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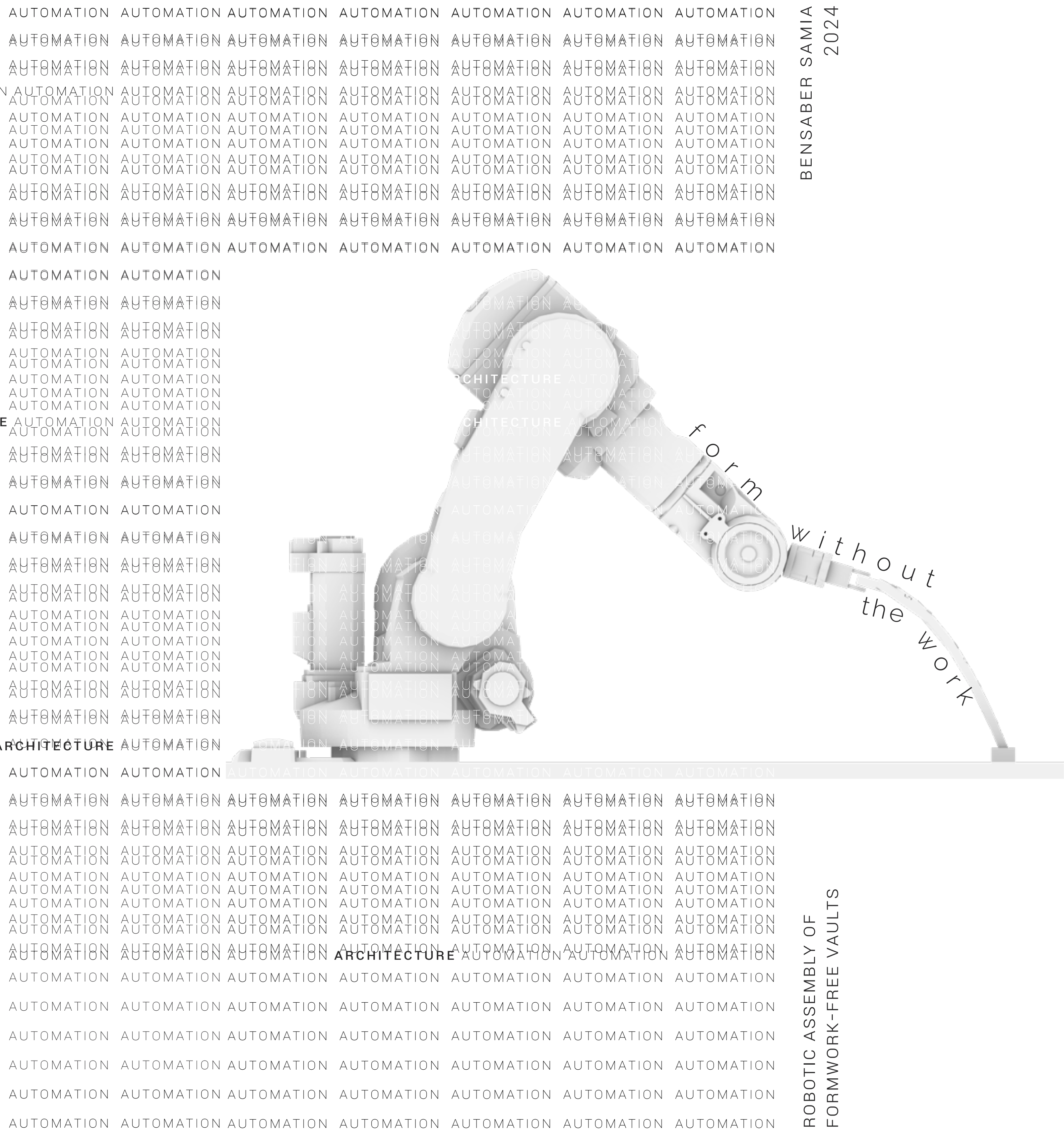

ROBOTIC ASSEMBLY OF FORMWORK-FREE VAULTS

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form without the work

robotic assembly of formwork-free vaults

Degree project for Msc in digital
architecture and emergent futures

Lund University
LTH, Faculty of Engineering
May 2024

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This publication is part of my research work at Lund University, funded by the Swedish Institute scholarship.

abstract

This thesis explores the potential of robotic assembly in constructing formwork-free vaults, aiming to modernize traditional vaulting techniques using robotic automation. The motivation behind it is to enhance buildability, sustainability, and efficiency in construction practices. Key hypotheses focus on the viability of using robotic systems to replicate and improve upon historical vaulting methods without the need for extensive formwork.

During the experimentation phase, manual experiments were conducted to understand the practical challenges of bricklaying and motion planning. Robotic experiments involved form finding, motion planning, and the use of various assembly methods such as binding agents and dry fitting. Key tests included the use of a hanging weight system and a place-and-hold method to evaluate the best use for robotics in creating stable vault structures.

The findings indicate that while the collaborative approach of robot and human interaction shows promise for achieving stable structures with improved accuracy, the research identifies significant areas for improvement, particularly in integrating materiality aspects into the process.

The implications of this work suggest that robotic assistance can play a crucial role in preserving and adapting traditional construction methods for modern applications, particularly in remote or resource-limited settings.

Keywords

Robotic assembly, formwork-free vaults, traditional vaulting techniques, automation in construction, digital fabrication, sustainable building practices, architecture in context, construction efficiency, building processes.

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A. motivation and aim

The construction industry is a significant contributor to global carbon emissions, with the building sector alone responsible for 38% of CO2 emissions related to energy usage and industrial processes (Global alliance for buildings and construction, 2020). Climate change stands as a significant challenge for cities: Cities, responsible for 60-80% of energy consumption and up to 70% of human-induced greenhouse gas emissions, primarily from fossil fuel use, face an urgent call for transformative action. Projections indicate substantial impacts on human development within the next few decades, necessitating immediate and radical measures to limit global warming to 1.5 degrees Celsius well before 2030 (UN-Habitat, 2019).

Constructing with the climate in mind is a timeless practice demonstrating human's ability to intelligently adapt to the environment, providing ingenious solutions tailored to specific spaces and lifestyles (Toussakoe et al., 2023). In hot, arid regions, domed and vaulted roofs were popular in traditional buildings due to their cost-effectiveness and superior thermal performance. They served to protect against wind storms and intense sunlight, reducing heat transfer into the buildings (Hadavand et al., 2008). These historically recognized climatic and cultural building techniques, have seen a decline in usage with the advent of modern standardized construction practices (Egholm et al., 2015).

Shell and vault structures boast remarkable material efficiency—shells capitalize on membrane action, while vaults achieve compression-only form without bending (Veenendaal & Block, 2014). However, their construction often involves the extensive use of temporary or permanent support structures, known as formwork, to maintain the desired shape and bear the load during construction. This reliance on formwork, especially in the case of unique and complex structures, results in custom-made formwork that not only increases material waste but also intensifies labor-intensive processes, impeding construction timelines and aggravating environmental impacts (Hyun et al., 2018). The materials are usually only used once because they are made specifically for a certain curved shape. Additionally, since this process involves a lot of work, these structures are generally not as competitive in the modern building practice where labor is expensive (Veenendaal & Block, 2014).

Many research projects aimed at taming down this shortcoming through various approaches, such as formwork optimization (Hyun et al., 2018), limiting material usage by employing creative materials with a lower carbon print (Bedarf et al., 2023), and adopting a circular economy approach by reusing the formwork material (Pronk et al., 2022). However, as the demand for more sustainable and creative architectural typologies continues to rise, there is a growing need to explore alternatives that not only reduce environmental impact but also enhance construction efficiency.

This thesis investigates the revival of an age-old construction technique, vaulting, as a solution to the challenges posed by formwork-dependent construction methods.

The incorporation of robotics and automation into construction processes has brought about a new range of possibilities. This thesis argues that deploying robotics to construct vaults without requiring traditional formwork can help transform the architectural landscape. The undeniable impact of building process automation on changing architectural topologies and urban landscapes provides motivation for studies on novel construction techniques that can balance design freedom, efficiency, and sustainability.

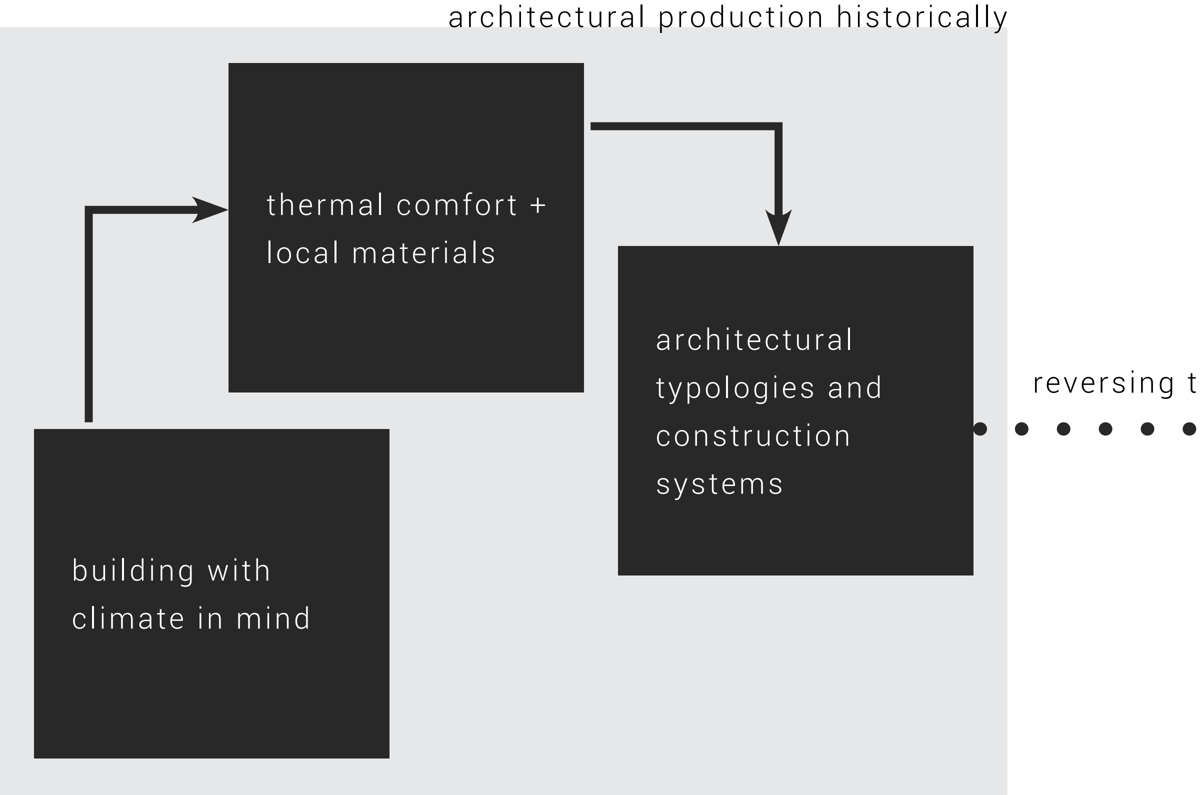


Figure 1: Hypothesis _ source: author

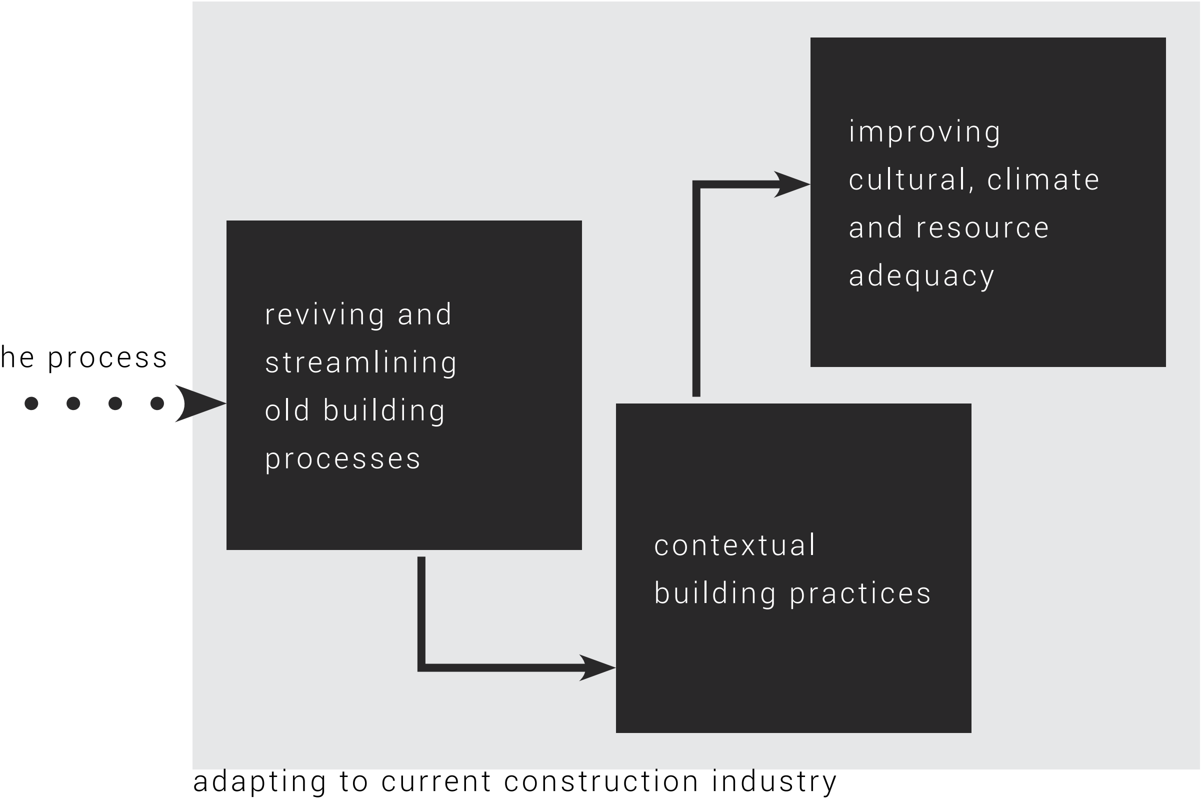
B. hypotheses and research questions

a. Hypotheses

Historical utilization of vaults in architecture, due to their climatic advantages and material adaptability, can be revived by combining historical construction methods and innovative technologies (figure 1). This exploration offers opportunities to develop simple operational methods while saving on formwork, therefore presenting a viable and sustainable solution to the environmental and efficiency challenges posed by current construction practices.

Automated building processes and by-passing formwork offer efficiency gains in time, cost, and human resources. Beyond these benefits, it presents a sustainable opportunity for preserving building know-how, as scripts have a longer life expectancy than individuals.

The automation of vaulting has the potential to evolve into a computational system capable of adapting to various shell shapes. By using a consistent and adaptive logic for computation, fabrication,



and assembly, this automated approach could facilitate widespread adoption of this building technique by transforming formwork-less vaulting into a readily deployable solution.

b. Research questions

How can robotics be effectively integrated into the construction process to eliminate the reliance on traditional formwork in vault construction, considering historical precedents and technological advancements?

How can we mitigate economic and logistical challenges that may arise in adopting robotic vault construction, to ensure the feasibility of this approach in contemporary construction practices?

What parts of the vaulting practice do we benefit most from automating? And what challenges does the human X robot collaboration present in this framework?

01

theoretical

framework

. A. the vaulting practice

a. Advantages and features

Vaulted masonry structures are among the simplest and most elegant solutions for creating curved shapes in building construction. These structures have been a subject of interest since antiquity, with large, non-convex examples like Gothic cathedrals demonstrating their timeless appeal and structural ingenuity (Vouga et al., 2012). The continuous interest and research into vaulted structures today highlight their enduring relevance and versatility.

Shell and vault structures can be extremely materially efficient. Shells incorporate membrane action, while vaults achieve efficiency through the total avoidance of bending in compression-only forms (Elgholm et al., 2015). This compression-only nature ensures that vaults do not bend under pressure, making them inherently strong and durable. This efficiency reduces the need for additional support materials, minimizing waste and lowering construction costs. In addition, vaulting is particularly effective in covering large areas without the need for internal supports and has been historically used as such (Faghih et al., 2009). This ability to span wide spaces unobstructed makes it ideal for free-plan demanding structures such as places of worship and modern sports facilities.

Vaulting holds significant cultural and aesthetic value. Historically, vaults have been used in iconic structures worldwide, from Roman aqueducts to Islamic mosques. These structures are not only functional but also carry immense cultural significance.

Furthermore, vaulting's adaptability to various materials allows for the use of locally available resources, which can reduce transportation costs and environmental impact. This flexibility means vaults can be constructed using diverse materials such as stone, earth bricks, or wood, which ties the construction process to local craftsmanship traditions. This adaptability encourages the exploration of local building materials and techniques, fostering a deeper connection with the surrounding environment and culture. This connection to craftsmanship presents excellent opportunities for human-robot collaboration.

Vaulted structures offer excellent thermal comfort, particularly beneficial in hot climates. The self-shading shape of a vault minimizes solar radiation, keeping the interior cooler (Reda et al, 2024). The geometry of the vault promotes natural ventilation; hot air rises and can exit through ventilation openings, while the increased wind velocity due to the curved shape enhances airflow (Faghih et al., 2009). These properties reduce the need for artificial cooling, making vaulted buildings more energy-efficient and comfortable for occupants. Domed roofs, common in Middle Eastern architecture, are known for their ability to reduce heat gain and provide passive cooling effects, enhancing the thermal sensation of occupants (Faghih et al., 2011).

The thermal performance of vaulted roofs contributes significantly to energy efficiency. Domed roofs can act as thermal buffers, reducing energy loss and maintaining comfortable indoor temperatures. These structures are particularly effective in climates with hot summers and cold winters, where their geometry and materials help regulate internal temperatures (Heidari et al., 2021). The use of vaulted structures can thus lead to more sustainable and energy-efficient buildings, aligning with contemporary goals of sustainable urbanization and energy conservation.

b. Formwork in vaulting

Vaulting often relies heavily on formwork to achieve stability during construction. This reliance stems from the fact that the structure does not reach its full stability until it is completely assembled (Elgholm et al., 2015). As a result, formwork, or falsework, becomes essential to maintain the geometry and provide support until the vault is self-supporting. The production of formwork, however, induces significant costs in terms of materials, time, and (Elgholm et al., 2015). This is a major impediment to the feasibility of constructing architectural shells and free-form vaults, leading to their avoidance in many contemporary projects (Deuss et al., 2014).

Historically, various methods have been employed to support domes and vaults during construction. Elaborate timber-frame structures have traditionally guided the formation of vaulted structures. These timber frameworks often included additional sub-structures for intermediate points of support, as detailed by Fitchen (1961) and Fallacara (2012). Additionally, tensioned ropes were sometimes used in medieval vault structures to hold arch blocks in place, as noted by Fitchen (1961). Contemporary techniques, such as the Arch-Lock system (Drew, 2013), use chains in the construction of arches and vaults, reflecting an evolution from historical practices but still facing challenges in cost and practicality.

Deuss et al. point out that modern methods continue to rely on dense formwork to support all blocks until the entire construction is complete. This method, while effective for small-scale models, poses significant challenges for large-scale structures. Dense formwork capable of sustaining the weight of large stone blocks is often too expensive and impractical. Moreover, the removal of formwork demands technically complex and costly solutions to prevent structural failures during force redistribution (Deuss et al., 2014).

