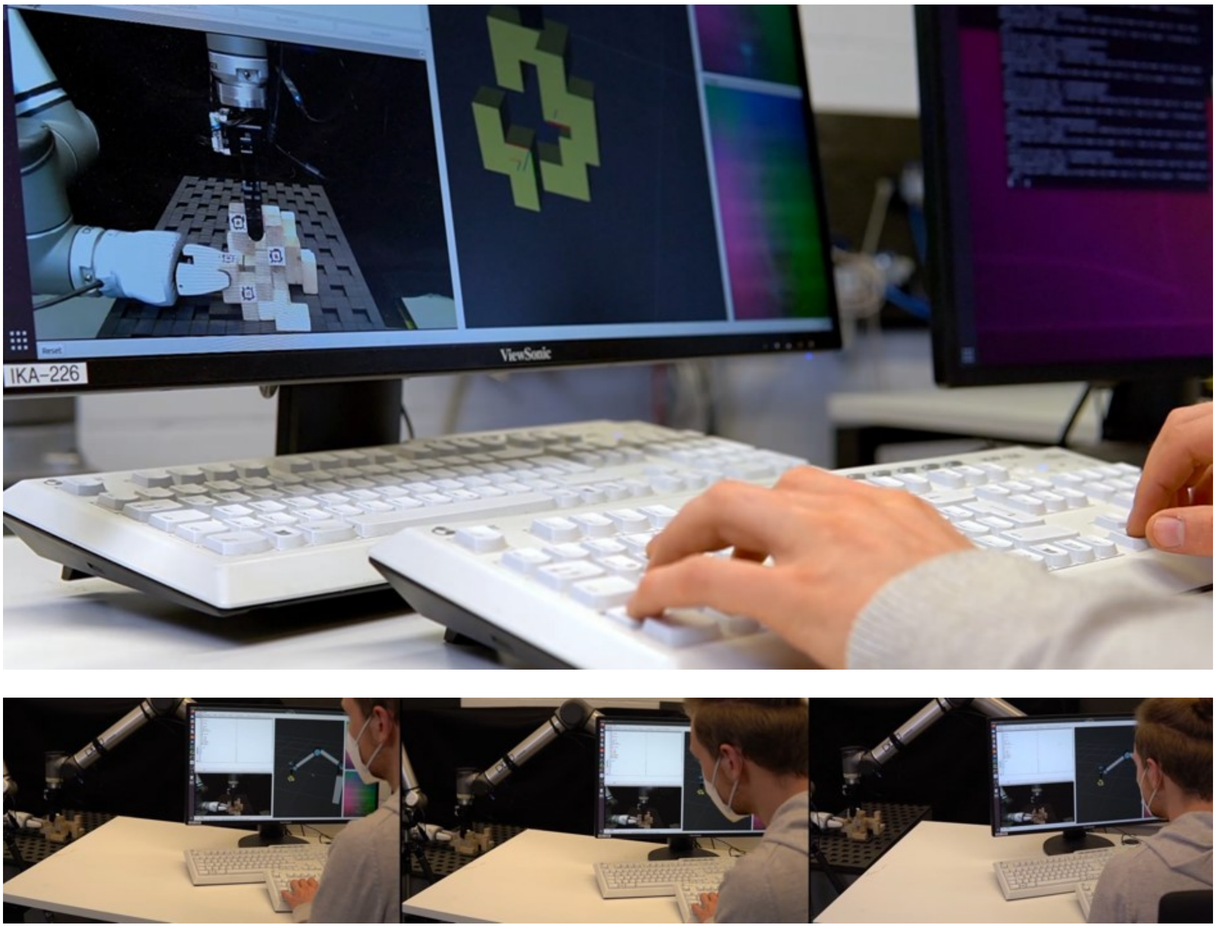
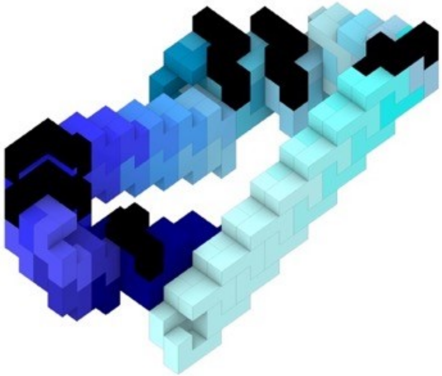


Figure 4-78 A human operating the robot via keyboard strokes, generating demonstrations for the robot learning

The robotic assembly was set up to be tested in a small-scale demonstration consisting of 36 SL Blocks. The figure is a closed rectangle with two grounded and two cantilevering corners (Figure 4-79). In order to minimize efforts in fixation of the figure to the ground, a perforated base plate was fabricated, enabling the blocks to be stably fixed to the box. The pick-up location was designed to hold SL Blocks in various orientations, minimizing the overhead of reorienting blocks during the assembly (Figure 4-80).



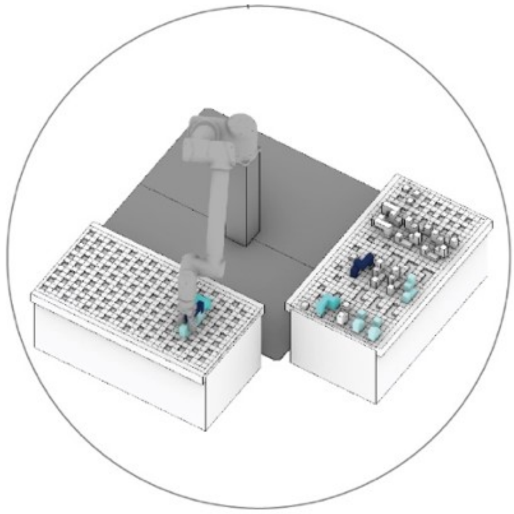


Figure 4-79 The elevated 3D rectangle with the assembly sequence indicated from light to dark. The black SL Blocks indicate the last-placed key pieces fixing the overall assembly.

Figure 4-80 The robotic assembly setup. The left box is the area for the construction, and the right box the pick-up location.

The SL Blocks in this case study were designed and fabricated with a voxel size of 3 cm. This scale does not have to be fixed and was chosen as a good fit for manual assembly and robotic assembly with our collaborative robots. Different materials and fabrication techniques were tested for the production of the SL blocks, including plywood, acryl glass, plaster, concrete, and 3D printed blocks made from PLA.

4.4.3. Results

The SL Blocks were the starting point for a reversible building element that can be dry joined. The perfect-fit blocks were set out to be challenging assembly tasks for a robot. To overcome these challenges, a tactile sensor and robot learning were tested.

Architectural Components from SL Blocks

The SL Blocks can be combined into a comprehensive set of arrangements. In the early stage of experimentation, various compositions of architectural components like columns, walls, and beams were investigated (Figure 4-81). The components in the figures are interlocked into stable structures. The placement of the black SL blocks is comparable to a key piece fixing all previously placed elements. The black pieces can only be removed in one direction while immobilizing all other blocks. Only by removing the black key pieces, the disassembly is possible without harming the blocks. Currently, these elements were created by manually defining the engagements, which was a tedious task.

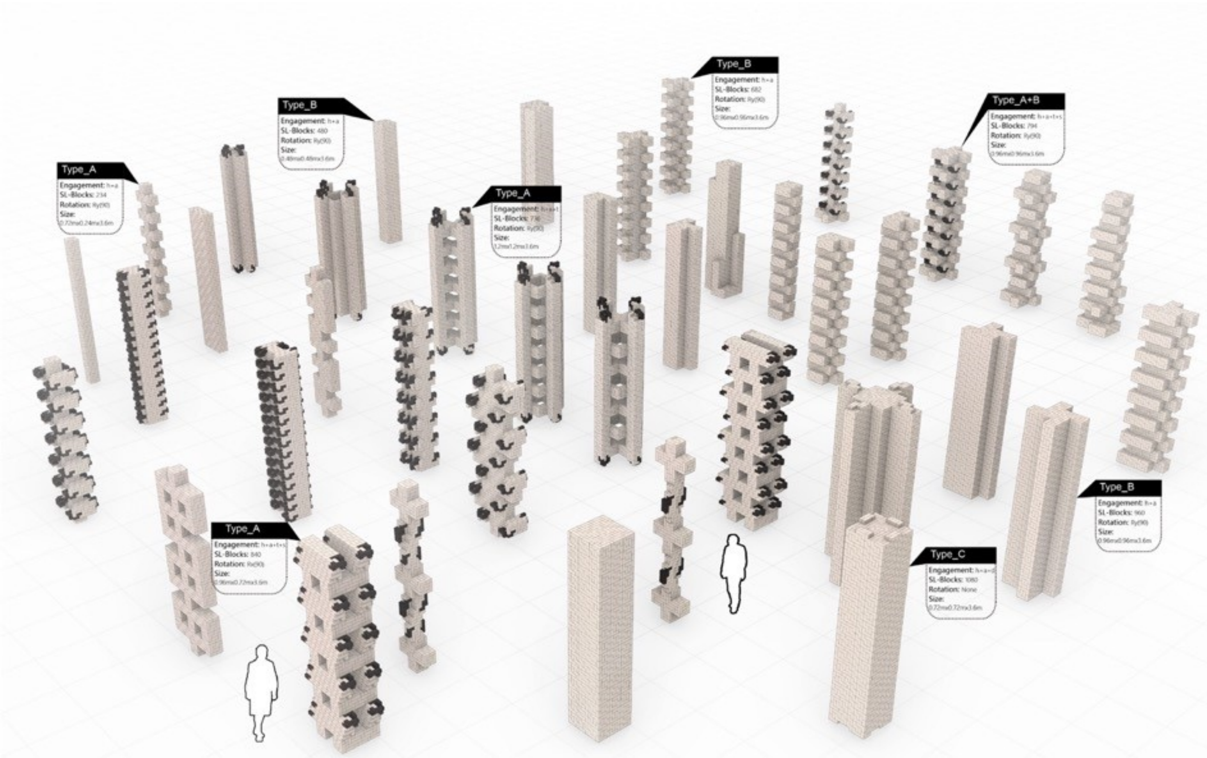


Figure 4-81 Various columns assembled from SL Blocks. The different designs were inscribed using manually defined block engagements. The black pieces indicate the only movable key pieces (image: Yuxi Liu).