Furthermore, different materials interact with formwork in unique ways. In thin tile vault construction, the use of lightweight tiles combined with mortar tensile strength can reduce the need for extensive formwork. However, this approach is not applicable to heavier masonry blocks where the mortar strength is negligible. In such cases, dense support structures are necessary during intermediate construction stages to ensure stability (Deuss et al., 2014).

The introduction of new digital tools into the architectural design process has profoundly impacted architectural practice. This development has shifted the design paradigm from a traditional representational process to a complex, generative digital process based on simulation and evaluation. This shift has led to the emergence of parametric architecture and related design approaches such as generative design and performance-based parametric design. In these approaches, architects no longer create forms manually but define parameters and control procedures to generate forms through a process known as "form-finding" (Ramadan et al., 2024)

In an interesting analysis of the success in scaling parameters in different industries, Buchli et al. identify a pattern in examining the industries that have benefited most from automation and recent advances in production technology: industries that can move workpieces around have reaped the most benefits. This is because keeping equipment fixed in a well-defined environment offers several advantages: It simplifies many complex engineering problems, such as ensuring precise and repeatable feeding of workpieces to machines. Additionally, fixed machines can be shielded behind safety cages, reducing the need to take into account unexpected circumstances such as human interference.

However, this approach has significant limitations, particularly for industries that produce large final products that cannot be efficiently moved around a factory and require numerous additional assembly steps at their final location. Examples include shipbuilding, aircraft manufacturing, energy infrastructure construction, and civil engineering and building construction. These industries have benefited far less from automation because their manufacturing processes and logistics closely resemble those from many decades, if not centuries, ago. A projection of this can be made on construction (Buchli et al., 2018).

One promising approach to addressing this challenge is the use of Augmented Reality (AR) technology to enable a collective construction process. Atanasova et al. used this technology to distribute and guide manual assembly tasks for multiple users, enhancing the efficiency and accuracy of on-site construction. As construction processes are still vastly undertaken by humans, AR can help them become more collaborative and adaptive, allowing for greater flexibility and responsiveness to the dynamic conditions of the construction site (Atanasova et al., 2021).

c. Case study - old vaulting techniques

Throughout the history of construction practices, different civilizations have employed varied materials and configurations to minimize the reliance on formwork in constructing vaults depending on local contexts, available resources, and historical building practices. While research into masonry vault construction has conventionally categorized studies based on materials, trades, or historical eras (López-Mozo, et al. 2021), our study will focus on the assembly process itself.

As explained by Deuss et al., contemporary freeform shells still utilize traditional methods such as cutting wood panels according to specific section curves; while historically, many civilizations have come up with ingenious systems to get around this technical shortcoming. Whether it's tensioned elements, creative temporary support or thin lightweight material, there is a lot of knowledge to capitalize on and use.

The aim of this chapter is to examine the relationship between form and the necessity for formwork in vault construction, and detect the crucial factors for that, whether it be decisions concerning the overall design, arrangement, bonding techniques, or specific shapes of elements. This will hopefully allow us to extract valuable knowledge of principles and practices applied then to bypass formwork, that could now be adapted and/or implemented into digital processes for manufacturing and assembly.

- *Gothic – the stone weighted rope*

The first construction principle for vaulting to be studied is the stone weighted rope, reported by Lassaux while observing the erection of Gothic vaults in Vienna. This system is mainly known to us through John Fitchen, through his book "The Construction of Gothic Cathedrals: A Study of Medieval Vault Erection".

It is a creative solution that tries to minimize the use of formwork, by using a system that only necessitates timber frames on the outlines of the vault being constructed (Figure 2.C). A few ropes are in turn tied to these frames along the section of the vault, with heavy stones tied to their free end. These are used to hold the stones in place by pushing them against the bed-joint, preventing them from sliding (Figure 2.A). Multiple ropes can be used as a time to hold a whole row in place, and cords can be easily moved to clasp a new block (Figure 2.B).

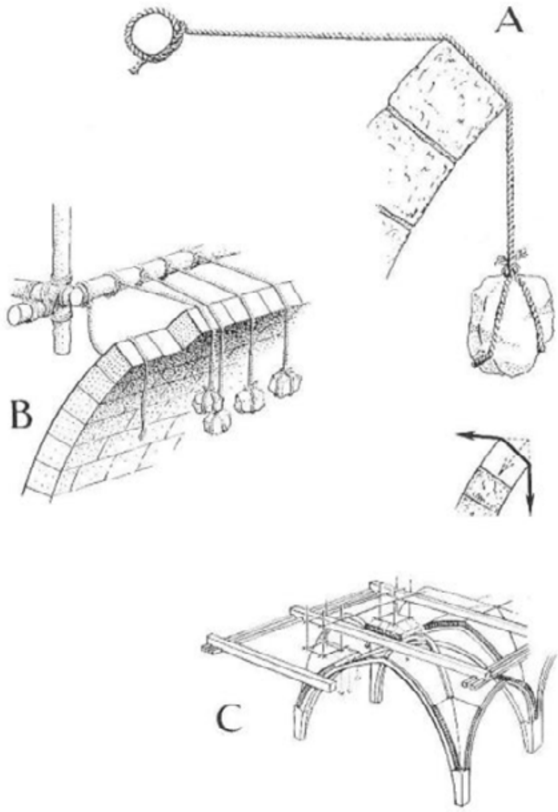


Figure 2: The stone-weighted rope device for erecting Gothic vaults
source: (Fitchen, 1981)

This specific case has some strong advantages that are worth investigating. First and foremost, among these benefits is the configuration's capacity to drastically lower the need for formwork. This cut has the potential to result in significant improvements to building methods' time and cost efficiency. The technique in question is also notable for its high degree of sustainability since the formwork is generally reusable. This is because none of the formwork components are tailored to the vaults they support, which minimizes material waste and maximizes resource efficiency.

Additionally, this system offers a great design flexibility: rather than being restricted by the construction's shape or structure, it acts as a flexible exterior support mechanism. This feature enables for innovative design execution without formwork constraints, in addition to providing architectural flexibility.

Furthermore, one important aspect that offers great potential for future advancements is its inherent simplicity. It offers a potential for abstraction which facilitates adaptability to novel building techniques, especially robotic assembly techniques. By embracing this simplicity and potential for abstraction, we benefit from the potential of fine-tuning and augmenting its qualities further, thereby enhancing its overall efficiency in construction practices.

- *Inca – the wedge-stone*

The Inca masons were adept of a special technique for building with stones which produced intricate constructions and

Figure 3: Sacsayhuamán, part of the Inca Ruins in Cusco _ source: (Delso, 2015)

exact alignments. Their specialty was a practice that formed long-lasting stone structures with classic craftsmanship; which is rooted in sequential, rule-based, and flexible procedural logics, is in line with contemporary ideas regarding integrating computation and fabrication , as studied by Clifford and McGee. These factors manifest in multiple aspect of the building process: first in the planning of the global composition, then in the stone shaping so the bed matches the rock to be positioned, and finally to calculating the wedge as a trade-off between having enough space to allow for joining and flexibility, and keeping it limited to not affect the overall stability and alignment.

One of the crucial practices employed by Inca stonemasons was the use of hammerstones for stone dressing, resulting in three distinct geometric conditions—face, edge, and wedge. Stones were drafted to create an approximate profile. The stone is then flipped and progressively dressed from the face, achieving the rounded face characteristic of Inca stonework. This rounding is not only a result of the

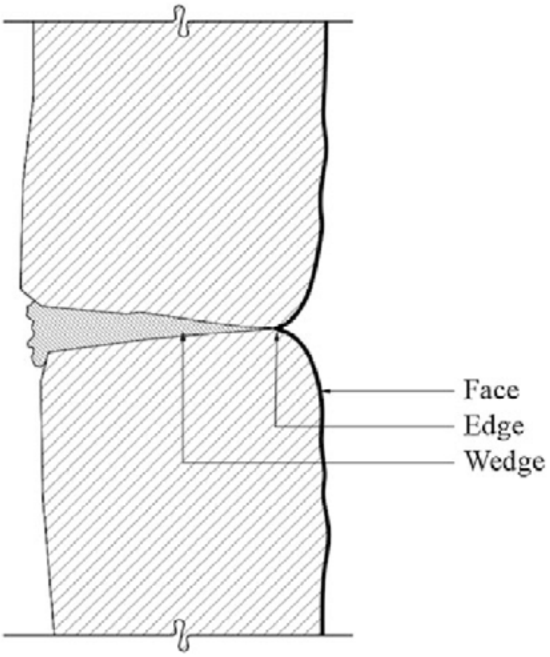


Figure 4: Section through an Inca assembly revealing the three geometries Source: (Clifford et McGee, 2015)

carving method but also serves to disguise subtle misalignments that occur during assembly. The drafting and dressing define the cleft sides, rounded face, and the most critical element—the edge. This edge, although clearly defined, is formed at an oblique angle and serves as the only point of alignment between the stones, allowing negative corners to be filled with crushed stone, thus creating an assembly that in appearance does not require mortar.

The piedra-cuña (wedge-stone) technique, introduced by Harth-terré, allowed Inca masons to create the illusion of assembly without mortar, primarily through the strategic use of the wedge method, which requires less cutting and adjustment than the full-contact stone alignment, and produces similar visual results while favoring one-sided rendering, thus hiding the rubble at the back of the stone.

Contrary to common assumptions, Inca walls contained mortar, although concealed by wedge techniques on the visible side. However, the Inca approach differed significantly from conventional mortar techniques. While conventional masonry relied on layers of mortar to align stones using viscosity and precision adjustments, the Inca method focused on precise carving, enabling stones to dry align before setting.

The interest of this construction principle for this study lies in the high precision factor in various steps of the process: in the stone dressing method which is even easier to achieve using robotic fabrication; in the assembly method (less mortar for less error margin) which is compatible with robotic assembly. Additionally, this method's reliance on robust yet heavy materials contributes significantly to its durability. As previously highlighted, its adaptable and rule-based logic aligns well with modern computation and fabrication methodologies, offering substantial potential for innovating a more efficient vaulting system (Clifford et McGee 2015).

Figure 5: A series of Inca constructions that reveal the voided wedge between stones _ source: (Clifford et McGee, 2015)

- *Catalan – bòvedas tabicadas*

Catalan vaults, also known as bòvedas

Figure 6: The attic from La Pedrera or Casa Milà by Gaudi, made of catalàn vaults
source: (Jordi Play, s.d.)

Figure 7 : Catalàn vaults in the Mapungubwe Interpretation Centre
source: (Fagan, 2010)

tabicadas, were widely adopted in Catalonia in the 19th century and were used by many renown architects. The Catalan arch technique is characterized by the unique properties of the use of fast-setting mortars and their considerable shape-dependent load-carrying capacity, which ensures substantial elasticity despite their low thickness. Those vaults are essentially curvilinear structures consisting of successive "rasillas" - tiles measuring 15×30×1.5 cm - placed evenly and reinforced according to the base layer ("sencillo") with chalk paste, followed by subsequent layers using cement and lime mortar ("doblado") (Benfratello, Palizzolo, et al. 2010).

This architectural method is based on achieving a low thickness - compared to the other two dimensions - by alternating the length of the brick with layers of mainly plaster mortar.

The vaults of Catalonia are of great importance in literature, and many studies mainly examine their historical and technical aspects. In their paper "Tradition and modernity of catalan vaults: Historical and structural analysis"; Benfratello, Caiozzo, D'Avenia and Palizzolo gathered from Palermo's historic center several samples extracted from walls constructed using the bòvedas tabicadas technique, varying between two, three, or four layers of bricks. They performed an assessment of the compression characteristics of the aforementioned samples. Additionally, they conducted suitable petrographic and chemical examinations on mortar samples.

During their tests, they observed that cracks usually occur where the thickness of the mortar decreases and at the interface between bricks and mortar. Further analysis shows that the behavior of the two-layer samples is stiffer compared to the average of the four-layer samples, but weaker than the average of the three-layer (without plaster) samples. This behavior is due to the layering of the material.

The way these vaults hold up, along with the characteristics of the bricks and mortar, significantly relied on how the construction was carried out and the skill level of the workers who laid the materials. As more layers were added, a marked increase in irregularities —geometric, technological and mechanical— was noticed, which had a considerable impact on the final results (Benfratello, Caiozzo, et al. 2012). This could explain why the 2-layer sample had more stiffness than the 4-layer one.

This technique presents many advantages that can be beneficial for robotic construction processes, such as the freedom in form, the lightness and slimness of the shell, and the fact that the structural soundness depends more on the execution technique and material than it does on the force equilibrium generated by a specific form.

B. automated building processes

a. Industrialization, mass customization and automation in construction

The introduction of new digital tools into the architectural design process has profoundly impacted architectural practice. This development has shifted the design paradigm from a traditional representational process to a complex, generative digital process based on simulation and evaluation. This shift has led to the emergence of parametric architecture and related design approaches such as generative design and performance-based parametric design. In these approaches, architects no longer create forms manually but define parameters and control procedures to generate forms through a process known as "form-finding" (Ramadan et al., 2024)

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b. Automating the vaulting practice for enhanced buildability

In the realm of architectural design and engineering, there exists a delicate trade-off between various design constraints, and structural equilibrium. For projects based on vaulting, navigating this trade-off involves considerations of angles that allow non-reliance on formwork, optimization of material usage, motion planning, and ensuring structural stability to prevent mishaps during construction.

To address these challenges, different digital form-finding strategies have been developed, each offering unique advantages and insights into the design and construction process. Veenendal and Block have developed in their paper a holistic framework for comparing form-finding methods. They categorize existing form-finding methods can be into three main families: force density methods, dynamic relaxation methods, and stiffness matrix methods. These methods play crucial roles in determining the shape of form-active structures, which means that form follows force, as the final shape cannot be designed beforehand (Veenedaal et al., 2011).

Surface rationalization and decomposition techniques can further enhance the buildability of vaulted structures by reducing construction costs and optimizing block tessellation. These approaches leverage computational tools to generate construction sequences for masonry structures composed of arbitrarily shaped blocks, streamlining the assembly process (Deuss et al., 2014).

Augmented Reality (AR) technology presents an exciting opportunity to revolutionize traditional vault construction methods. An example for that is the InnixAR project: by overlaying holograms onto physical reality, AR can guide on-site construction, eliminating the need for physical molds, guides, and formwork. This innovative use of AR not only saves time and materials but also enhances precision and monitoring throughout the construction process (DesignBoom, 2023).

Furthermore, the integration of AR technologies into digital fabrication workflows opens up new possibilities for intuitive and spontaneous design decisions during the building process. By leveraging people's cognitive abilities alongside explicit machine intelligence, digital fabrication can become more flexible and responsive to the dynamic conditions of construction sites (Atanasova et al., 2021).

c. Case study - robotic adaptation of vaulting techniques

Many contemporary projects using digital design, robotics, and assembly have undertaken the challenge of using formwork in vault construction. These projects utilize innovative methods, emerging technologies, advancements in materials, and interdisciplinary collaborative models (Lindner, 2020), contributing to the continuous evolution of creative solutions and fostering a dynamic landscape within the construction industry.

The concept of 'digital stereotomy' was first introduced in 2000 in Italy by Politecnico dei Bari and has since been widely discussed in the academic world. It is based on a deep understanding of traditional building techniques combined with the principles of stereotomy, combined with proficiency in modern infographic design technology for building structural elements. This approach explains the applications of load-bearing stone to modern architecture, highlighting the relationship between traditional practices and technological progressions (Fallacra et Gadaleta 2019).

Computational design tools, prototyping, additive manufacturing, newly developed construction materials or newly acquired understanding of old ones, mass customization, robotics for fabrication and/or assembly; are some of the many tools offered to today's designer to find creative solutions to a design problem. This multitude of angles to tackle the design task has allowed the emergence of different processes and results to a new way to construct vaults: integrating these technologies with a deep understanding of how compressive forces influence structures enables more efficient building practices (Fearson 2016).

In the following chapter, we will take a look at a few contemporary projects that focused on harnessing the potential of traditional building technique and/or modern design, fabrication and construction technologies, to come up with creative vaulting systems. This selection could have englobed many of the afore-mentioned techniques and strategies, but we will mostly focus on the ones that align with the digital stereotomy philosophy.

- *Digital Inca*

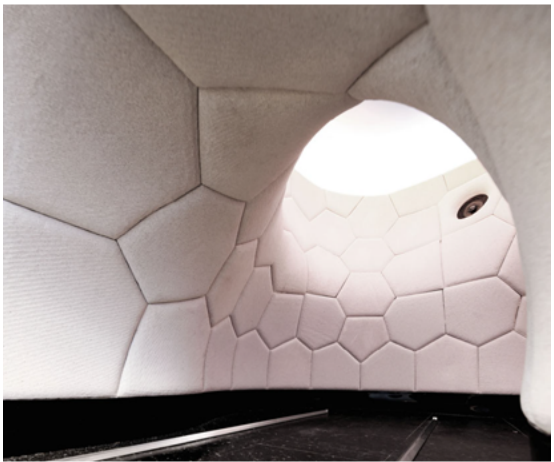


Figure 8: The 'round room' by matter design and quarra stone _ source: (Clifford et McGee, 2015)

This study by Clifford and McGee explores the potential of learning from the Inca wedge method combined with the Guastavino method (inspired from the Catalan vault) to enhance the creation of modern shell structures and apply it to carve Autoclaved Aerated Concrete (AAC). The lower density of AAC allows for larger panels, resulting in faster installation. The aim from combining these three techniques is to construct free-form shell structures without the need for templates or formwork, which are commonly used in construction. Their process went as follows:

GEOMETRY (Figure 9):

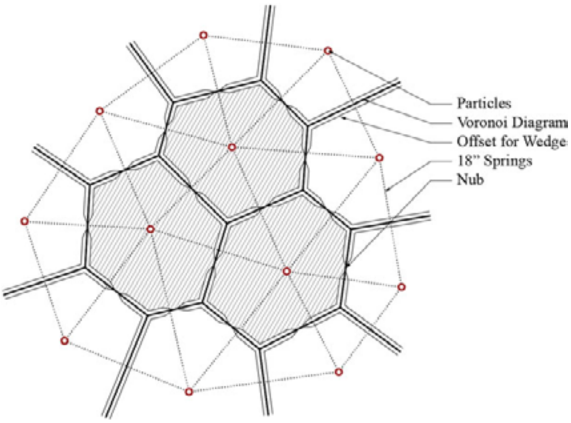


Figure 9: A 2d diagram of the unit discretization, wedge offset, and indexing nub geometries _ source: (Clifford et McGee, 2015)

1. Outlining a free-form geometry;
2. Distributing points evenly through a particle-spring system;
3. Three dimensional Voronoi generation;
4. The center of each Voronoi defines a normal, which generates a fabrication face;
5. The face is offset to create the back-face, which is modified to generate the wedge;
6. Ruled surface geometry between the front and back, and refinement of the units.