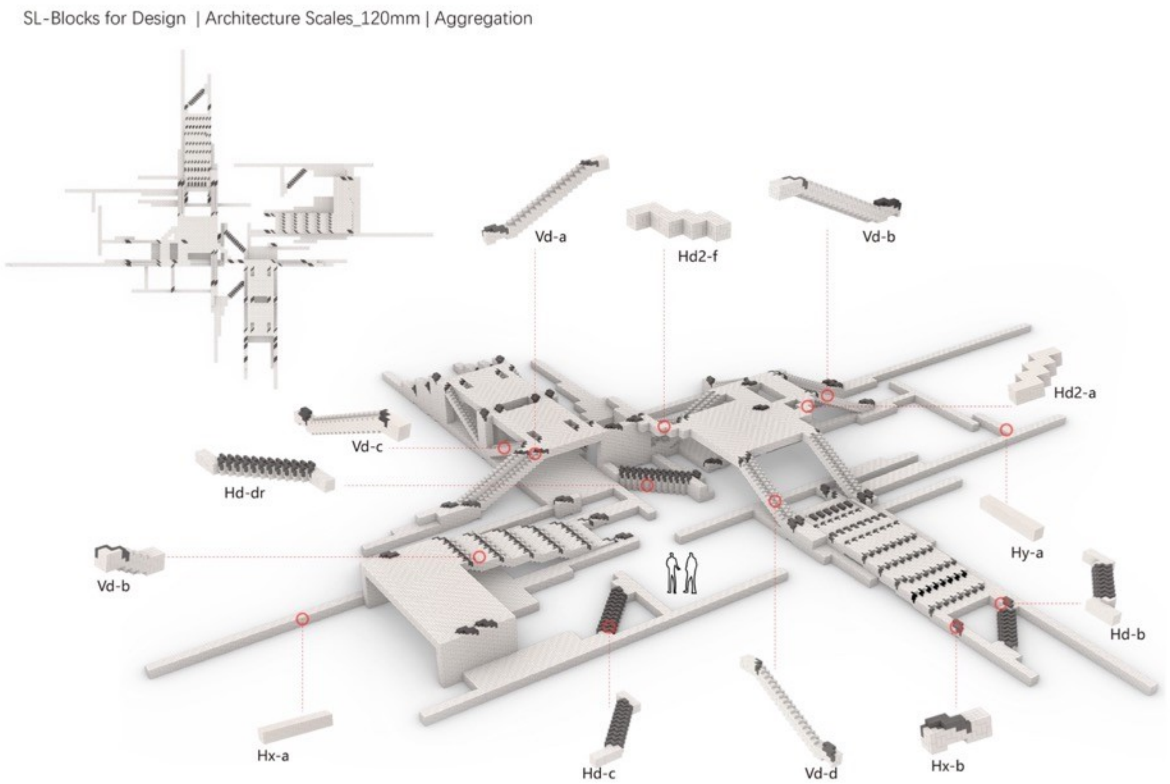


Figure 4-82 Spatial composition for testing the combinatorial repertoire of SL Blocks (image: Yuxi Liu)

The proposed interface where an architect specifies a curve and an algorithm finds an assembly sequence can be utilized in different ways as a creative tool in the design process. Here, we provide an example of stacking the curves to generate a wall, as shown in Figure 4-83. The assembly sequence generated by the considered algorithm is suitable as an instruction plan for an interlocking sound structure. The reinforcement learning algorithm supported the design preferences indicated as curves and translated them into volumetric arrangements of SL Blocks.

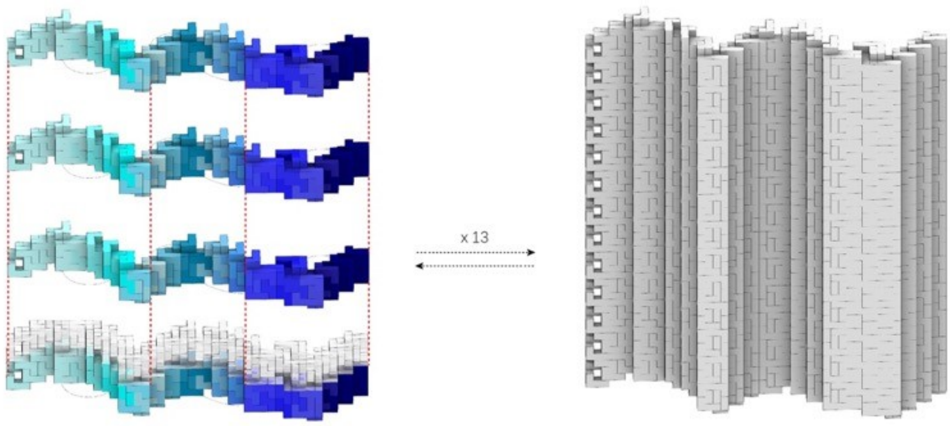


Figure 4-83 Results from the RL algorithms on the 2D curve. Such curve base aggregations can be stacked vertically to obtain a wall made up of SL blocks (image: Yuxi Liu).

Tests for articulating the SL Blocks in different ways were conducted. For coherent assembly of the blocks, it is prohibited to extend any geometry outside the bounding volume. A subtractive approach is suitable as long as the contact faces are provided (Figure 4-84). Most of the SL Blocks were fabricated from plywood. Additionally, 3D printed blocks from PLA, cast blocks from plaster and concrete, and laser-cut blocks from Acryl were fabricated. The SL Blocks from various materials could be integrated into the overall building block. The different surface qualities resulted in more or less friction between the blocks. The general building kit was assembled into different figurations (Figure 4-85).

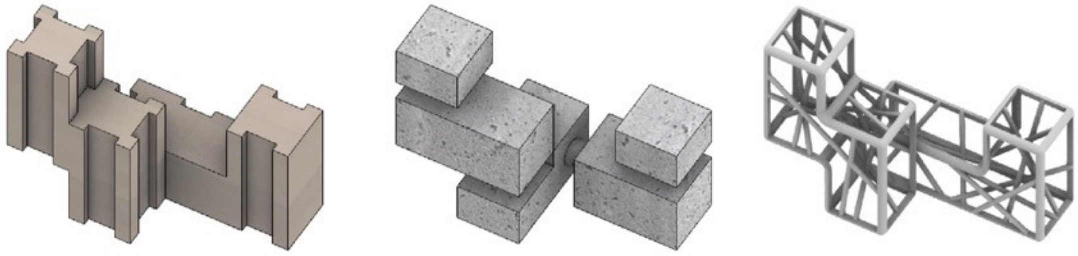


Figure 4-84 The bounding geometry of the SL Block filled with different articulations

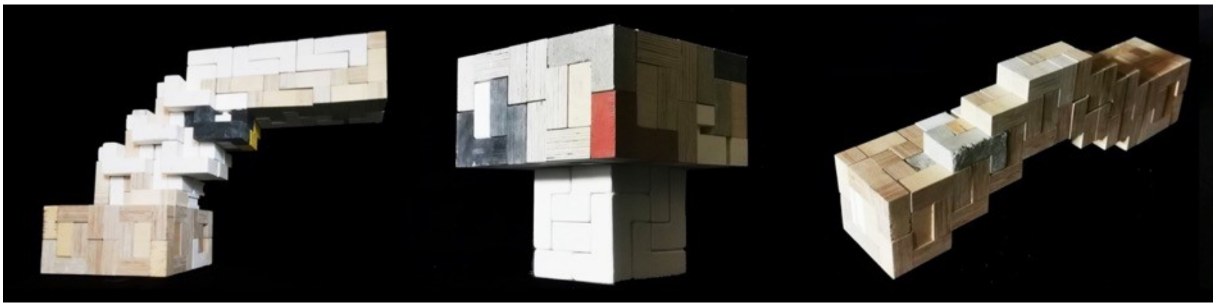


Figure 4-85 Three different aggregations form the same kit of SL Blocks with various materials

Tactile Robotic Assembly

The evaluation of the approach for the robotic assembly was tested in a small-scale demonstrator. A small cantilevering figure was assembled from 36 SL Blocks. The assembly of the SL Blocks was very sensitive to tolerances of the blocks. To address these issues, a tactile sensor was implemented. The initial trajectory for placing the block was successfully captured by demonstration. Based on the demonstration, a curriculum learning approach was developed.