STRUCTURAL COMPUTATION (Figure 10):

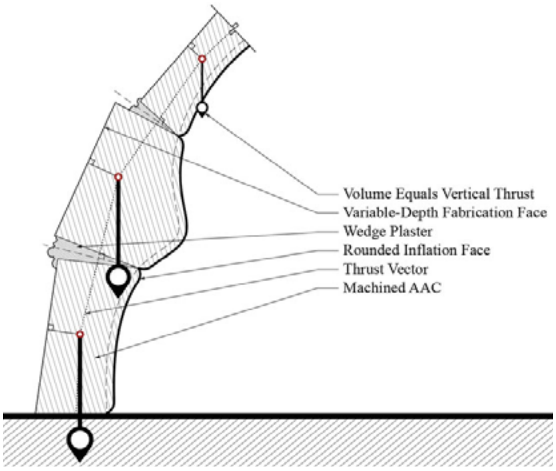


Figure 10: A section revealing the wedge method as well as the geometries of the variable depth back face that redefined the volume in order to ensure the thrust network falls within the depth of material _ source: (Clifford et McGee, 2015)

1. Using the volume of each unit to inform another particle-spring system to verify whether the thrust-network may fall within the thickness of the material;
2. Using the depth dimension of the unit below to determine how heavy/light the unit should be;
3. Adjusting If a specific node appears too elevated, by adjusting the back face nearer to the initial offset, thereby decreasing both the volume and mass of the structure.

ASSEMBLY (Figure 11):

1. Gluing the first course wedges to the base for a strong foundation;
2. Dry fitting the units to their neighbors;
3. Holding the units in place from the front

(installer 1);

4. Placing one quick-dry mortar bead to fix the unit (installer 2);
5. Squeezing the plaster from behind to fill the wedge after the first installer lets go of them (the mortar is rather liquid to obtain the correct viscosity);
6. Letting the misalignment tolerance build up to a visible level (3mm), then using the Inca dry fitting method for a precise fit

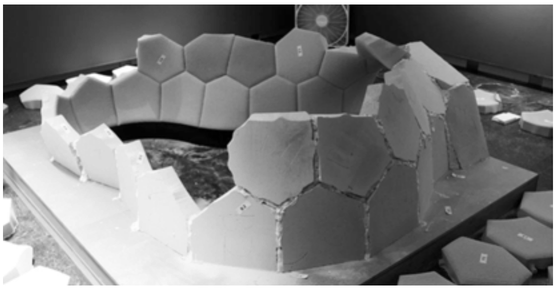


Figure 11: The first couple courses of the 'round room' assembly process _ source: (Clifford et McGee, 2015)

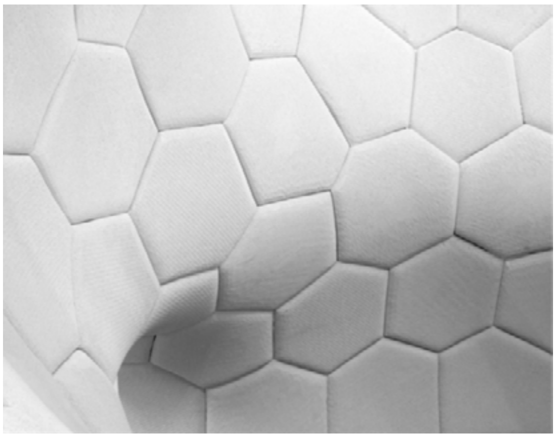


Figure 12: Image of the final visible assembly of the 'round room' _ source: (Clifford et McGee, 2015)

- *livMatS Biomimetic Shell*

The livMatS Biomimetic Shell represents a joint research project from two Clusters of Excellence: Integrative Computational Design and Construction for Architecture (IntCDC) at the University of Stuttgart, and Living, Adaptive, and Energy-autonomous Materials Systems (livMatS) at the University of Freiburg, exploring a combined approach to design and construction aimed at creating sustainable architecture. This is the description of the design, fabrication and assembly processes as described on the ICD website:

GEOMETRY:

The design of the building's outer shell is inspired by the plate skeleton of sea urchins. It took the segmental shell construction a step further, creating a highly insulated structure for year-round and continual use.

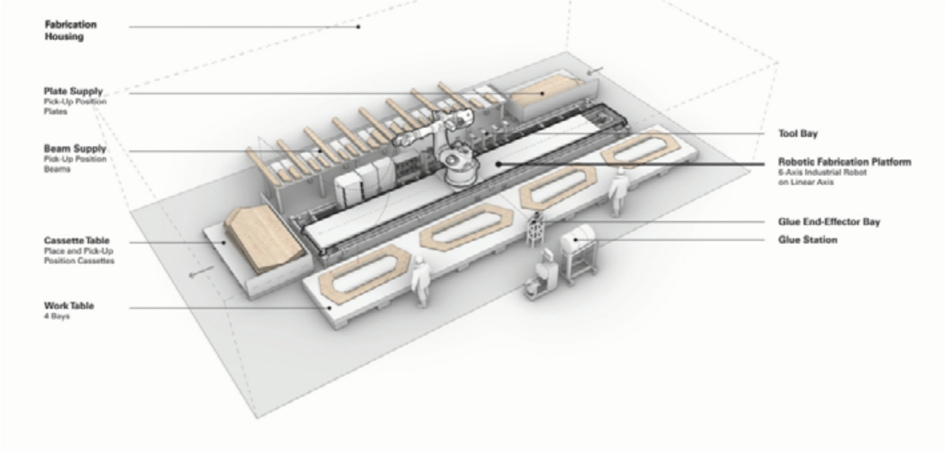


Figure 13: Diagram representing the fabrication station _ source: (Institute for Computational Design and Construction, 2023)

FABRICATION:

Figure 14: The heavy duty robot assembling a cassette _ source: (Institute for Computational Design and Construction, 2023)

The innovative timber structure covers an area of 200m² and consists of 127 different hollow cassettes, linked using cross-screwed joints. When assembled, the curved wooden shell serves as a structure, spanning 16 meters freely, but weighing just 27 kg/m² of the shell surface.

Each hollow cassette is crafted from three-layer spruce boards and spruce edge beams, acting as building modules. They are put together by a heavy-duty robot, digitally programmed wooden parts are glued, milled, drilled, and then cut with precision using a saw blade, with accuracy down to sub-millimeter range.

ASSEMBLY:

Assembly involves a robotic spider crane using a vacuum gripper to pick up components, placing them precisely and holding them in place until they are screwed together. Another spider crane equipped with a specialized screw device

Figure 16: Picture of the real-life assembly process _ source: (Institute for Computational Design and Construction, 2023)

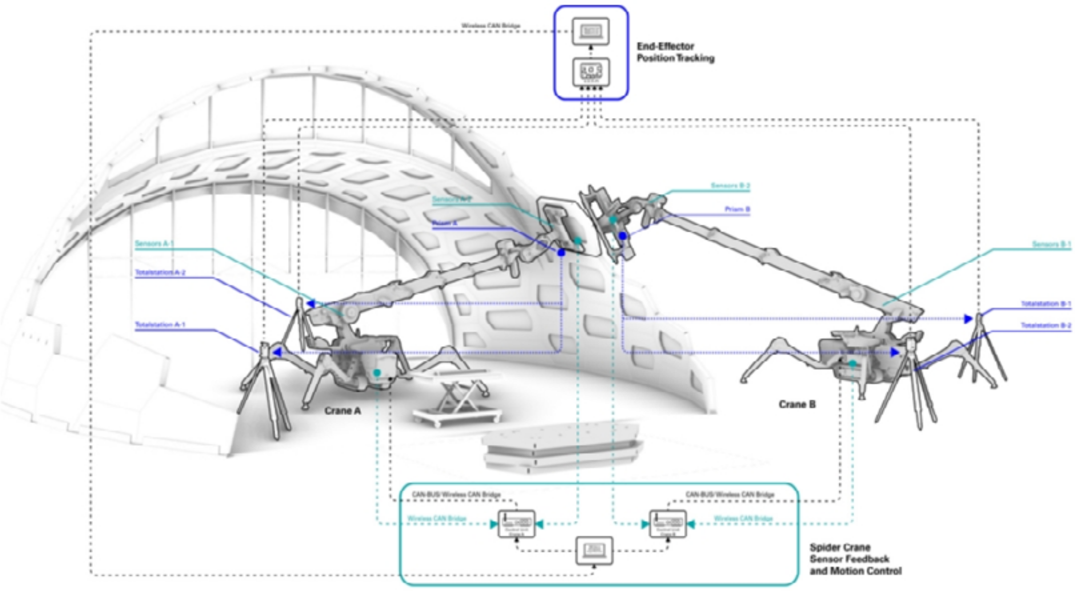


Figure 15: Diagram of the robotic assembly setup, with two co-operating robots source: (Institute for Computational Design and Construction, 2023)

automatically inserts all the screws. For precision, an automated real-time total station network with four total stations was developed to pinpoint the construction robots' locations.

This project was thought integrally using the robotics manufacturing and assembly logic in mind. From the materials used, to the shape and composition of the cassettes, to the joining of the elements, everything was mechanized. It offers many undeniable advantages, such as the possibility for mass manufacturing, very high predictability and precision of the outcome, and a huge potential for time and cost efficiency. However, it is this same precision that might make it difficult to abstract these processes and use them to build with other materials that are less tamable. Additionally, this process being very highly engineered doesn't leave a lot of room for robotic/human interaction, which could make it hard to imagine its integration in the current construction sector which might need a more gradual transition.

c. Self-supporting puzzle

This study by Deuss et al. proposes an innovative construction system for free-form vaults, substituting the predominant dense formwork with a sparse collection of temporary chains to facilitate a gradual construction of the masonry model in

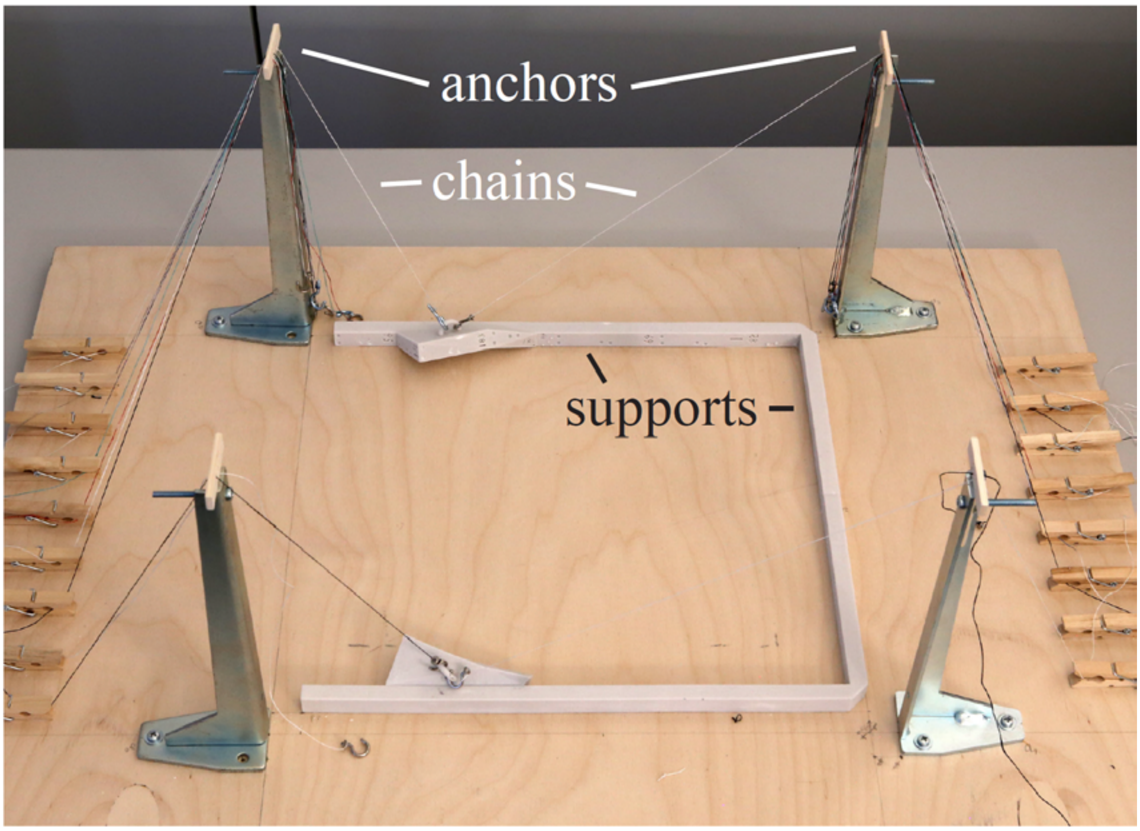


Figure 17: Construction site mock-up _ source: (Deuss, et al., 2014)

stable sections, thereby reducing both the material requirements and construction costs significantly. Self-supporting structures have been historically and presently crucial in architecture due to their beneficial structural characteristics and efficient material utilization. Architects now dispose of new design tools that enable the creation and interactive exploration of self-supporting freeform designs. However, the physical construction of such freeform structures remains challenging, particularly on smaller scales. The current construction processes necessitate extensive formwork during assembly, resulting in remarkably high construction costs for realizations at a building scale. This limitation significantly limits the practical impact of existing freeform design tools (Deuss, et al. 2014).

STRUCTURE COMPUTATION:

This construction method arranges a random group of blocks into a step-by-step construction plan, ensuring each step adds only one block to the structure and maintains valid construction states. From numerous construction plans possible for a set of blocks and anchor positions, the aim is to identify the sequence that minimizes effort. That is evaluated by considering the total number of chains added and removed during the process, which aligns with real-world construction issues: adding or removing a chain demands a significant investment of time and energy, directly impacting construction expenses.

PROTOTYPE:

To showcase the adaptability of this algorithm, a prototype was developed devising a compact self-supporting model using RhinoVault. The algorithm was employed to identify a construction sequence that adheres to the restriction of three blocks supported by chains at any moment. They enforced this criterion by disregarding all construction states wherein more than three blocks were linked to anchors. The construction sequence serves as the solution to the puzzle, facilitating its assembly with four individuals: three to mimic the chain forces and one to insert the pieces.

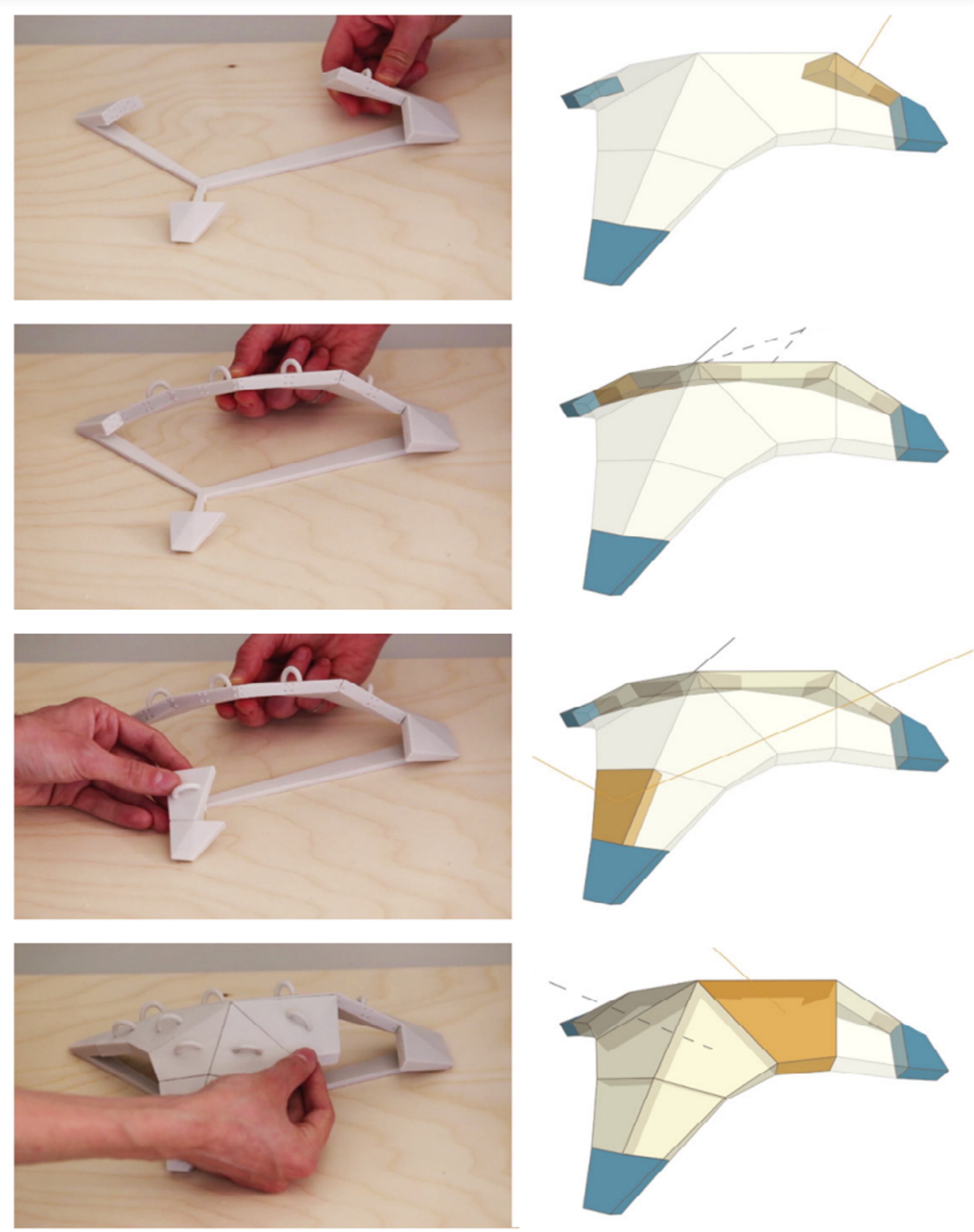


Figure 18: Challenging design physical puzzles calculated via the algorithm _ source: (Deuss, et al., 2014)

02

experimenta

ation and prototyping

A. methodology

Successfully conducting the construction of a vault requires the careful study and fine-tuning of a wide variety of parameters, each impacting the successful completion of the endeavor to different degrees. The conceptual cluster in the figure (pp. 38-39) gathers many of these parameters, establishes their hierarchy and relationships, and identifies some of the key questions for each displayed parameter.

For the purpose of this project, the focus had to be narrowed down to these four aspects:

- Standard/custom bricks
- Assembly medium (dry fit/binding agent/imbrication)
- Assistance of the robot (placing or support)
- Type of formwork

The impact of the remaining aspects of the cluster was considered while engineering the experiments, but they were not the main focus.

From this, an experimentation matrix emerged, which allowed further design of the experiments to conduct. After narrowing down the research area, a few manual experiments were designed to explore certain aspects more swiftly than the computational process allows (placing sequence, binding agents, brick topology). Following this, the geometries were developed computationally to conduct the desired tests, followed by motion planning to test their feasibility in the RobotLab setup.

The software used for this section includes Rhinoceros 3D, Grasshopper, and the Robots plug-in for motion planning.