Two collaborative robots sufficiently assembled the perfect-fit blocks into a steady structure. Minor material and fabrication tolerances occurred during the assembly. Although the error seemed to accumulate throughout the assembly, the structure became stable and steady once the last block was placed. Figure 4-86 shows how the cantilever would settle a bit due to these tolerances. A support structure could avoid this problem during assembly.

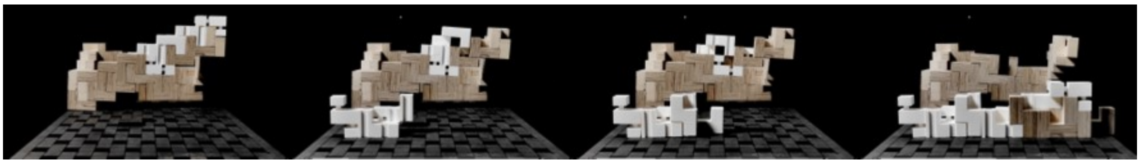


Figure 4-86 Manual disassembly of the blocks

The tactile sensor readings were sufficient to indicate the orientation of the grasped blocks. Figure 4-87 shows the changes in the sensor image during the assembly of the blocks.

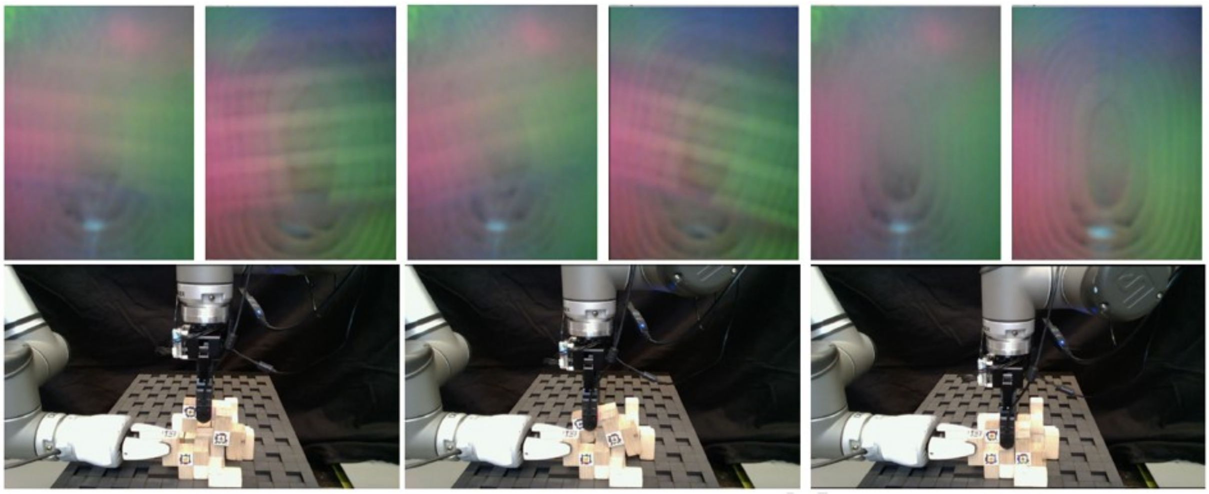


Figure 4-87 The tactile sensor readings for the left and the right finger with their corresponding assembly steps. The block is grasped in a neutral position parallel to the already placed block (left). The orientation of the block changes due to contact with the existing block (middle). The block is placed and released from the fingers (right).

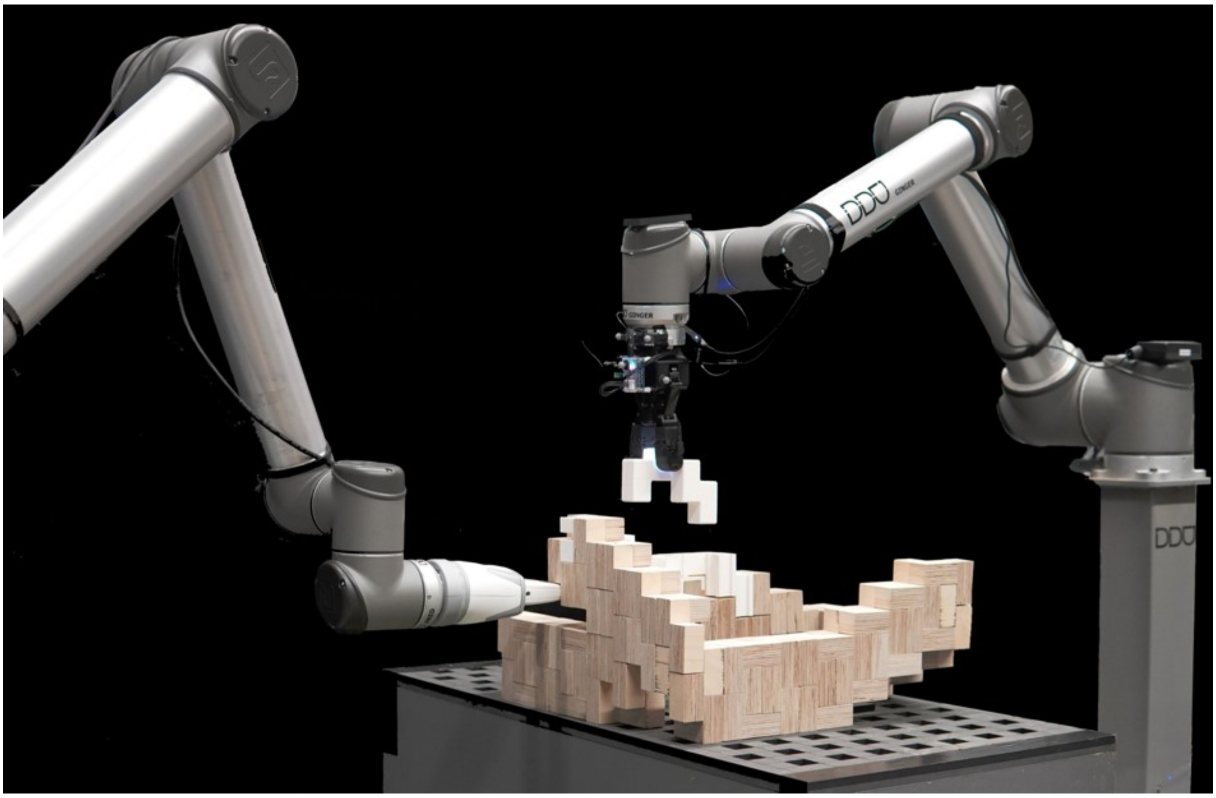


Figure 4-88 Robotic collaboration for the assembly of the demonstrator

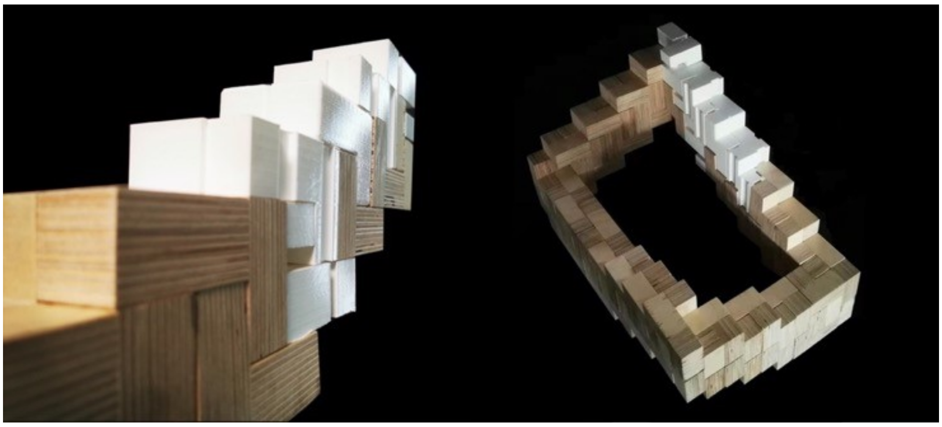


Figure 4-89 A detailed view of the final demonstrator showing the combination of plywood and 3D printed SL Blocks (left) and the overall figuration (right)

4.4.4. Discussion

This case study addressed the problem of autonomous construction for interlocking assemblies. The used SL Blocks were successfully implemented into a design tool to trace curves with an interlocking sequence. The perfect-fit blocks were aggregated into various architectural components in which a few key blocks immobilize all elements. Finally, a robotic assembly strategy with tactile feedback for the perfect-fit elements was tested.