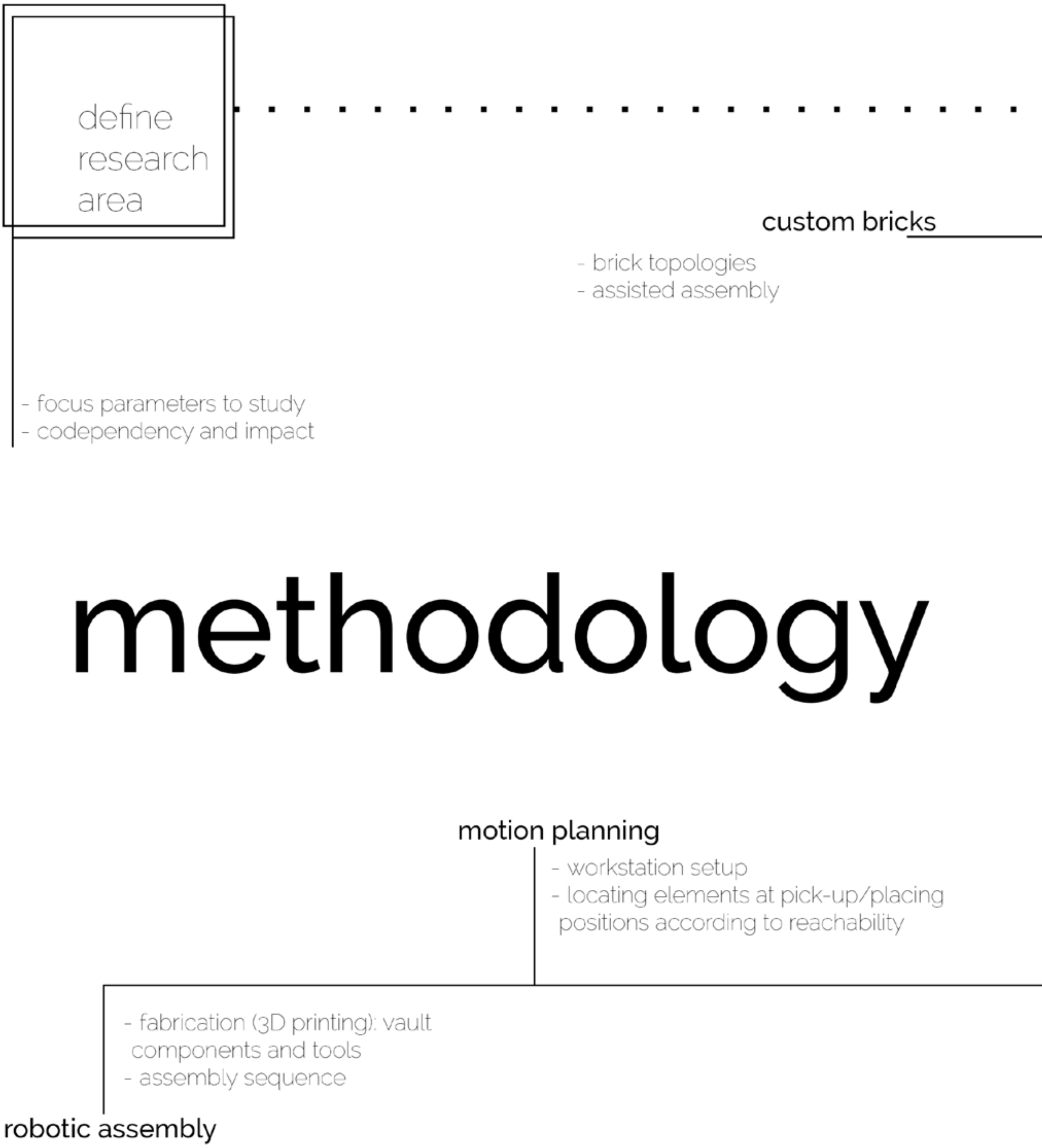
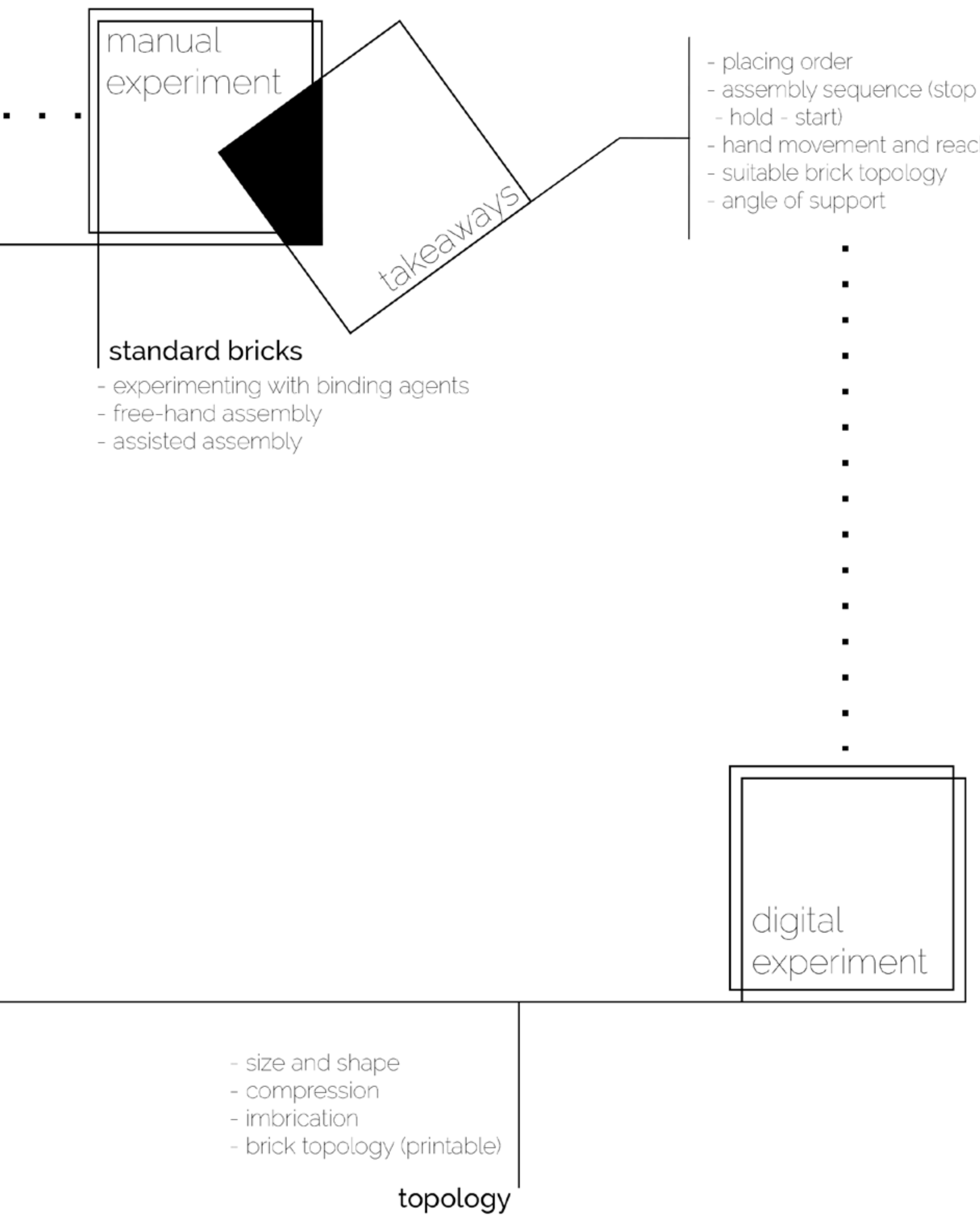


Figure 19: Research methodology breakdown_ source: author



manual
experiment

takeaways

- placing order
- assembly sequence (stop - wait - hold - start)
- hand movement and reachability
- suitable brick topology
- angle of support

standard bricks

- experimenting with binding agents
- free-hand assembly
- assisted assembly

digital
experiment

- size and shape
- compression
- imbrication
- brick topology (printable)

topology

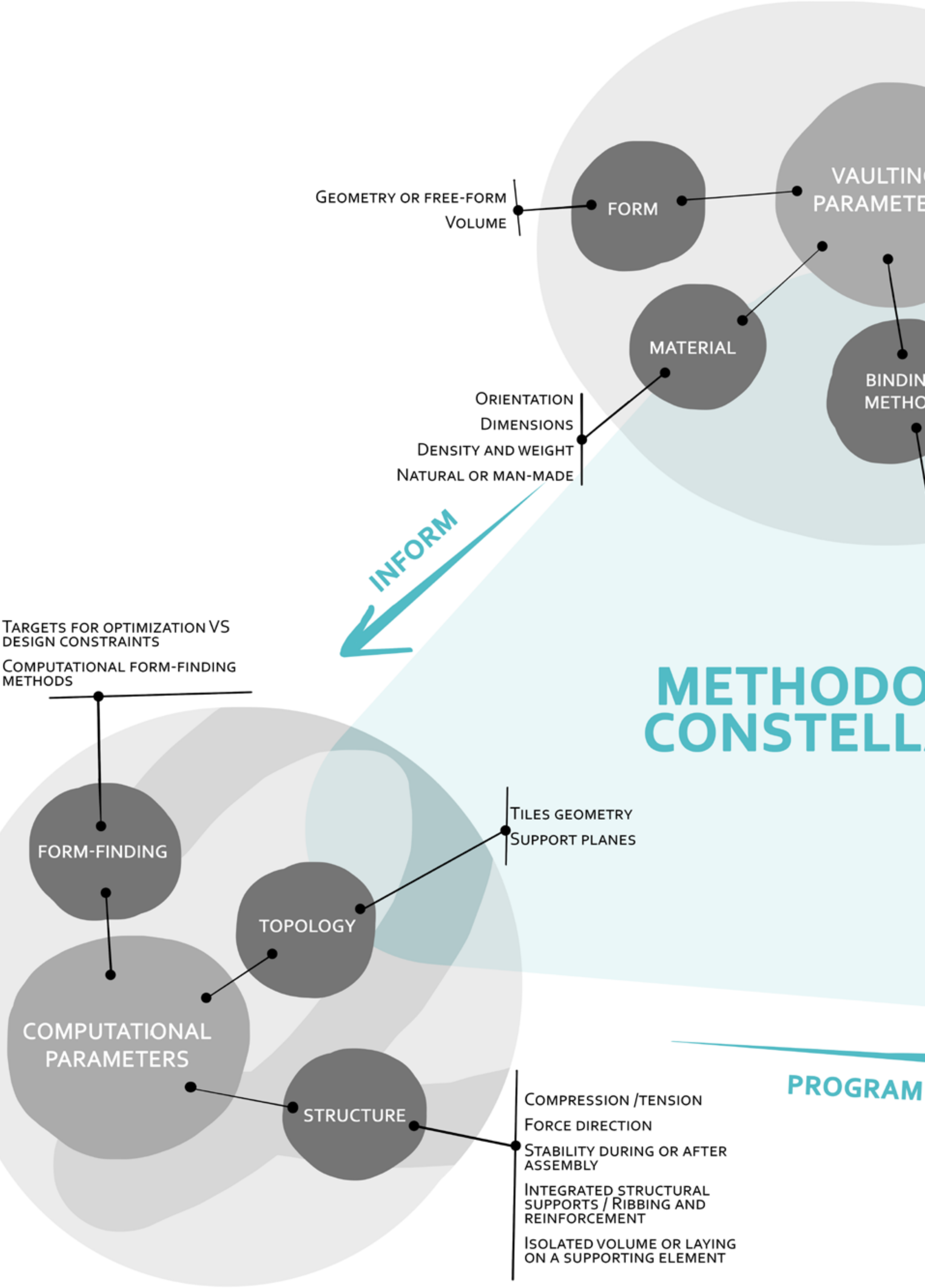
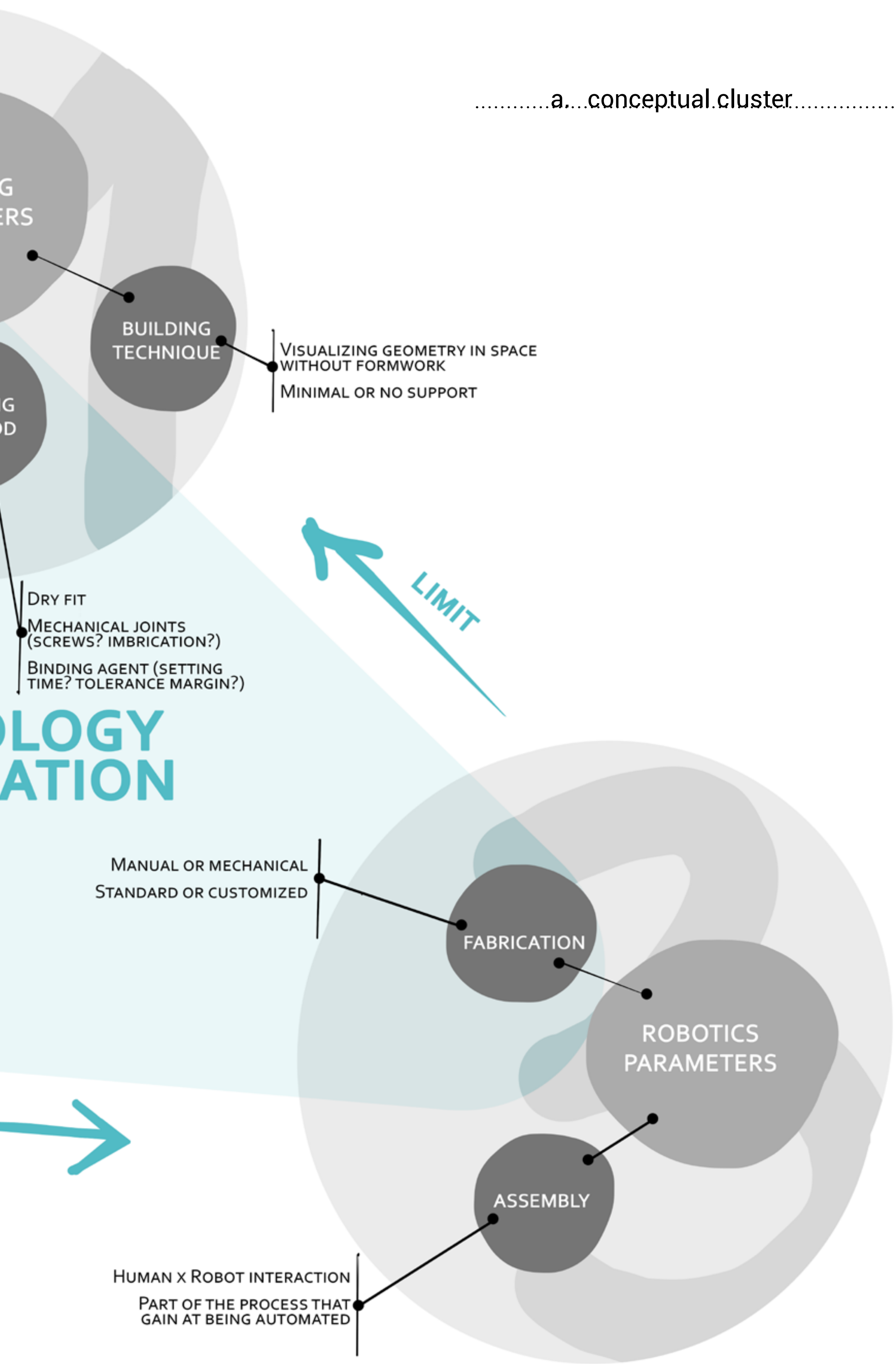
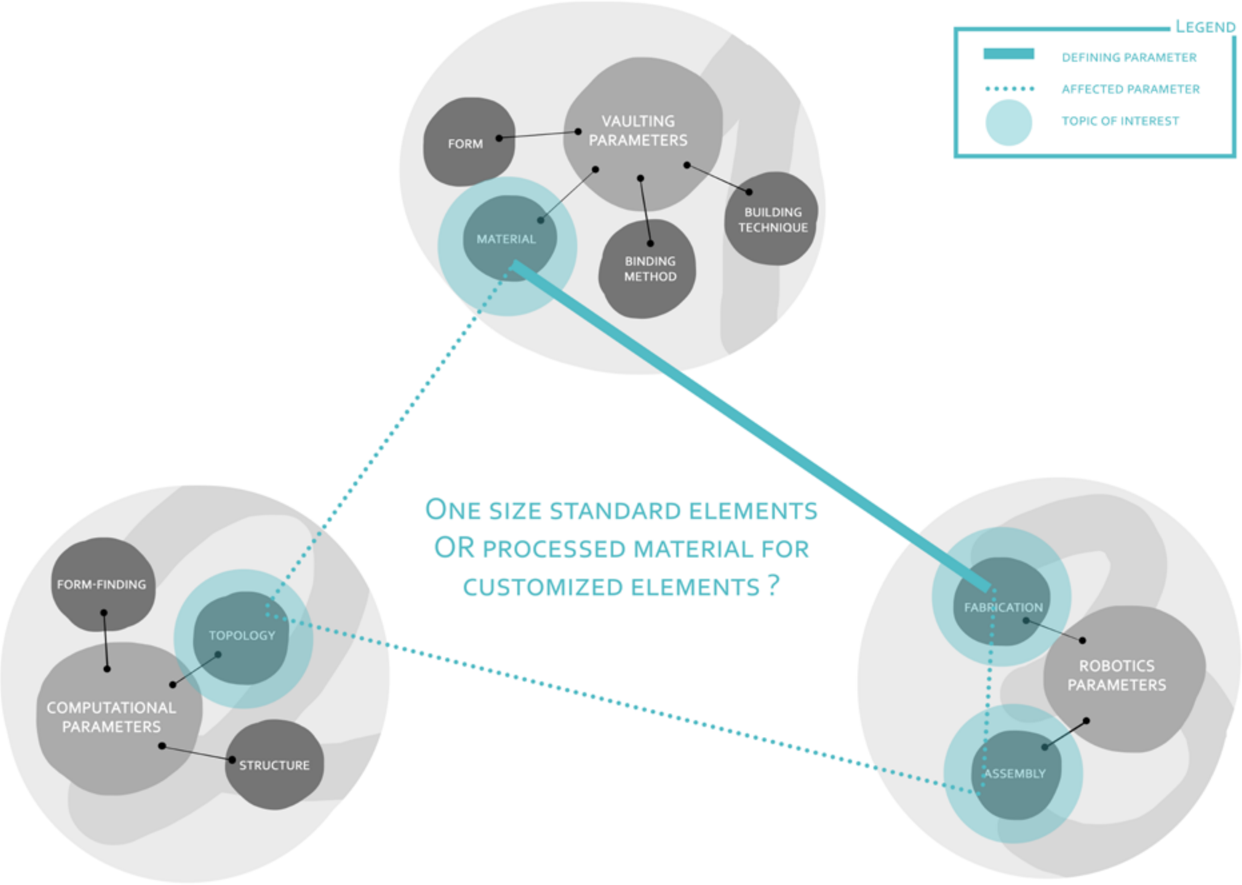
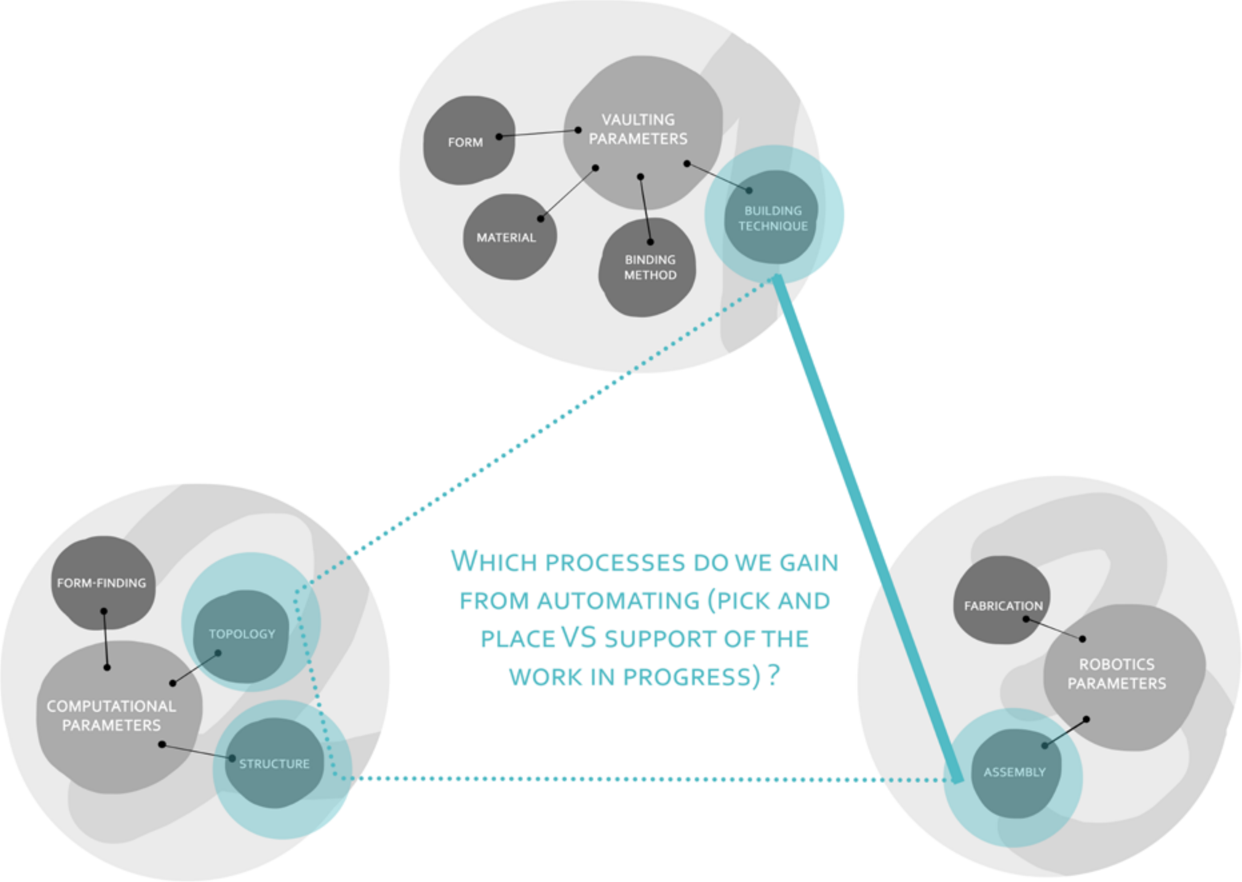