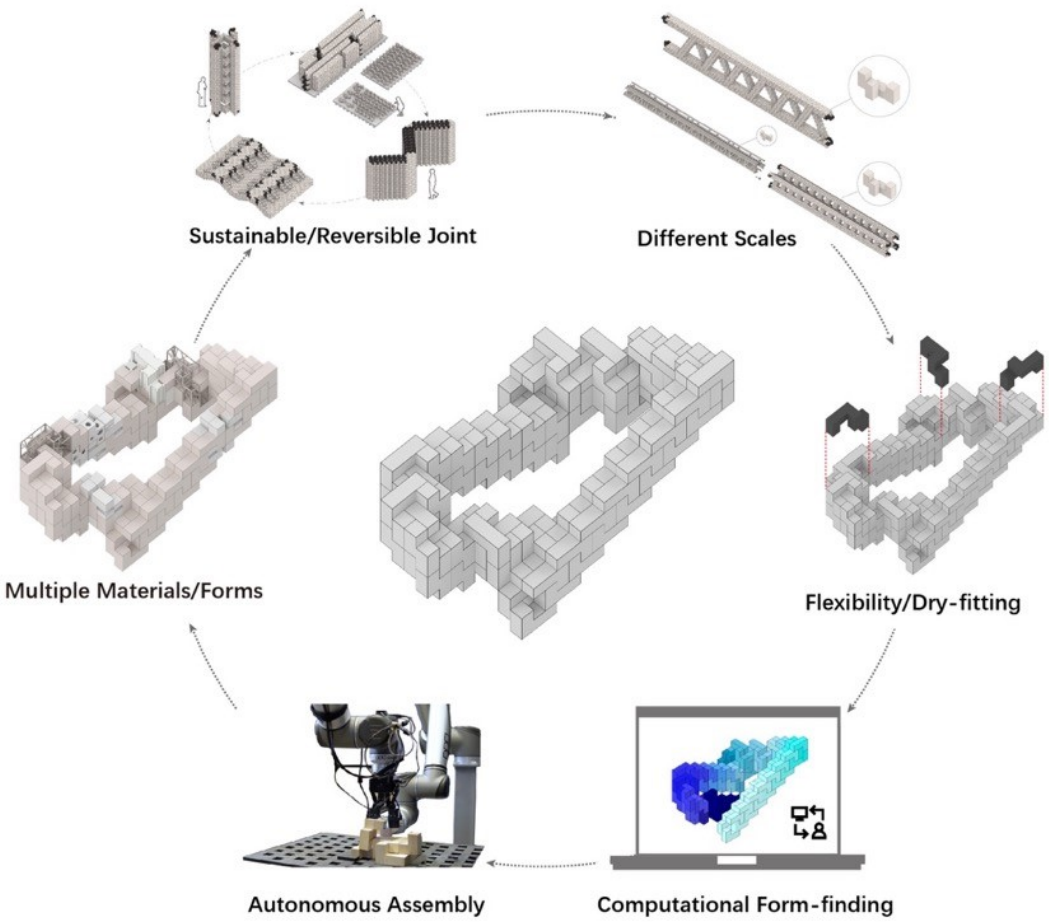


Figure 4-90 The properties of the investigated building elements, the robotic assembly, and the computational design tool

Learning Design Tool

The design tools provide an accessible interface to define the engagements of SL Blocks. The connection between various curves still has to be addressed manually. Nevertheless, it was proved that various architectural components could be designed, including columns, walls, and beams. Thus, the study contributes to the body of research focusing on discrete design in which small elements without predefined functionalities can find their place in more extensive aggregations. The architectural components and the composition are early tests and not meant literally but show the vast possibilities of the design tool.

They can be made from different materials and with a wide variety of fabrication techniques. The quasi-perfect-fit connections are exceedingly robust while offering variable connection interfaces. The blocks were fixated only using sequential assembly, which has both error-correcting and reversible properties. Thus, the discrete blocks inhered properties of digital materials. The geometrical principle is scalable. The mechanical properties of the blocks in their different arrangements have to be further investigated.

Learned Assembly

The assembly of the test with the SL Blocks highlights robot capabilities towards perfect-fit connections. The blocks were not designed for robotic assembly but were still assembled by means of supporting technologies. The demonstration of the trajectory for the blocks provides an accessible interface, enabling interaction with the system without programming skills. The tracking system could be improved, as the blocks should not be cast in shadow from the viewpoint of the camera system. Reinforcement learning was shown to be effective at learning closed-loop control policies to enable block insertion. However, the training time may become a bottleneck if more parts are added to the scene.

The tactile sensor was suitable for the small-scale blocks and provided sufficient data for robot control. However, for architectural construction, the sensor needs to be adjusted towards durability. The silicon does not last too long, and the coating was susceptible to damage. It was not tested on objects heavier than 300 g. For elements of a bigger scale, the whole system will have to be scaled. First attempts to scale vision-based tactile sensors are currently undertaken by Toyota Research (Kuppuswamy et al., 2020).

Conclusion

The introduction of reinforcement learning for both the design and robotic assembly renders a promising path to embed learning systems into the production of architecture on both ends. Designers can benefit from an assistant that takes over the tedious and complex definition of interlocking sequences, while the robot learning approach offers opportunities to assemble more complicated connection details.

Future research has to test the stability of the dry joined structures. Slight tolerances may propagate and lead to breakpoints in the overall structure. The automated assembly needs further investigation for autonomous assembly. Several steps have to be further investigated, like the path planning, assembly of different materials with varying frictions. With limited resources, a small-scale demonstrator was assembled and disassembled. The feasibility of large-scale construction with tactile sensors is still to be tested.

This case study presents an approach to reversible construction that relies on mathematical research into building elements. The research provides insights into the usage of tactile information for autonomous robotics in construction. The conceptual study presents multidisciplinary research to integrate the different fields of study for reversible buildings. These kinds of collaboration should be further advocated by architects, making use of such technologies for solving the complex tasks of reversible buildings.

5. Discussion

> "[...] every object is threatened from within and without by entropy such that it faces the question of how to perpetuate its existence across time." (Bryant, 2011, p. 227)

The goal of this thesis was to identify factors that extend the transformation and programmability of architectural structures. Dry-fitted, prefabricated elements were designed to meet robot capabilities for reassembly. The different case studies show how design tools, building elements, robotic assembly, and reassembly can be integrated. The order of the integration follows the robot's capabilities, which result in a specific building element design, that is then implemented into the design tool. Thus, the case studies clearly illustrate the imperative nature of robot-oriented design. The existing robot technologies impact the design of the elements to be assembled. The elements impact the design tool. Nevertheless, the case studies also suggest that this starting point can be altered. The first case study focused on the design of building elements for reassembly. The second elaborated on algorithmic assembly strategies for rule-based stacking and a dual robot system. The third study introduced material differentiation in order to build cantilevering structures through weight distribution. Finally, the fourth case study started with SL Blocks and investigated robot skills like tactile sensing and robot learning for their assembly.

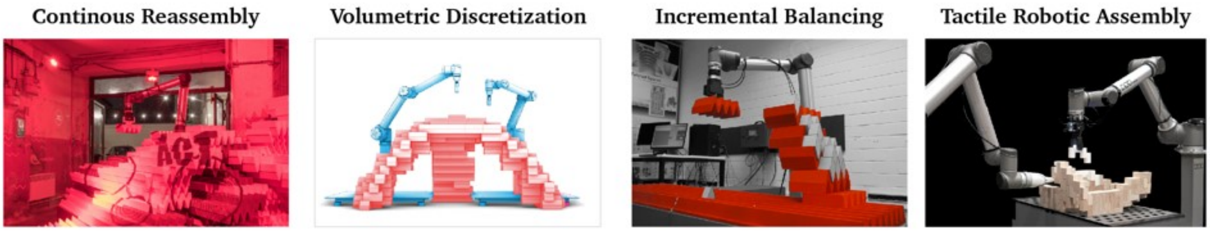


Figure 5-1 The four distinct case studies

The research on reassembly used the case study method to explore the building elements, design tools, robotics, and integration. The results of the four case studies are discussed in relation to each other and the broader spectrum of existing research. Finally, limitations, directions for future research, and the broader implications of the research are described.

5.1. Case Study Method

The case study method was chosen to open the discussion and produce physical demonstrations in the field of architecture towards an approach of automated reassembly. It generated many meaningful insights and highlighted various directions for further investigations as presented in the individual case study reports. The case studies successfully built a profound understanding of the different topics related to reassembly. The method was able to identify the integrative nature of the three main topics, robot skills, connection detail of building elements, and computational design tools.

The comprehensive definition of the case study for such technology-driven design investigations may become a valuable contribution in the field of digital design and fabrication. By providing a rigorous case study protocol and reporting structure, future researchers in the field of digital fabrication can use the chapter Method as a guideline for their investigation. It illustrates the advantages of the method to open a field for discussion and to raise new research questions derived from the studies. In that, it is in line with existing research works on robots in architecture (see e.g., Dörfler, 2018; Parascho, 2019). The detailed description clearly distinguishes the case study method from the experiment. While in an experiment, the researcher controls the parameters, the case study focuses on exploring problems and challenges on a defined case. The case study method seeks to generate questions that might be answered in experiments rather than examining the relationship between variables.

Each case study was set out to yield a small-scale physical demonstration. The understanding of the building elements and the robotic assembly procedure present valuable insights into their physical relationships. The problem of connections fit for robotic assembly reveals the tectonic challenges of editable assemblies. It has been argued that digital fabrication technologies such as robotics hold the potential to overcome the Albertian separation between designing and materialization (Carpo, 2011). This concept led to digital fabrication focusing on non-standard, bespoke, and highly variable artifacts embracing the concept of material behavior through physical making (Ercan Jenny et al., 2020). Such studies seek to formalize material behavior to be manageable within digital design tools forming material systems, unleashing the computational power of materials (Menges, 2016). Here, computation is understood as processing information, linking physical and digital making through sensing, simulation, searching, processing, and interacting in real-time (Menges, 2015a). The artifacts following these concepts might present material computing and might be digitally designed, yet such artifacts are analog (N. Gershenfeld, 2015).

Opposed to that, the case studies in this dissertation seek to integrate digital properties into physical artifacts. Materiality does not become the driver for the design tools; instead, digital concepts like error correction and editability were incorporated into physical assemblies. The information contained in the design model was translated into the physical through the robot. Instead of material computation, the building blocks were computed. Similar to existing studies on Digital Materials (e.g., N. Gershenfeld et al., 2015; Jenett et al., 2016; Andrea Rossi & Tessmann, 2017b), the importance of materialization in this study is consistent with this approach. Would this study be done only on a conceptual level, many of the challenges and problems would stay undiscovered. Hence, the exploration through physical prototypes and demonstrations played a vital role in this investigation. Without this type of validation, the design tool would stay uninformed, and the building elements would not exceed the conceptual level.

The topics for the case studies developed iteratively, based on insights from the previous studies. Thus, the curve-based design tool from the first case study was further improved into a volumetric-based tool in the second study. Additionally, a dual robot setup was implemented to build a cantilevering arch. Both problems were revealed during the reflection phase between the two studies, as suggested by Manelius (2012). Also, the building kit from the first and second case studies was extended in the third study with weight modules to introduce a differentiation of material properties, again based on the limitations of the previous studies. Finally, the robot programming challenges like sensing and feedback were addressed in the fourth study. Thus, the iterative sequence of the case studies has proven vital for uncovering these aspects and presenting solutions (Eisenhardt, 1989). Nevertheless, further case studies should be conducted to investigate the developed concepts.

The distinct case studies give insights into how to integrate design tools, building elements, and robots. In the case studies, the technology readiness level (TRL) was situated at levels three to four, described as experimental proof of concept, and validated in the lab (see method chapter). The case studies did not increase these levels for the used technologies. Nevertheless, the usage of robot learning and tactile sensing, as presented in the fourth case study, contribute to proclaim the TRL at the lab validations level. For the first three studies, the integrated technologies are within reach of the architectural domain, while the fourth study depends on the integrations of computer scientists and roboticists. In general, the case studies revealed that this research benefits from an interdisciplinary research approach. The fourth study provides such a multidisciplinary collaboration with computer scientists.

5.2. Building Elements as Connections

The results of the case studies illuminate how building elements can be designed for robotic reassembly. One of the first steps in all conducted case studies was related to the building elements' choice and design. Two different types of reversible connections were investigated. The first building kit featured self-calibration to minimize robotic sensing overhead, as suggested in research on Digital Materials (Ward, 2010). The second building element, the SL Block, consists of perfect-fit connections that required advanced tactile sensing technology. Both came without adhesives or fasteners; instead, dry-fitted stacking or interlocking was utilized.

The zigzag contour blocks were manufactured for stacking and error correction during the assembly, reducing redundancies during the robotic assembly. It followed the concepts of robot-oriented design (T.-A. Bock, 1988) while adding reversibility and self-aligning properties (Popescu et al., 2006). The blocks were discrete in two axes, allowing continuous movements along the third axis.

The study on SL Blocks provides insights into how emerging robot technologies like sensing and learning can be utilized for dry joined building elements. The previous building blocks provided simplified connections with self-aligning properties, while the SL Blocks were challenging to assemble even for humans. The SL Blocks were not designed during this study; they were based on research by mathematicians (Shih, 2016), highlighting how interdisciplinary research may benefit architects in the domain of combinatorics. Their geometrical connection principle does not allow tolerances, making them hard to assemble by machines without adapting features and feedback. Nevertheless, the sequential interlocking is well equipped for the sequential robotic assembly. Their interlocking hierarchy generates sound structures without adhesives or counterweights, opposed to the zigzag blocks. The serial elements have a discrete set of connections found in Digital Materials but did not rely on a press-fit connection as typically found in Digital Materials (J. Hiller & Lipson, 2009).

The connection details of all elements were inseparable from the building block (Figure 5-2). The ratio between building element and connection detail was relatively low throughout all studies. Instead of integrating a connection detail into the blocks, the whole block became the connection. The connection is highly integrated into the design of the blocks, which is conceptually different from most reversible connection interfaces known in construction, as reviewed in the background chapter. The distinction between the matter added and the connection is not possible in these elements. If one would remove the connection interfaces from the blocks, then the blocks would be unidentifiable. This aspect led to very robust building blocks, a crucial principle for reversible connections (Kissi et al., 2019). All of the SL Blocks stayed intact during the experiments. Some of the zigzag blocks had minor damages along the edges, which would, however, not render them unusable. In a few cases, the thinner side teeth broke apart. In comparison, the SL Blocks were more robust due to their compact design and the material choice of plywood. In general, both connection types were robust, a crucial aspect for connections to withstand repeated assembly and disassembly (B. Guy et al., 2008).

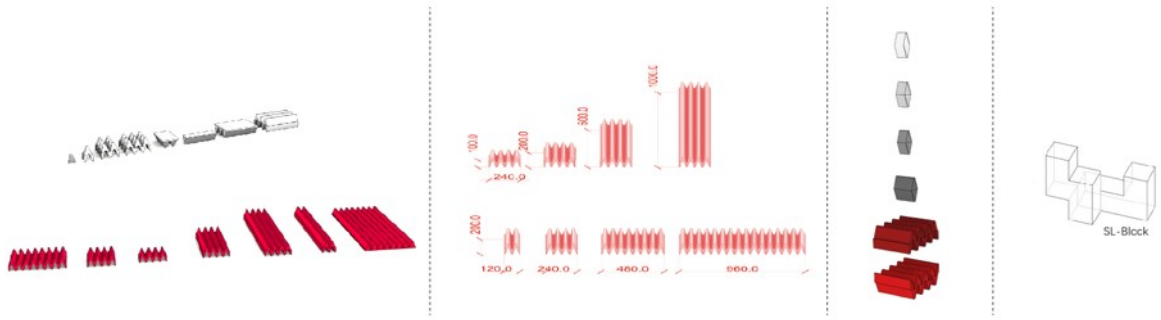


Figure 5-2 The different building kits used in the four case studies. The concrete and foam blocks from the first case study (left), the extended foam blocks for the second study (middle left), the foam blocks and the weight blocks (middle right), and the SL Block (right).

The first building kit was used in three case studies, highlighting the reusability of the blocks for different use cases. The improvements of design tools enabled previously unplanned solutions, highlighting the importance of software improvements for modular systems (Um et al., 2017). Thus, the extensibility of the building kit was demonstrated throughout these three case studies. The newly introduced elements were different in geometry and material. The initial building kit was extended by introducing blocks with more teeth (case study two) and weight-differentiated blocks (case study three) (Figure 5-2). The new elements fit into the existing kit while offering additional capabilities such as creating layered bonds or cantilevering figurations without falsework. As traced in the background chapter, too often, modular design was centered around the idea of the self-containing building kit. However, modularity is also the property of integrating new modules (Lipson, 2007). The reusability and extension of the building kits in this study illustrate an evolutionary growth of a building kit. While introducing new modules into the kit, the overall system acquired new capacities (Lipson et al., 2002), as illustrated by the bond in case study two and the cantilevering in case study three. This property enables the system’s evolution to new demands (Clune et al., 2013), a crucial feature in order to avoid obsolescence of building elements (Elma Durmisevic et al., 2017).

The building elements were material unspecific; instead, their design was driven by geometrical principles. Material constraints for the geometry-based elements were mainly friction and weight. Both block types, the zigzag and the SL Blocks were materialized in different materials. Such differentiation and integration could embed functionalities and services that go beyond structural considerations. Existing studies provide insights into how the geometrical principles of interlocking blocks can be used as a container for embedding properties like electricity circuits (J. D. Hiller et al., 2011). While the geometry of the blocks could be adapted to particular materialization, it was shown that geometrical considerations towards the robot capabilities could become the main driver for the design of the elements.

The combinatorial aspects that the elements enable them to adapt to various design intentions. As shown in the chapter Background, most reversible components applied in architecture had designed usability or positions within a building system. While the poles below a beam might be moved along the beam, creating different spatial arrangements, they still form the same topology. The two components are preassigned to form this relationship of the one being placed on top of the other. This invariant topology can be overcome by the variable combinatorics and not predefined building elements presented in this study. Thus, the building elements offer more potential to be transformed.

Based on the building elements, the case studies can be put into different categories. The first category focuses on self-calibrating building elements made to reduce redundancies during the robotic assembly. The robot does not need sensing to execute the stacking. The second focuses on interlocking elements that are precise-fitted and require an adaptive robotic assembly procedure. The research on automated assembly in the last decade was focused on building elements already used in construction. Bricks and wooden plates that were manufactured for human assembly were used in robot-aided construction processes. Humans were able to circumvent tolerances and misplacements by adaptation; for robots, this would require further implementation of sensors. Robot-oriented design focused on a reciprocal connection between the robot and building components (T.-A. Bock, 1988). In this study, connection systems were presented that are fit for robotic assembly in one set of building elements due to their self-alignment. And in the case of SL Blocks due to the exploitation of the tactile skills learned by the robot. Hence, the importance of negotiating the robot capabilities with the available building elements became evident.