Figure 20: Conceptual cluster combining all the variables impacting on the vaulting process_ source: author


BUILDING TECHNIQUE
VISUALIZING GEOMETRY IN SPACE WITHOUT FORMWORK
MINIMAL OR NO SUPPORT
DRY FIT
MECHANICAL JOINTS (SCREWS? IMBRICATION?)
BINDING AGENT (SETTING TIME? TOLERANCE MARGIN?)
LIMIT
LOGY
ATION
MANUAL OR MECHANICAL
STANDARD OR CUSTOMIZED
FABRICATION
ROBOTICS PARAMETERS
ASSEMBLY
HUMAN X ROBOT INTERACTION
PART OF THE PROCESS THAT GAIN AT BEING AUTOMATED

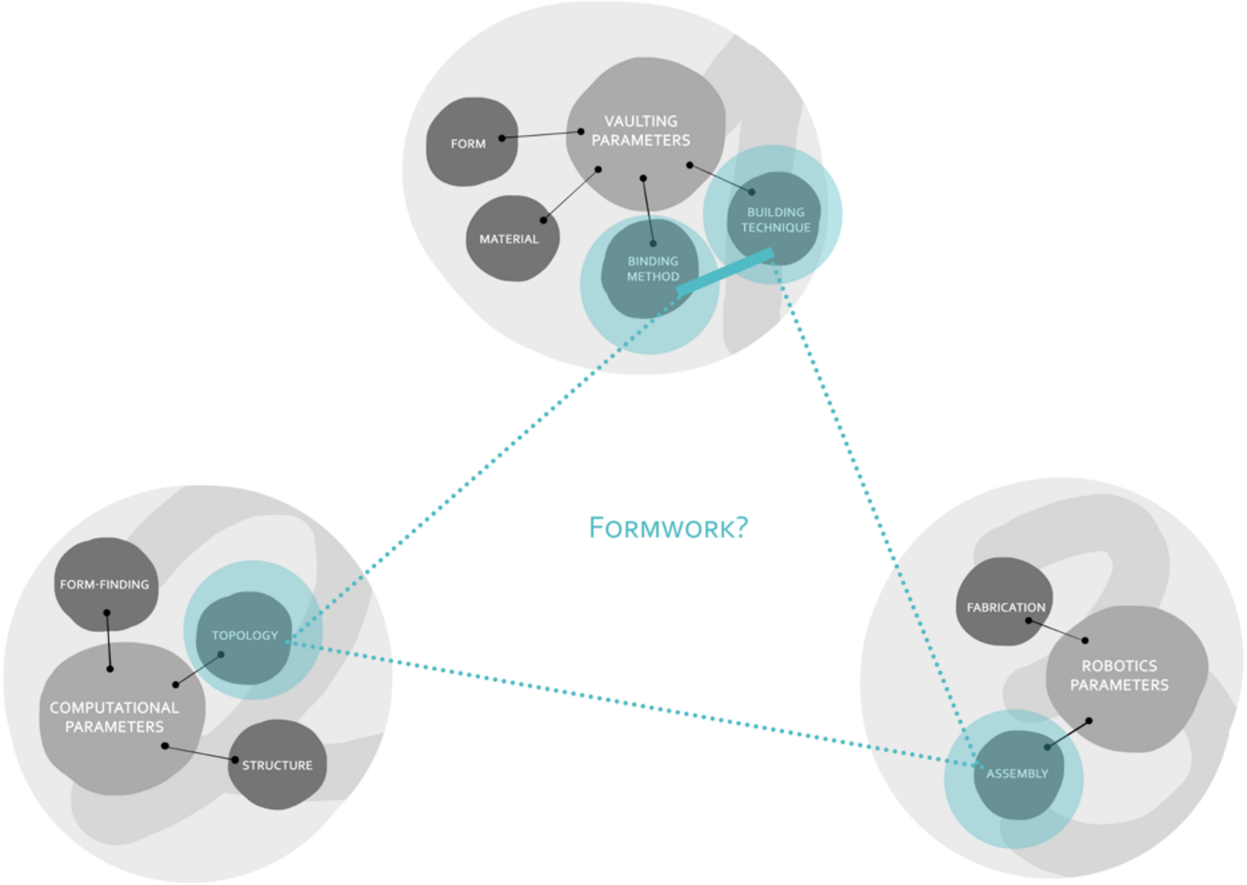


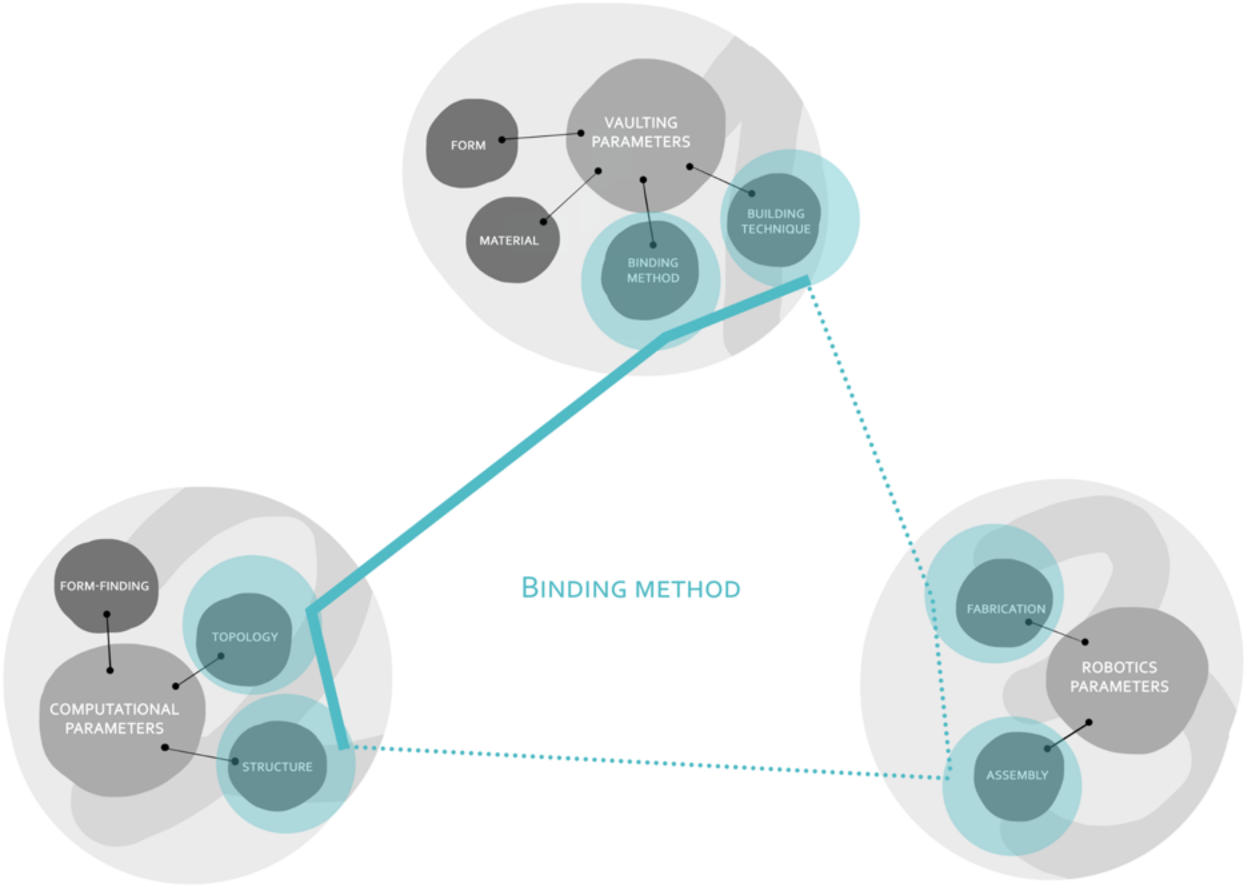
ONE SIZE STANDARD ELEMENTS OR PROCESSED MATERIAL FOR CUSTOMIZED ELEMENTS ?



WHICH PROCESSES DO WE GAIN FROM AUTOMATING (PICK AND PLACE VS SUPPORT OF THE WORK IN PROGRESS) ?

Figure 21: Framing the research axes from the conceptual cluster _ source: author


FORM
VAULTING PARAMETERS
MATERIAL
BINDING METHOD
BUILDING TECHNIQUE
FORMWORK?
FORM-FINDING
TOPOLOGY
COMPUTATIONAL PARAMETERS
STRUCTURE
FABRICATION
ROBOTICS PARAMETERS
ASSEMBLY


FORM
VAULTING PARAMETERS
MATERIAL
BINDING METHOD
BUILDING TECHNIQUE
BINDING METHOD
FORM-FINDING
TOPOLOGY
COMPUTATIONAL PARAMETERS
STRUCTURE
FABRICATION
ROBOTICS PARAMETERS
ASSEMBLY

c. Experiment framing

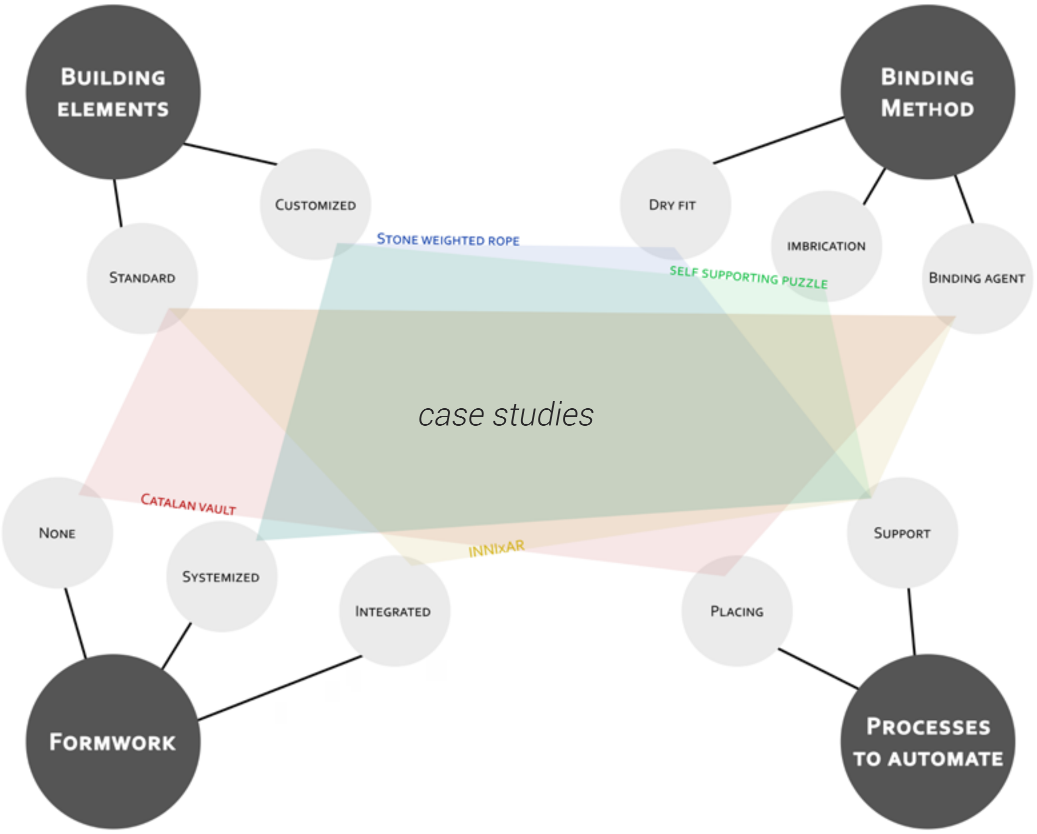


Figure 22: Case studies fitting into the experimentation matrix _ source: author

This matrix was created to further frame the exact experiments to undertake. First, some of the key case studies explored during the historical vaulting practices overview (Annex 1) were laid out. The process to automate for these was a personal speculation on how these building systems could benefit from robotic automation.

This matrix helped visualize the aspects to study, identify patterns in other practices (which ones usually go together), and ultimately craft the experiments to conduct for this thesis.

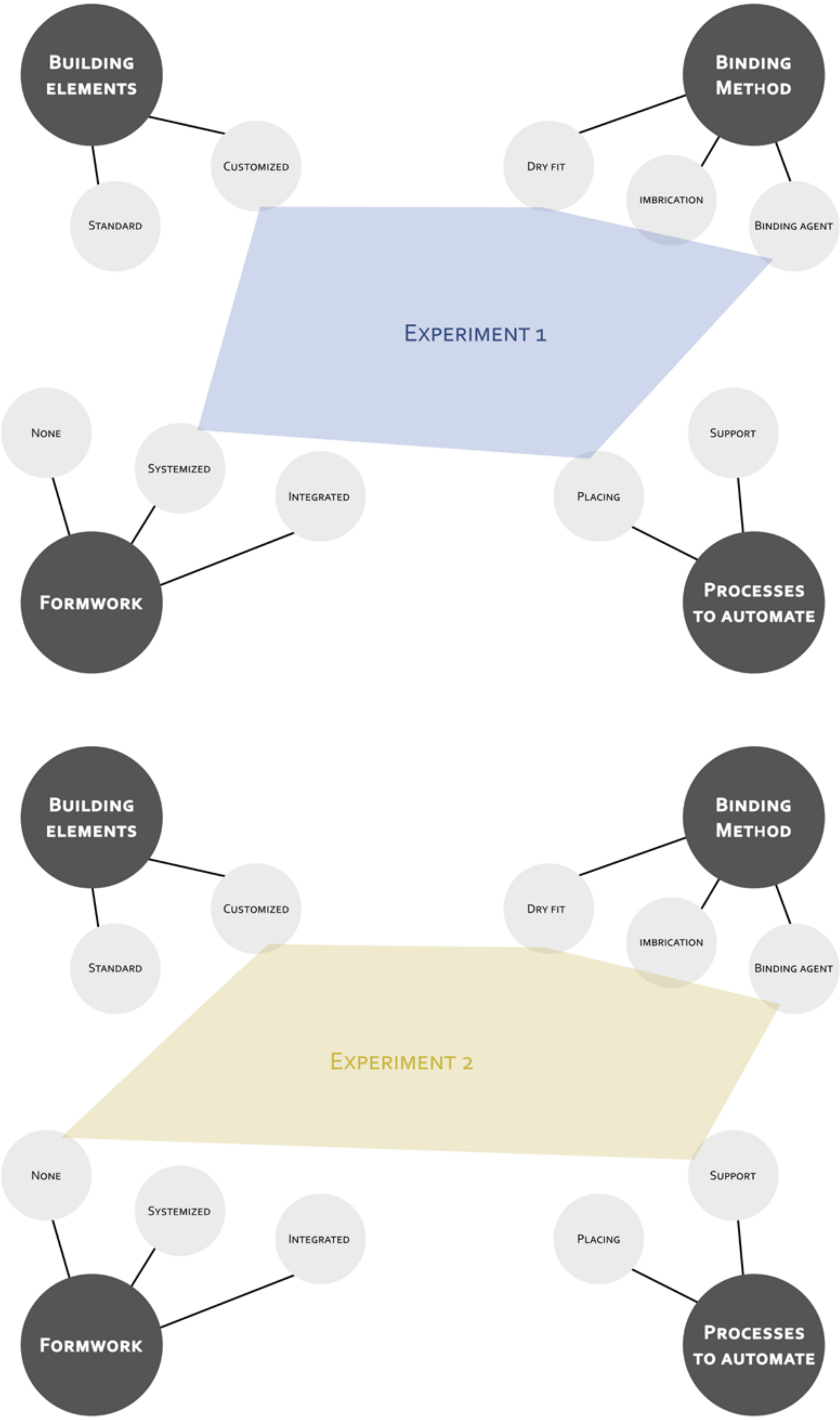


Figure 23: Defining the experiments to conduct on the matrix _ source: author

B. manual experimentation

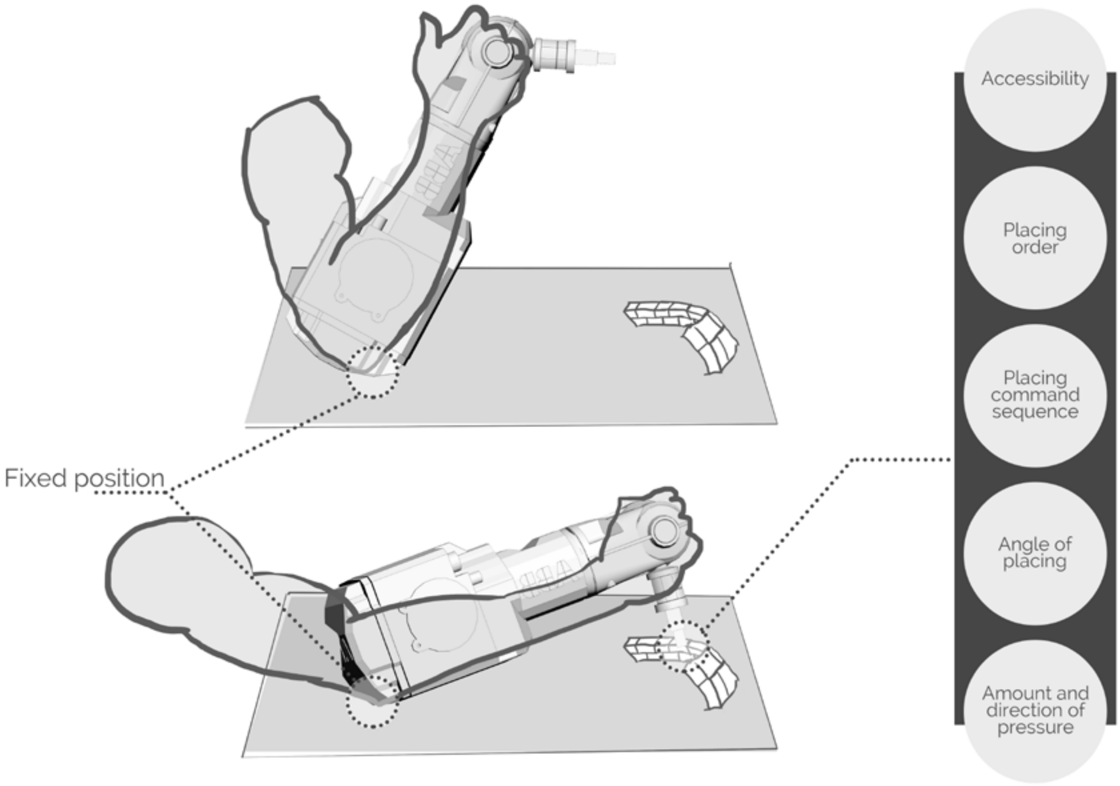


Figure 24: Robotic motion simulation as concept for the first manual experiment _ source: author

a. Desired outcomes

In order to get a first intuitive understanding of the commands to provide to the robot, a manual experiment was necessary. This allowed observation of certain aspects of motion planning while laying the bricks and reflection on the following questions:

- Are there any difficult angles or inaccessible spots?
- In which order does the brick laying feel sensible?
- What is the command sequence repeated for each brick laid, and how did it change as the building process advanced?
- At which angle is it most beneficial to place the bricks?
- What are the optimal amount of pressure and direction? Is the placement done in sequence (move along z then x, for example)?

Overall, the manual experiment offered an intuitive, fast, and forgiving context to understand the experiments to be designed and to play with the parameters.

b. Dry fit

Examining different brick arrangements in foam provides a straightforward method compared to complex digital techniques. The study compared two types of bricks: staggered bricks and those with a slit on the upper face. This comparison aimed to understand which type is better for stable vault structures.

By using foam as a medium, manipulation and testing of different brick arrangements could be easily and intuitively conducted , as opposed to computational modeling or digital fabrication processes. This hands-on approach allowed observation of how variations in brick design impact assembly ease, and overall stability.

While the staggered bricks offered a simpler shape and more flowy design, the slits on the second experiment helped stabilize the structure in a shorter amount of time.

manual experiment - staggered bricks

Figure 25: manual experiment 1 - dry fit staggered bricks
source: author

CLICK SCAN

manual experiment - small slit on upper bricks face

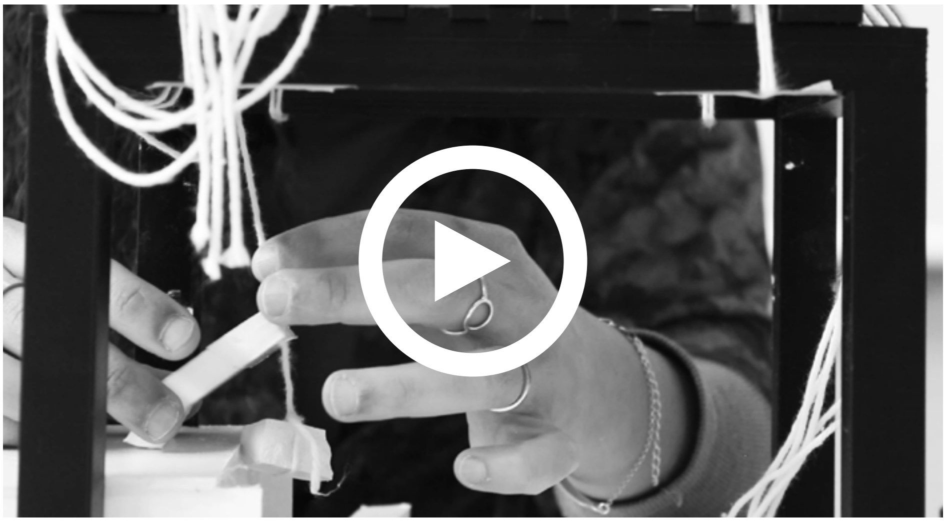


Figure 26: manual experiment 2 - dry fit slit on bricks
source: author

CLICK SCAN

c. Assembly with binding agent

The experiments with standard bricks and a binding agent, consisting of clay mixed with water, followed a two-part approach. In the first experiment, a vaulted shape that was self-supporting and free-standing, aimed to provide an intuitive understanding of robotic motion planning and the challenges associated with building vaulted structures. In the second experiment, an arch was assembled, requiring support for overhang. Here, a weighted rope system was utilized to hold the arch in place during construction. These experiments allowed to explore different aspects of robotic assembly, including structural stability, motion planning, and the effectiveness of support systems.

manual experiment - no support

Figure 27: manual experiment 3 - binding agent free placement _ source: author

CLICK SCAN

manual experiment - with support

Figure 28: manual experiment 4 - binding agent supported placement _ source: author

CLICK SCAN

C. robotic experimentation

a. Geometry, topology and motion planning

This section of the experimentation process explores the intricate interplay between geometry, topology, and motion planning logic. Understanding the relationship between form and motion becomes essential in optimizing the efficiency and accuracy of the construction processes.

The development of specialized tools plays a pivotal role in facilitating the experimentation. Tools such as the weight hanging tool, base platform, and brick holder are designed to support the assembly process, augmenting stability and precision during robotic operations. They are crafted to accommodate the unique requirements of the experiments, allowing the manipulation of brick topology, control motion sequences, and adjust pick-up/placing frame positions with precision and ease.

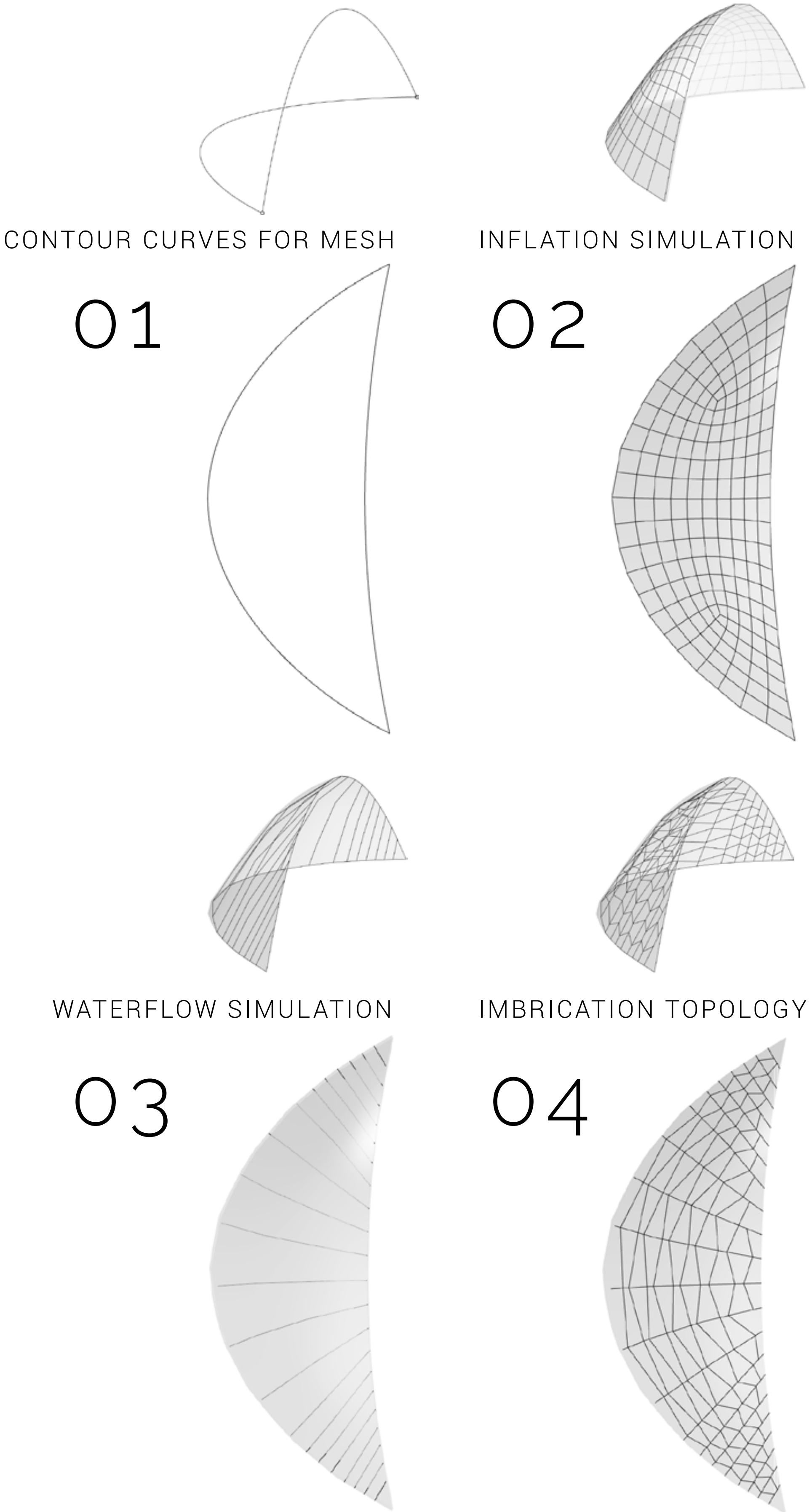


Figure 29: geometry 1 - topology process _ source: author

first geometry - canceled

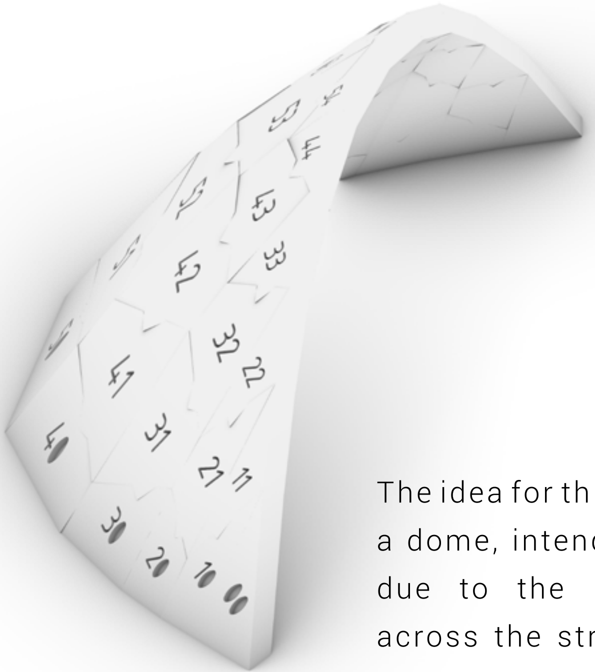


Figure 30: geometry 1 - final result _ source: author

The idea for this experiment was to construct half a dome, intended to be free-standing. However, due to the non-uniform weight distribution across the structure, the tiles varied greatly in size. This made it challenging to place them from the top face. Attempting to place the tiles from the side introduced another problem with robot accessibility within our setup. Therefore, this geometry was abandoned in favour of a simpler, non-free-standing design to proceed with the experiment.

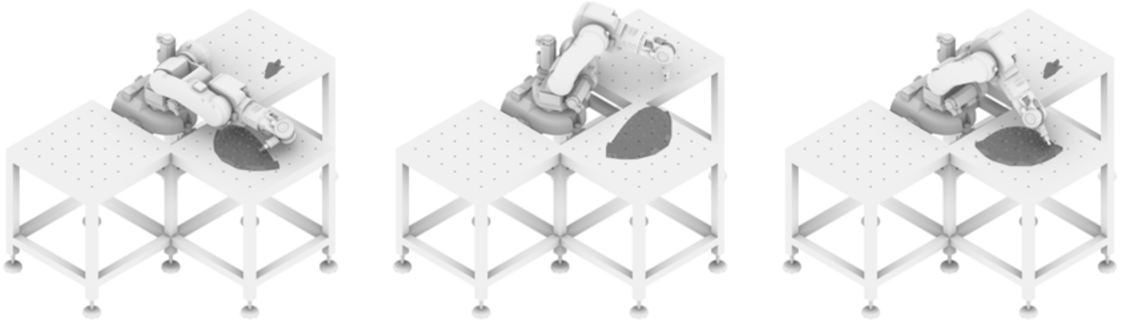
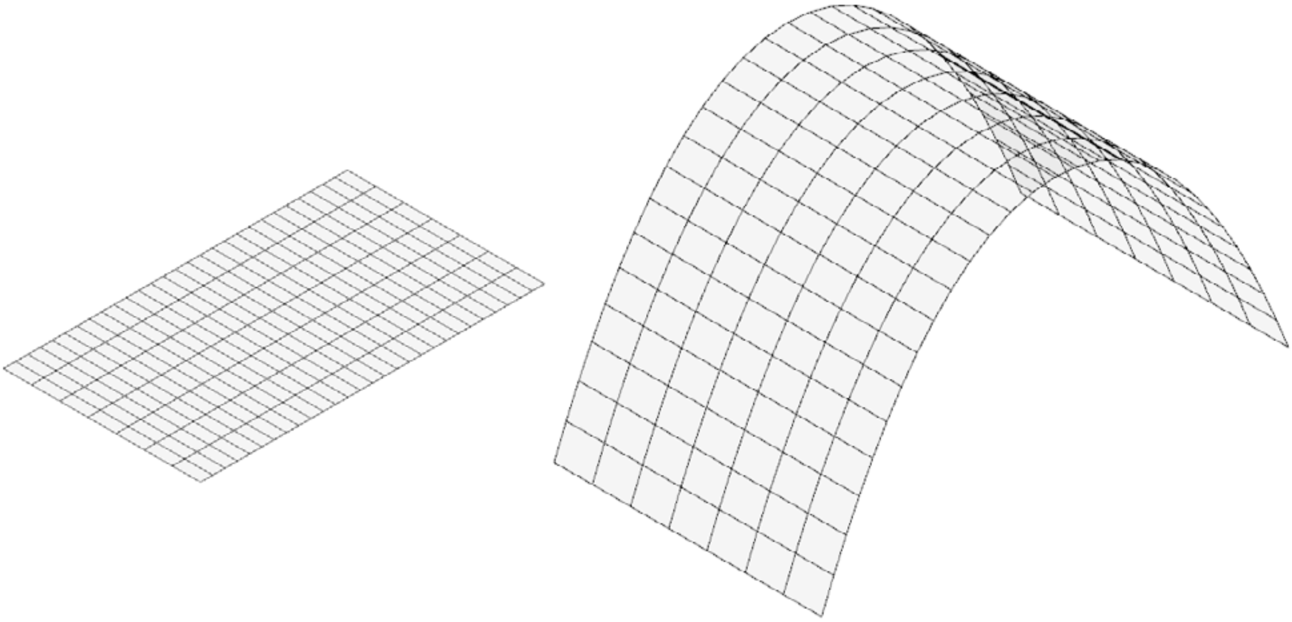
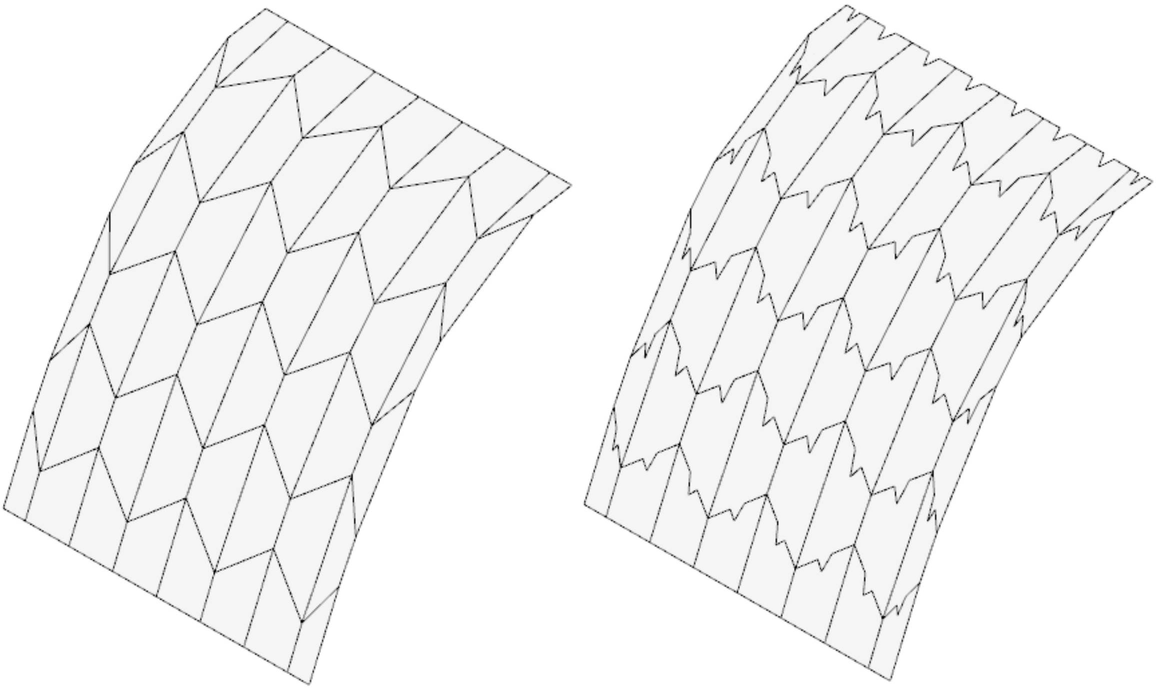


Figure 31: geometry 1 - motion planning trial and fail _ source: author



01 BASE MESH

02 INFLATION SIMULATION



03 SEGMENTATION

04 IMBRICATION TOPOLOGY

Figure 32: geometry 2 - topology process _ source: author

For this experiment, the vault was split in half for logistical reasons. This division was necessary because the weighted rope system requires placing a tool that would collide with the robot if positioned on both sides.