5.3. Design Environment as an Information Hub

All four case studies started with designing the building elements in a bottom-up fashion, which impacts the design approach. This element-based approach differs from an afterward discretization and is more similar to Discrete Design which starts the design from the elements. In all studies, it can be observed that the underlying design structure is based on curves as tangible design parameters, which is a tendency that can be observed in Discrete Design (Retsin, 2016). The curves guided the arrangement of the blocks and helped to map the elements into position. Even the volumetric figures in the second study were translated into lines before the elements were mapped. The element-based approach makes it necessary to provide designers with tangible interfaces to manage the vast number of elements, negotiating between the bottom-up and top-down approaches. In all cases, the constraints of the blocks were an inherent property of the design tool. Thus, the algorithmic design tools allowed rule-based modeling for reusable building elements. As such, the studies reduce the significant challenge due to a lack of tools, providing incentives to design products and buildings for reassembly and reuse, as found in a study on circular economy thinking in construction (Adams et al., 2017).

The first three case studies utilized the same building elements, varying approaches towards discrete design and robot programming. Several challenges could be addressed by iteratively enhancing the digital tool, an approach well-known in software development (Basil & Turner, 1975). Similarly, the robot programming tools for architects were refined directly by architecture students, providing them with insights into robot programming as described by Lim (2016). Although the building elements stayed quite similar, iterative software improvements enhanced their physical utility. The elements were serially manufactured with straightforward techniques to reduce their complexity, embedding their intelligence in the design tool. The extension of the building kit with secondary weight blocks was driven by a global design effort to build a cantilevering structure. Therefore, a cross-bond design tool was developed in the second case study, and extra weight blocks were added in the third study. Their usage was only made possible through the implementation of the design algorithms. Owners of the same building elements might have access to various software implementations that generate different outcomes.

Reassembly involves both assembly and disassembly. However, disassembly cannot be regarded as reversed assembly due to tolerances, misplacements, or damaged elements. Thus, the redesign of an existing structure would benefit from capturing the current state of the assembly and made available for the designer. As-built capturing is necessary for correlating the physical with the digital. It was shown that point cloud capturing of the existing structure and estimating the placement of elements within the design environment is possible. These investigations contribute to the field of as-built BIM (Tang et al., 2010) by adding an approach that could be used to capture the assembled elements in a sequential way. This procedure goes beyond the storage of geometrical data and informs the model with the actual becoming of the aggregation. Nevertheless, this part of the study is very preliminary and needs further investigations.

The focus of the design tools shifted towards combinatorial automation. The first case study presented a minimal set of combinatorial repertoires. The elements were stacked along curves in regards to their discrete connections. The second study focused on combining the elements based on their dimension to fill various volumes to create a layered bond. The third study introduced weight blocks into the building kit, enabling combinations for cantilevering figures. In all of these three studies, the elements were stacked. The fourth study presents blocks that can engage each other in various orientations and directions, thus, offering a higher complexity in the combinatorics.

Active Reassembly in a structure requires self-logistics, meaning the elements must be stored near or within a composition. This approach was reflected in all case studies by designing the pick-up locations that could also be used as in-between storages. The first study presented an attempt in which the elements are evenly distributed within the aggregation. The study illuminated a robot resting within an aggregation for live reassembly while spectators tried to decipher words projected onto the elements. Spatial aggregations may have to negotiate various needs like stability, visual and usability parameters. The linked information has to be computed into a coherent outcome, a planning problem difficult to solve, especially in larger aggregations (Beal et al., 2012).

The design environment was enriched with a bottom-up approach constrained by building element design and assembly parameters. All design tools generated the geometrical distribution of the elements in a sequential manner, enabling a straightforward translation of the design aggregation into robot instructions. The robot simulation within the design environment is helpful for an understanding of the engineered instructions derived from the design model. These generated instructions still rely on complex data flows within the algorithms, as Lim (2016) described. Hence, the architectural design environment served as the information hub for various tools as proposed by Davis & Peters (2013). Such a concept of integrating various tools into the design environment has been demonstrated by integrating design and engineering procedures with structural analysis data (Tessmann, 2008). This study extends this utilization as a hub for various information by adding simulation and programming of robotic assembly and storage of the as-built status.

5.4. Robot Skills for Assembly

Basic robot programming was provided inside a design environment. It was sufficient in all case studies to generate instructions for the robot. The simulation of these instructions inside the design environment enabled visual feedback to the designer for understanding the robot constraints. The capability for architects to define the assembly instruction, in turn, impacts the design (Lim, 2016). Robotic reassembly calls for design solutions that most likely will only emerge through an understanding of the technology by the designer.

The demonstrators were all built without any printed manuals or plans as instructions, highlighting a shift towards the digital flow of information for assembly. While it has been argued that digital fabrication is tackling the separation of the intellectual act of designing and fabrication (Carpo, 2009), the assembly of digitally fabricated components and elements was often driven by manual processes (Tibbits, 2010, p. 15). The granular models in the case studies call for a digital assembly plan due to the sheer amount of information (e.g., exact position, orientation). Especially the study on SL Blocks would be hard to communicate to a human in a conventional notation system due to the various orientations and engagements of the blocks—the combinatorial assembly potential. Thus, the geometrical and combinatorial complexity of the study also points to human limitations, as pointed out in the following quote.

> “Every material entity that can be represented and grasped only with the help of a robot becomes at the same time the reason why the robot facilitates what human beings cannot do. A robot unfolds its potential precisely where an increasing number of complex relations and individual requirements justify its use, without leaving human beings out entirely.” (Jan Willmann et al., 2014)

While the quote points towards the concept of the robot outperforming humans, it should be borne in mind that not only material usages have to be cultivated but also emerging machines. The robot may play a special role as it shares some of human capabilities;

nevertheless, "[...] in no way to a devaluation of human complexity; on the contrary, human capabilities can be considerably expanded through the "operationality" of the robot" (Jan Willmann et al., 2014).

All case studies used robot grippers to pick and pace the elements. The zigzag blocks called for the adaption of the gripper's fingers. While grippers are broadly available with various specifications, the fingers were produced with 3D printing. The tactile sensor is a technologically more advanced adaptation as it also required a PCB chip and other materials to build the finger. To reduce the technical development, the dimensions of the sensor were maintained, and instead, the SL Block was adapted in size to match the fingers. The two approaches present different ways: the adaptation of the robot towards the elements (case studies one, two, and three) or the adaptation of the elements towards an existing gripper (case study four). Nevertheless, even in case study four, it was suggested that these fingers have to be scaled and appropriated towards the building elements. Thus, the integration of robots started from the design of building elements and led to the design of the fingers and gripper, which is in line with the customization approach (Gramazio et al., 2014, pp. 478-479).

The assembly and disassembly of building elements are a high contact rich task. The industrial robot usually is blind and comes without any sensing skills. The sense of touch is crucial to detect contact and friction between elements. In contrast, humans continuously use vision and touch during assembly. Once the building plan leaves the digital and is materialized, tolerances and accuracies come into play. These could be addressed by designing the building elements as discussed above or adapting the instruction to meet the tolerances. The implementation of the tactile sensor for architectural driven assemblies was the first of its kind. The robot needs to sense these tolerances and act accordingly (Bonwetsch, 2015a). For adaptive programming, the currently available robot programming tools were not suitable. Instead, robot learning is a control strategy to addressing deviations from a building plan.

Robots need to build an understanding of the as-built status. Especially for on-site assembly, the feedback from the construction environment is crucial (Dörfler, 2018). Therefore, multiple forms of perception were investigated in this thesis. But how to perceive built structures in order to plan their reassembly? The sequential as-built capture presented in the second case study could serve as ground truth for the deduction of the disassembly instructions. However, the disassembly cannot be understood as reversed assembly due to tolerances, damages, and misplacements during the previous assembly. While current approaches to capture as-built models rely on geometrical information, tactile sensing could be implemented into the gathering process for the model.

Finally, the design of the connection interface can be revisited once robots acquired human-level skills for assembly. The tactile sensing capabilities and robot learning approach can be considered one step in this direction. Although it was argued in the earlier case studies for a reduction of the sensory overhead through the design of the building elements towards error-correction and self-alignment, it has been shown that emerging robotic skills can challenge these assumptions. Intelligence as the ability to perceive and adapt behavior within an environment might help to move robots to the construction site as autonomous actors; however, as Melenbrink et al. (2020) have argued, this would be unfruitful if the construction industry does not address more fundamental principles. These could be achieved by novel hardware moving away from machines and building elements designed for human operators towards the unsupervised building of autonomous construction robots (Melenbrink et al., 2020).

5.5. Integration of Physical Editing into Assemblies

This research highlights possible concepts for integrating the design tool, building elements, and robotic assembly. All four case studies provide insights into such integration. The design environment became the managing hub for combining the three systems. While other digital fabrication techniques transmit the digital designed model into a frozen artifact once, the reassembly of the aggregations presented in this thesis offers exponential reprogramming in the physical world, as argued for by Gershenfeld (2015). The integration approach provides opportunities to redefine the system architecture and develop new products within that system. The research developed systemic innovations to capture value from digital manufacturing technologies that were not addressed so far (Hall et al., 2020). The presented case studies can be understood as a further trait into a more accessible, editable built environment. Building elements might become as many and as small as needed while their assembly is left to an AI-driven robot, as suggested by Carpo (2019). The approach of constant reassembly in the future might challenge the idea of the standard towards programmable pieces and the question of authorship.

Beyond the integration of these concepts, another crucial aspect highlighted in the fourth study is interdisciplinary collaboration. Due to the complexity of the various systems, architects have to reach out to experts from other fields, as already argued for by Dörfler (2018). During this thesis, an interdisciplinary collaboration with roboticists was started. Computer scientists were involved in developing the robot skills and an optimization algorithm for the design tool. Challenges like finding common ground on research interests, their definition, and vocabulary for communication were experienced. The current compartmentalization of university departments may hinder such collaborations that are so important for fundamentally changing how these technologies are integrated into construction (Melenbrink et al., 2020).

Similar to the ongoing negotiation of top-down and bottom-up approaches in architectural design, these tensions can also be found in robot-oriented design. The clear hierarchy for the order of robot, connection detail, and design method can be tackled from both directions. As for architects changing the robot, capabilities are relatively complex; one must first understand these. Although design tools can integrate various constraints such as robot workspace and connectivity of building elements, it still requires the operator of these tools to develop insights into the properties that make up these constraints.

Finally, the presented processes bring digital technologies into the domain of design for disassembly and reuse in construction (B. Guy et al., 2008) by enriching the repertoire with robotic assembly processes that are reversible. The proposed direction for the development of design tools for reversible constructions may further promote circular construction techniques, reducing some of the barriers for structures that can be disassembled easily as suggested by Kanters (2018).

5.6. Conclusion

This research began with the question: How can we integrate the design of building elements and robotic skills for reassembly? The different case studies provided insights into the hierarchy in the design of aggregations that can be reassembled. Different building kits were investigated for their integration into the design environment and in regards to robotic assembly capabilities. It was shown that the design environment could become the hub for combining these previously separate steps into a coherent process. It can be concluded that the editability of an aggregation depends on a concise integration of these various parameters of the system.

The research was based on the case study methodology to increase insights into the challenges of automated reassembly. The results of the case studies yielded physical demonstrations for dry-fitted aggregations assembled with robots. These provide evidence and theoretical support for the feasibility of the concept. It revealed many technological challenges for robots in the assembly processes and highlighted which robotic skills have to be improved. The case studies raise the question of the importance of robotic skills towards reassembly.

The main contribution of the thesis is the integration of reversible building elements, robotic fabrication, and the design environment for editing physical aggregations. The research indicates that automated reassembly depends on the reciprocal relationship between robotics, building elements, and design system. The research points towards the importance of a deep understanding of robot technologies embedded into the design of building elements and their connections. The rising technology of robotics was the starting point for rethinking the design tools and building elements towards an editable built environment. The case studies successfully presented a digital approach to reassembling building elements. This idea was investigated for elements that can be positioned at various places within an aggregation following the concept of Digital Materials and Discrete Design.

5.6.1. Limitations

The findings of this study have to be seen in light of some limitations. It must be borne in mind that the case studies were conducted in a lab environment, canceling out many of the fundamental construction challenges. The collaborative and stationary robot system limited the scale of the prototypes. The operating range of the robots was only 1.3 m in radius. While this could be overcome with mobile robots, it would introduce complexities such as mapping and localizing the robot in its environment (Dörfler, 2018). The maximum payload of 10 kg limited the weight of the elements and the forces applied for connecting them. Thus, fixation details that would have required high forces were not tested. The third case study could be scaled up and tested with higher weight differentiation. Nevertheless, the scale demonstrations present valuable insights into the relationship between the different phases of implementing automated reassembly. It was beyond the scope of this thesis to address the question of on-site construction and large scale demonstrations. For the construction of large-scale structures, the use of larger robotic systems would have been indispensable. At the same time, these would have had significantly higher safety requirements and would have slowed down the assembly work considerably, since manual intervention would not have been possible.

These limitations restricted the material choices for the building elements, such as heavy materials. This limitation is also valid for the gripper system with tactile sensors. As the maximum payload is unknown, it was only used for small building blocks of a maximum of 500 g. In order to draw generalizable conclusions, further studies on robot-oriented building elements for reassembly are necessary. This study investigated only two instances of such elements, which, as a sample size, is too few to derive a general theory. The same is true for the extensibility of the building kit, as that was only investigated for one building kit. The prefabricated elements were prototypical; scaling up the production of the building kits could enable exploration with more elements.

Rhino 3D, in conjunction with Grasshopper, was used as a design environment. While various tools were implemented and available, this research would have benefited from a stability check for discrete elements. Most available tools for such simulations are only rough estimations or are not suited for the many contact interfaces in the investigated aggregations. Such a stability simulation would enable elaborate checks for complex figurations. The design and robot programming tools developed for the demonstrators were highly specific and adapted towards a more abstract level to address a broader scope of design exploration.

The body of existing work on robotic assembly for dry-fitted building elements is minimal and just started to grow in the last years. Many of the found examples and studies were only produced during the investigation for this thesis. Hence, the valuable findings from other researchers were available too late or could not be addressed.

The interdisciplinary collaboration was only started during the research. The time-consuming process of a collaboration called for a lot of implementation work and developments for data exchange. The vocabulary and problems in computer sciences, roboticists, and architecture had to be aligned. With a collaboration that emerged during these investigations, this kind of research can speed up. With the demonstration and learning approach, the exploration of building elements and their connection could drastically improve.

5.6.2. Future Research

This research propagates design systems in correlation with building elements that can be robotically reassembled, revealing the characteristics of a physically editable built environment. However, within the scope of this thesis, these could not be investigated exhaustively. The robotic assembly technology, the building elements, and corresponding design tools were developed to such an extent as to allow feasibility tests in a lab environment. Nevertheless, especially the design implications of robotically assembled elements and the yielding results provide valuable insights and starting points for future research. Therefore, further studies are required to deepen and extend the findings. It has been shown that such investigations benefit from physical demonstrations and the sequential alignment of case studies. The presented research has revealed the unique versatility of dry-fitted building elements for robotic reassembly. It is expected that with the described design criteria and robotic technologies, further surprising and unforeseen solutions will emerge.

The further development of connection details and building elements fit for robotic assembly should focus on their reversibility, following the promising directions of dry-fitting and interlocking. The study of SL Blocks highlights the possibility of optimization of building blocks for various functions and positions in a structure. Future research may seek to identify other modular and serial building elements for sequential interlocking. Optimization and search algorithms could help to find additional building blocks with similar combinatorial and interlocking properties. Such a search could further expand the building kit instead of relying on one type of block. The materiality of such building blocks for reversibility is of special interest; future elements do not have to be mono-material and could be manufactured as compounds from various materials. Instead of recycling materials, the compound building blocks could be reused.

Discrete Design and Digital Materials are promising avenues for designs that can be physically edited. In order to fully exploit the potentials inherent to the element-based approach, the design environments have to facilitate interfaces for discrete elements further. Various developments like WASP at the DDU in Darmstadt (Anrdea Rossi, 2021) and Monoceros (Jan Pernecky, 2021) provide discrete design tools for Rhino 3D/Grasshopper, promising directions, and more implementations of this kind would proliferate discrete designs. The linkage of the design environment to existing element stocks could proliferate reusability. This topic is also linked to the as-built capturing of buildings and the contained elements. Beyond these implementations, future research on physically sound element simulations are required to provide stability checks.

Future studies could address interdisciplinary, fundamental research into robotic reassembly to better understand the implications of the results. The research on robotic skills should involve interdisciplinary work, providing further investigations into novel robotic skills such as tactile learning. These investigations may include scaling up the tactile sensing technology for construction robotics. Advanced robot control strategies and robot learning call for collaborations with computer scientists and roboticists. At the same time, architects need to understand these approaches to integrate them into the design of tectonic systems to be physically editable. The various sensing and control technologies present an extensive field for future research. Especially investigations into tactile sensing for construction would elevate the design of connection details.

Robot learning could minimize the programming overhead for complex assembly tasks. The demonstration approach could enable non-experts to interfere with robots in construction by training the assembly and disassembly.

The capturing of as-built status for representing aggregations using volumetric primitives rather than surface representations could be exploited in more depth. The current gap between 3D scans with their imprecisions and the perfectly modeled geometries has to be closed. Minimizing the afford for designers to use physically existing elements should further fuel the concept of editable assemblies.

5.6.3. Implications

This research shows a direction for reprogrammable matter, based on robot technologies for physical editing of architectural aggregations. The proposed strategies could help create more mature techniques for reversible building elements, increasing the likelihood of buildings being designed to be reassembled rather than demolished after their initial life span. This may imply reconsidering business models in construction towards building elements with a temporary assignment, in-between storing, and future prediction for reuse. Thus, the former linear model of buildings will be replaced by one that focuses on editing.

This study highlights the importance of negotiating the error-correcting features of building elements with robotic assembly technology for architecture. The concepts of Digital Materials and Discrete Design introduced digital properties for approaches of reversible building systems, rendering them fit for robotic assembly. The understanding of such digital properties in building elements could significantly contribute to a design practice that focuses on the editability of spaces, with buildings being seen as material banks or storages. The elements could fluctuate from one building into another or rest within existing buildings until needed.