Figure 33: geometry 2 - final result _ source: author

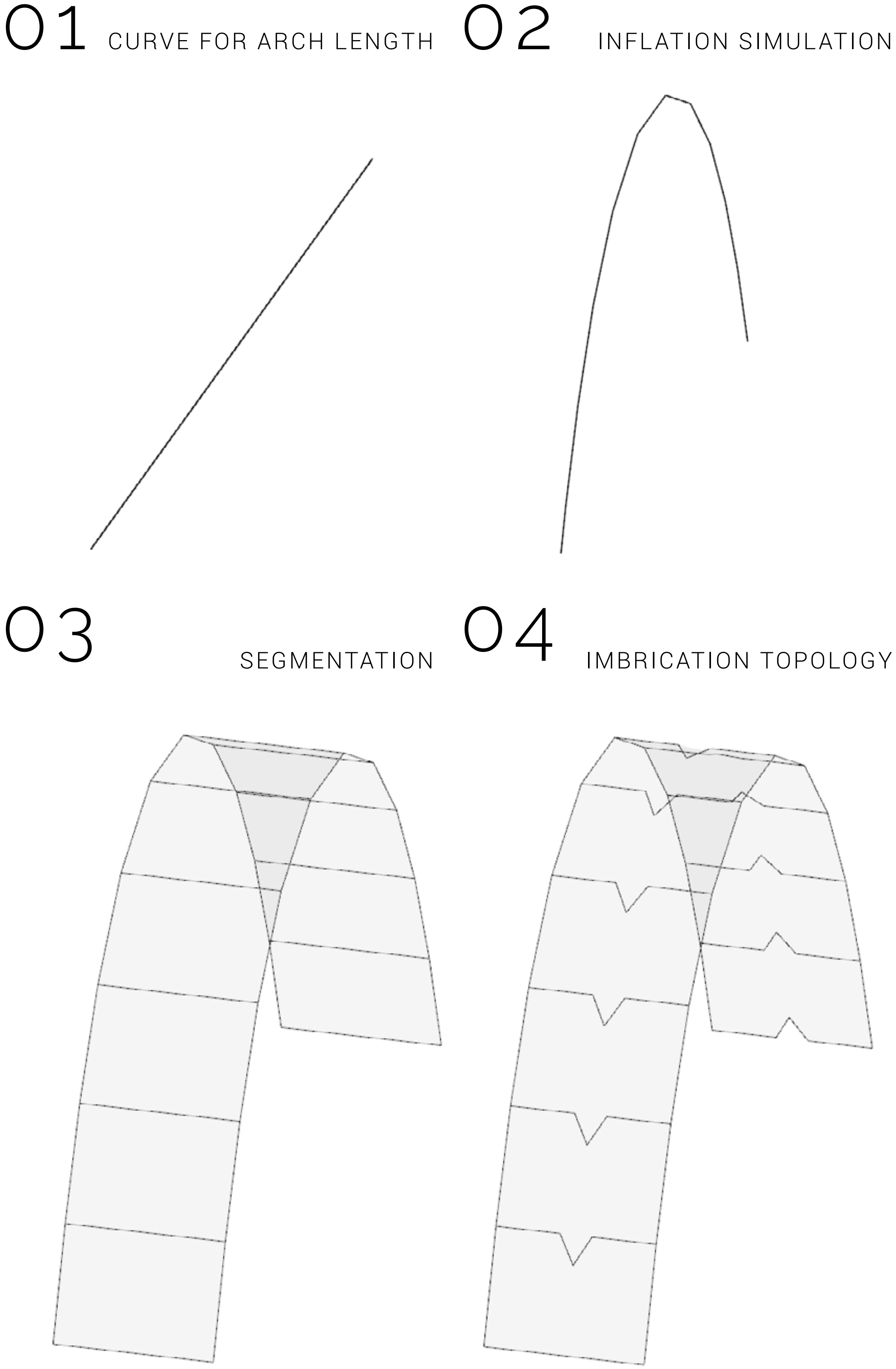


Figure 34: geometry 3 - topology process _ source: author

Due to time constraints, the experiment could not incorporate a more complex geometry. Therefore, a simple pilot prototype was designed to verify the concept of using the robot as support rather than for placement. The bricks had to also be simple enough to accommodate human error, as the placement was performed manually.

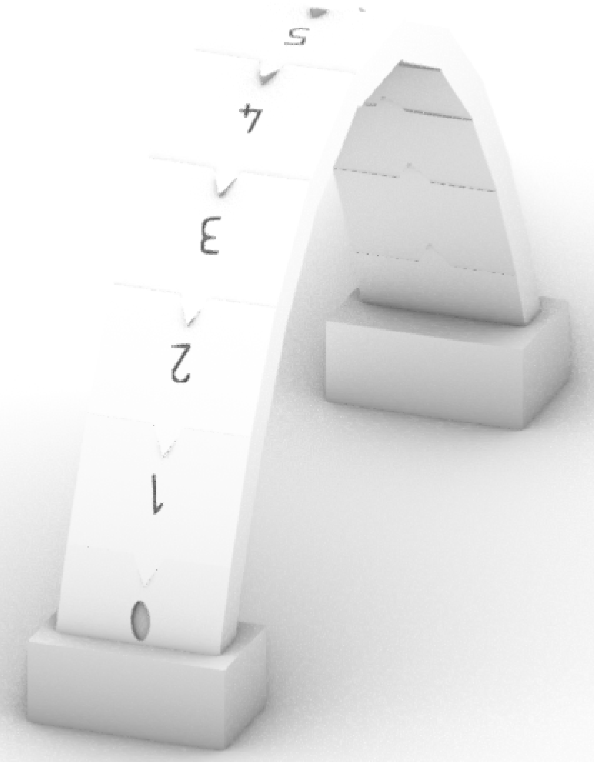


Figure 35: geometry 3 - final result _ source: author

target frames

1/ Home position

2/ Y-50 _ pick-up frame moved 50cm in normal direction

3/ Y _ pick-up frame

4/ Home X _ Home position with X position aligned with brick to place

5/ X-50 _ placing frame moved 50cm in normal direction

6/ X _ placing frame

targets sequence

1 - (2-3-2-4-5-6-5-4) -1

cycle for each brick

EXPERIMENT 1

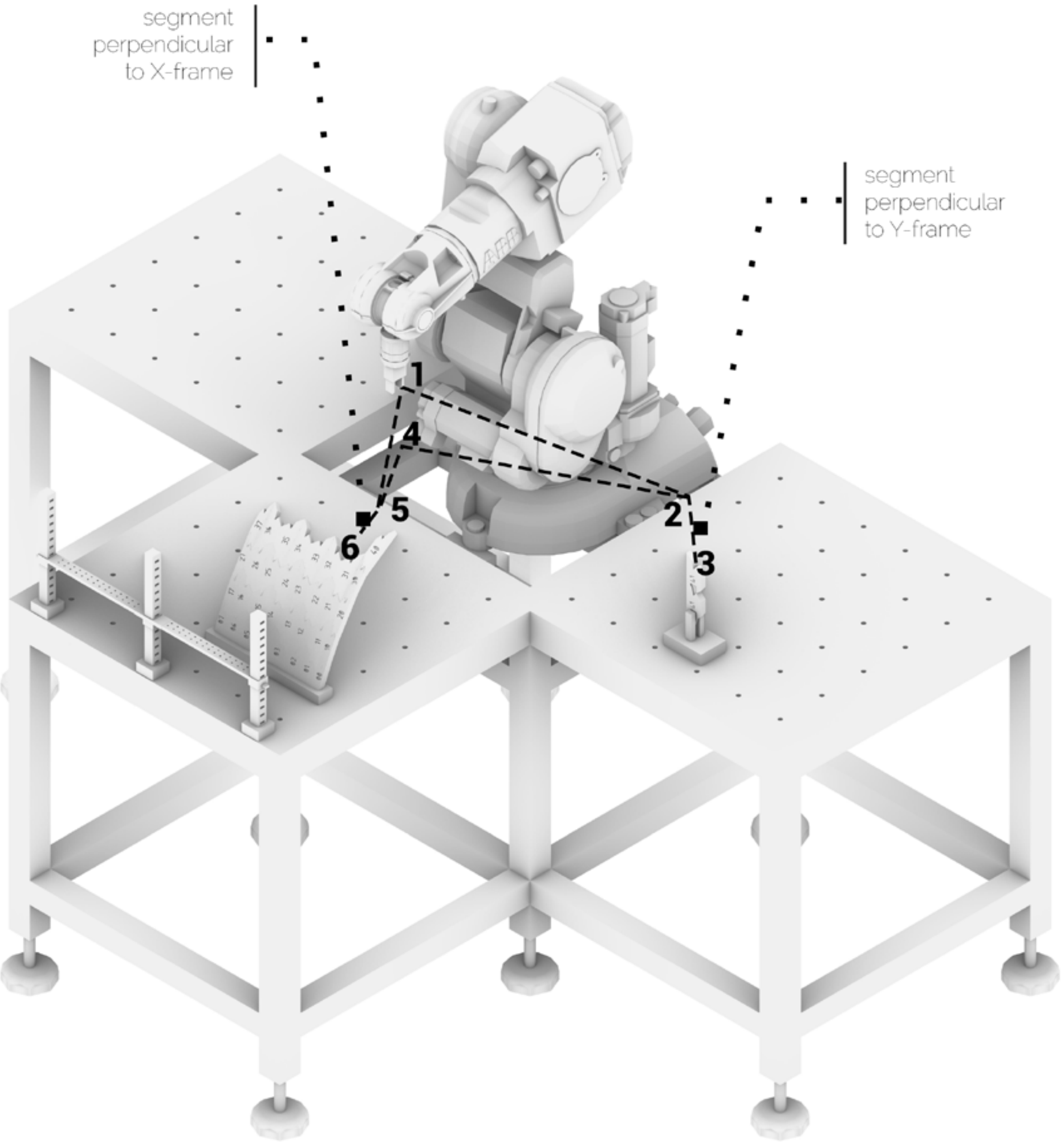


Figure 36: Experiment 1 - motion sequence _ source: author

EXPERIMENT 2

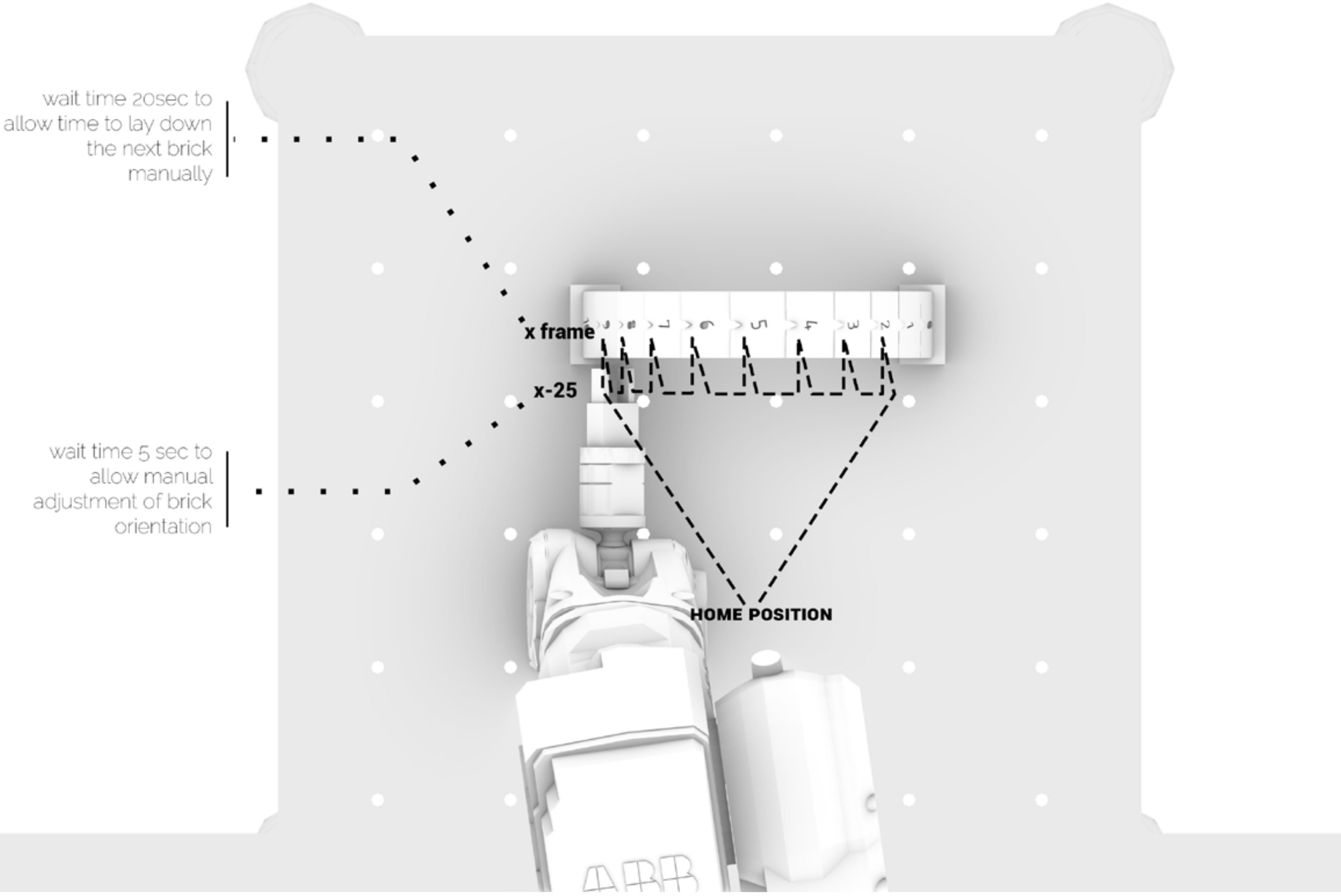


Figure 37: Experiment 1 - motion sequence _ source: author

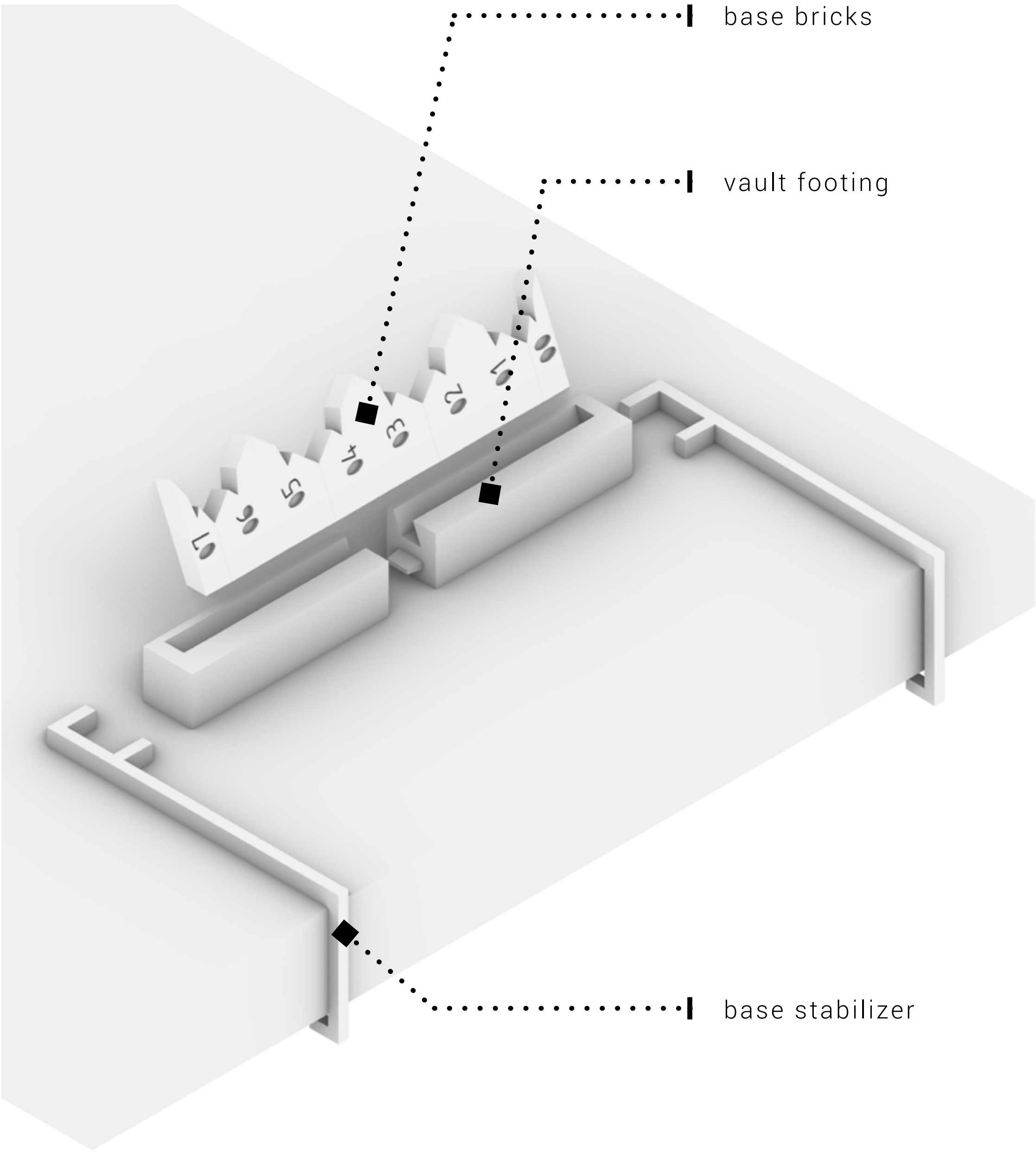


Figure 38: base stabilizing components _ source: author

VAULT FOOTING

Providing stability at the base of the vault is fundamental, as the stability of the structure relies on compression. For that, a custom 3D printed base for the bricks to be inserted into was needed. In order to stabilize it on the table, double edged tape was inefficient as the base would part in the middle when too much force was applied by the robot, so a 3D-printed tool linking it to the table was necessary..

MOTION FOR INSERTION

When moving the brick to its final position, the motion direction should take into account previously placed elements, so as to not disturb their stability.