The linkage of building elements with software implementations might become an essential benefit for the digital construction industry. Similar to the development in car selling businesses, in which the modality of self-driving has to be additionally acquired, the editability of buildings could be a modality correlated with software implementations. Two companies might produce and sell similar physical building blocks while the software implemented design features differ. The concept of linking building elements with such tools may improve the competitive situation by creating a new business segment for companies in the prefabrication sector. Business models for reversible building elements and following concepts of circularity might want to put focus on supplier buy-back agreements and product-service systems.

Robot technologies are developing at a swift pace, offering novel solutions for construction. The investigations on tactile sensing and robot learning underline this trend. These two skills are crucial components of autonomous robotics, circumventing many challenges on real construction sites. As the technology gaps are closed, automated reassembly should be further investigated. The trend towards circular economy predominantly focuses on recycling, while the editability of the most extensive products in our cities may offer huge potential. Robotics and automation, in general, could be the enabler for the editing of our built environment. The past concepts of reassembly implemented in building components and parts also failed due to the immense labor required. Today, automation might change this hinderer. Construction companies and real estate owners might start to reiterate parts of their business models by implementing the physical editability of the buildings they construct.

The integration of various questions and technologies in this research was tackled by the case study method; in iterative studies, physical demonstrations for reversible designs have been created. The implementations of the presented case studies relied on the rethinking of previously disconnected processes for architectural production. The interdisciplinary approach developed in this thesis can serve as an example to help blur disciplinary demarcations. Architects might turn to computer scientists to collaboratively investigate the challenges of automated assembly and reassembly.

As architects are at the forefront in making systematic decisions on the performance and tectonic systems that make up our built environment, they could be trained in designing for a physically editable world. Architecture students are exposed to robots and learn to generate digital instructions, streaming their expertise into practice. The construction industry may develop tools and machinery to address this emerging knowledge. The students that participated in the case studies built up some of this knowledge; it is now part of their repertoire, influencing their future decisions.

The United Nations Environment and the International Energy Agency called for actions towards reducing the material and energy consumption in the construction sector. In their 2019 Global Status Report for Buildings and Construction, they state that dramatic improvements urgently have to be implemented in the way the world's buildings are built, designed and operated if the vast global building and construction sector is to meet the international goals under the Paris Agreement. It is predicted that the world's building stock is set to double by 2050, which would further increase the scarcity of raw materials. At the same time, this development gives room to implement and promote clean solutions to make buildings future-proof. Concepts for extending the cradle-to-cradle life cycle in construction and emphasizing the impact of building demolition versus reuse are some of the key action steps. In 2021, the European Commission initiated the New European Bauhaus to tackle these challenges, calling for transformation projects that embrace circularity while cultivating novel aesthetics, putting design at the service to fuel systemic changes.

Construction based on Discrete Design fosters the usage of precisely fabricated building elements. The previously labor-intensive process can be automated through intelligent robots – allowing a resource-efficient assembly and disassembly process. At the end of a building's life cycle, the components can be reused in the sense of a circular economy. Various industries are reconsidering the assembly of their products; reversibility becomes more critical as politics start to understand and foster the life cycle of these. The large-scale architecture products provide a very challenging case for an approach to circular buildings, especially their masses, logistics, complexity, and the one-off products in architecture. The proposed systematic shift, in turn, enables designers not only to produce changeable structures but to gain control and thoroughly explore the design space resulting from reversible building elements. In Robotic Digital Reassembly, materialization and production of architecture are not a one-off process. Instead, they become a series of instances shifting and adapting into an ever-unfolding future.

Project Credits

The case studies in this dissertation were all embedded into the academic teaching environment at the Digital Design Unit led by Prof. Oliver Tessmann at the Architecture Department at TU Darmstadt. The teaching formats included seminars, workshops, study projects, and master thesis.

The author set up the initial concept for two collaborative UR 10 robots and the primary hardware platform during the first year of this thesis. This setup included a pneumatic gripper and the connectivity between Rhino/Grasshopper and the UR 10 robots. At a later stage, a connection between Grasshopper and the UR robots was established using ROS, allowing the extension of the robot programming concepts available. This setup was established in collaboration with Boris Belousov from the Intelligent Autonomous System Lab (IAS).

The following sections give an overview of collaborators in the different case studies. In cases of related publications to this dissertation, the role of the author is described.

Case Study: Continuous Reassembly

The author conducted the first case study with students during a 5CP seminar in the winter semester of 2017/18. The realization of the architectural installation Luminale 2018 'If you want to see, you must learn to act!' was enabled by the Digital Design Unit, led by Prof. Oliver Tessmann. The project has been supported by Alexander Stefas' know-how in programming and physical computing. He connected the abcd (Zumtobel Group) LED lights to the robot program by setting up an interface to the lamps that would react to digital outputs from the robot program. Andreas Rossi supported the project with his knowledge of digital fabrication and technical questions regarding robot programming. During the seminar, Martin Knoll and Samim Mehdizadeh supported the students with programming and digital fabrication skills under the author's supervision. Finally, the following students participated in both the elective seminar and the two-week workshop at the end of the semester. They contributed to successfully realizing this installation: Aleksandra Buchalik, Anastasia Oboturov, Bastian Nispel, Begona Roget, Cindy Drummond, Daniela Hoffmann, Eric Göbel, Eva Streng, Felix Graf, Franz Georg Theobald, Frederica Aguiar de Melo, Gunel Aliyeva, Hendrik Beckers, Janine Schlaak, Julian Weber, Lukas Koser, Maximilian Vincent Gehron, Olivier Stoos, Philipp Riebel-Vosgerau, and Richard Oliver Gerspach.

The project was part of a conference paper at CAAD Futures 2019 with the title 'Interactive Assemblies - Man-Machine Collaboration through Building Components for As-Built Digital Models.' The paper was written by the author of this dissertation.

Case Study: Volumetric Discretization

The case study Volumetric Discretization was conducted in the summer semester of 2019 as part of a 5CP seminar. The students were introduced to Discrete Design with the existing building blocks from the previous study and robot programming for assembly tasks. At the end of the semester, students formed groups of two to four students to implement a design tool and build a demonstrator under the supervision and guidance of the author. During a two-week workshop Shakeu Abdallah, Jianpeng Chen, and Andreas Schmidt finalized the demonstrator with the guidance and support of the author.

Case Study: Incremental Balancing

The case study Incremental Balancing was conducted during the same seminar as the case study Volumetric Discretization in the summer semester of 2019. The final demonstrator in this study was designed and fabricated by Timm Glätzer, Janine Junen, and Leon Wietschorke under the supervision and guidance of the author.

The project was published in the CAADRIA 2020 proceedings under the title 'Multi Modular Aggregations - Robotic Assembly of Cantilevering Structures through Differentiated Load Modules.' The paper was written by the author with minor support from Leon Wietschorke for some explanations on the algorithm and from Timm Glätzer creating graphics under the supervision of the author.

Case Study: Tactile Robotic Assembly

This case study has been conducted under the title Tactile Robotic Assembly and was supported by the Forum for Interdisciplinary Research at TU Darmstadt. The collaborating professorships enabling this case study were the Intelligent Autonomous System Lab (IAS), led by Prof. Dr. Jan Peters, and the Digital Design Unit (DDU), led by Prof. Oliver Tessmann.

The concept for the case study was developed in close collaboration with Boris Belousov, a PhD student at IAS. While Boris Belousov gave input towards the robot control and the machine learning approaches for the algorithms used in the design tool, the author developed the architectural components of the project, including the choice and materialization for the SL Blocks, the design of the demonstrator, and the formulation of the architectural research questions of reusability and dry joining.

The design tool and the fabrication were developed during a research seminar (5 CP) with student Yuxi Lui, supervised and guided by the author. The implementation of reinforcement learning into the design tool was done in collaboration with Niklas Funk, Samuele Tosatto, and Boris Belousov, all PhD students at IAS. Later, Yuxi Liu intensified his work in a study project (15 CP) guided by the author, including the fabrication of various materializations of SL Blocks (e.g., plywood, concrete, 3D printed) and generating robot instructions based on the aggregation.

The tactile sensor was developed and manufactured during a research seminar (5CP) by Christian Betschinske, supervised by the author. An earlier study on a related sensor technology (FingerVision) was conducted with Alymbek Sadybakasov, yielding into a Master thesis supervised by Boris Belousov and the author. The control algorithms and the robot learning for the sensor were implemented during teachings in the Integrated Project (2 semesters) 'Architectural Assembly with Tactile Skills: Simulation and Optimization Students' by Tim Schneider and Jan Schneider, supervised by Boris Belousov (IAS), Georgia Chalvatzaki

(IAS), and the author.The robot learning approach is currently under further development in the Master thesis: 'Learning Vision-Based Tactile Representations for Robotic Architectural Assembly' by Frederik Wegner, supervised by Boris Belousov (IAS), and Roberto Calandra (Facebook AI Research).

The related publication 'Interfacing Architecture and Artificial Intelligence - Machine Learning for Architectural Design and Fabrication' was published in The Routledge Companion to Artificial Intelligence in Architecture by the author as the primary contributor and Prof. Oliver Tessmann.

Overall, the demonstrations' design was driven by the architectural research questions and objectives defined by the author. The computer science relevant topics such as the correct choice of algorithm and robot learning approach were defined by Boris Belousov and his team in close collaboration with the author.

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