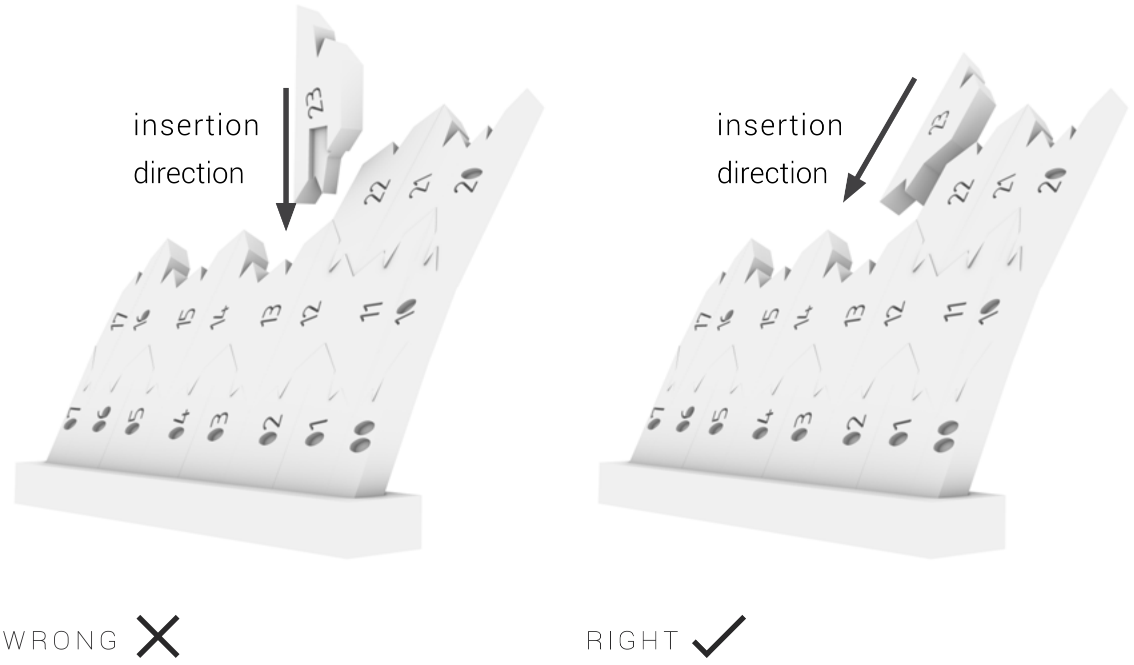
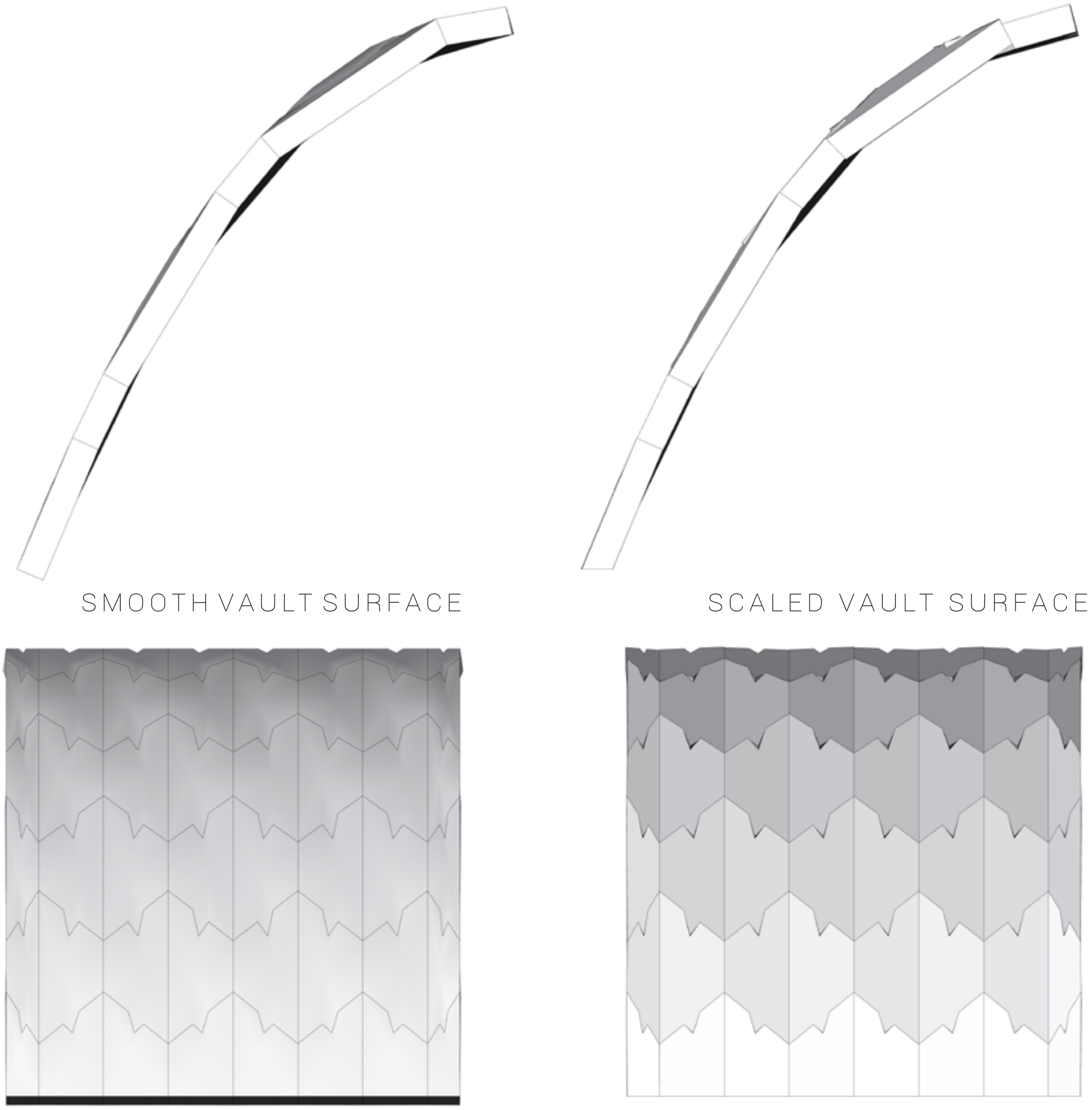


Figure 39: insertion motion _ source: author

BRICK SURFACE FOR MANUFACTURING

Since the process for manufacturing was 3D printing, flattening the outer and inner faces and making them parallel highly facilitated the operations, both for the printing and for planning how to pick them up. Alternative solutions could of course be found, especially when using other fabrication techniques, but this is an aspect to keep in mind.


SMOOTH VAULT SURFACE

SCALED VAULT SURFACE

Figure 40: Dome surface resolution _ source: author

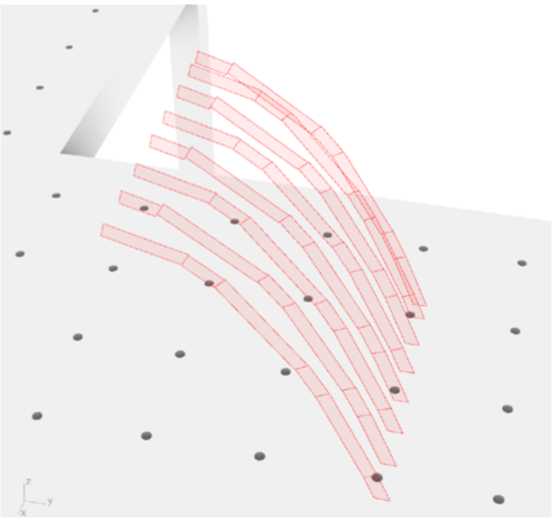
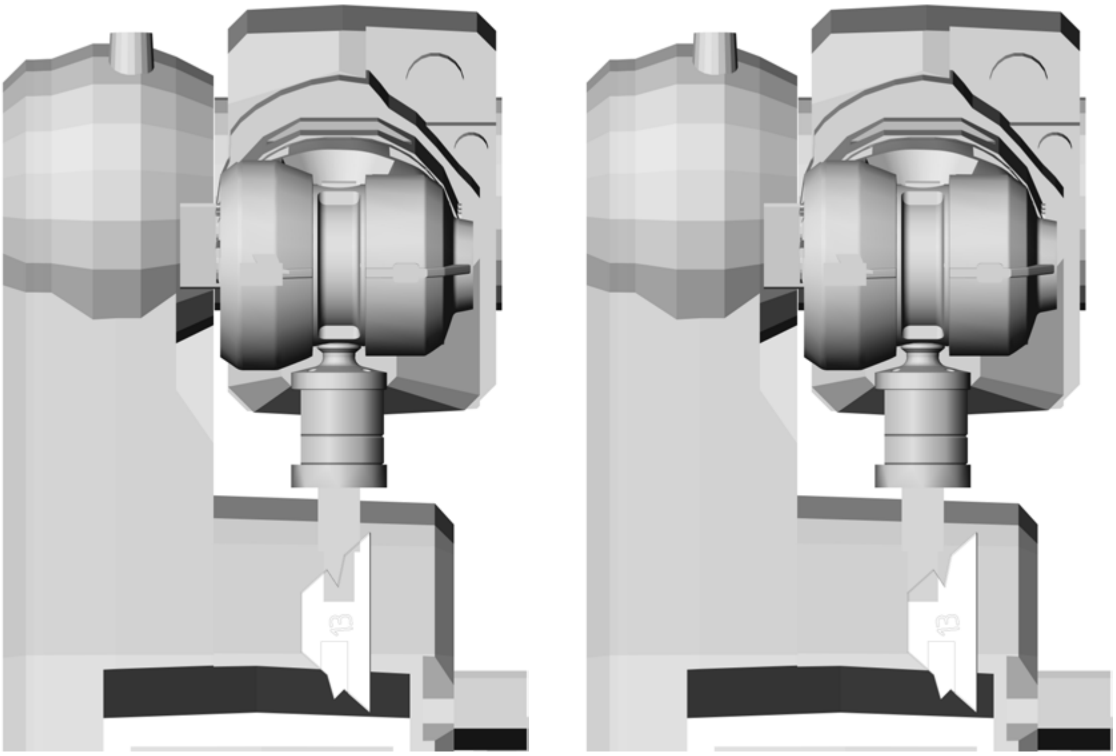


Figure 41: weight path continuity _ source: author

ROOM FOR ROPE

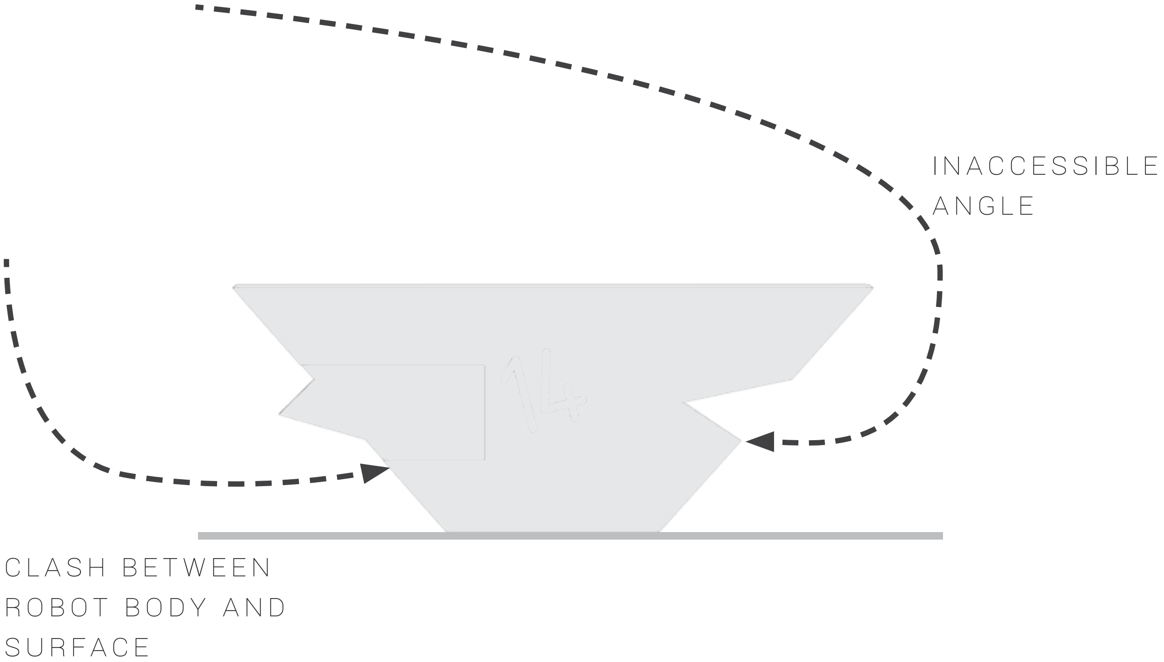
When defining the pick-up/placing surface, one must keep in mind not to obstruct the slit for the weighted rope

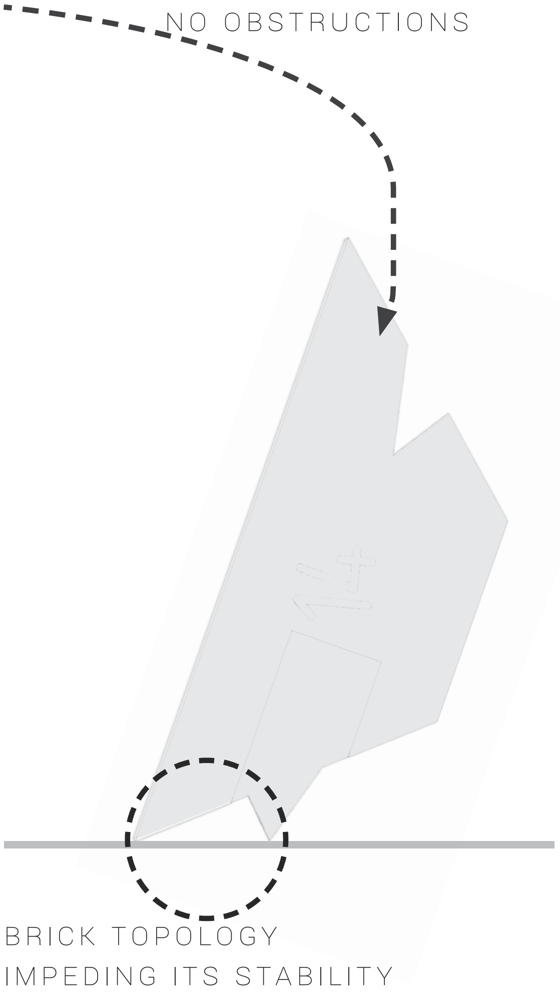


WRONG ✗

RIGHT ✓

Figure 42: room for rope _ source: author





ACCESSIBILITY FOR PICK-UP FRAME

There are many factors to take into consideration when choosing how to place the bricks for pick-up:

- **Placing sequence**: which elements are placed before and which faces remain unobstructed, and what is the motion needed to assure imbrication if needed;

- **Brick geometry**: which faces can be reliably placed flat with a consistent reference point, the size of the brick for the robot to pick it up depending on the tool used (gripper width in this example);

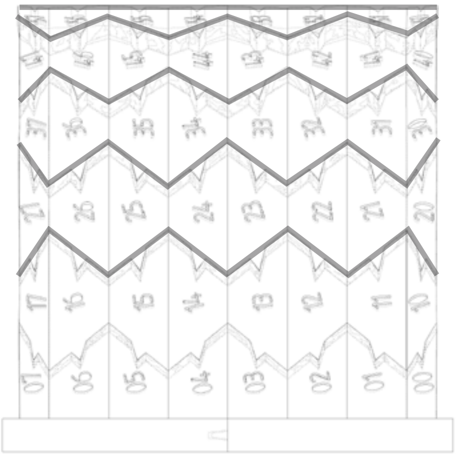
- **Accessibility**: the angle of the pick-up surface, possibility of access for the robot without collision with the placing surface (for example if the pick-up face is to the side it will necessitate some elevation to allow access)

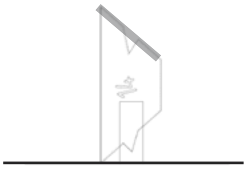
Figure 43: pick-up frame accessibility _ source: author

PLACING FRAMES

PICK-UP FRAMES

TOP PLACING FRAMES





LATERAL PLACING FRAMES

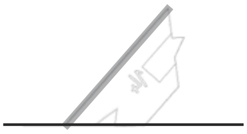


Figure 44: relationship between pick-up and placing frame _ source: author

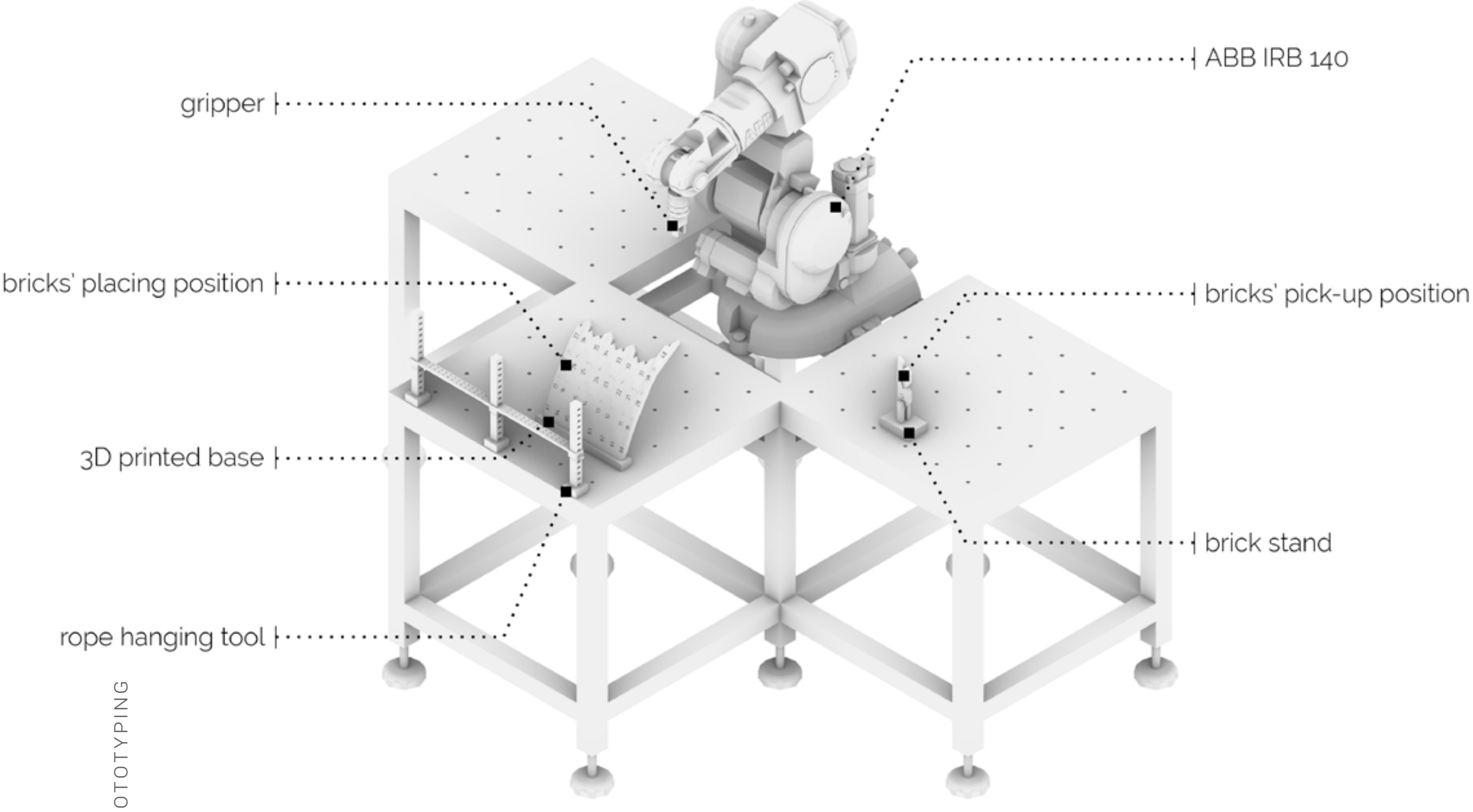


Figure 45: experiment 1 - robotic station setup _ source: author

b. tools and setup

robotic station setup

EXPERIMENT 2

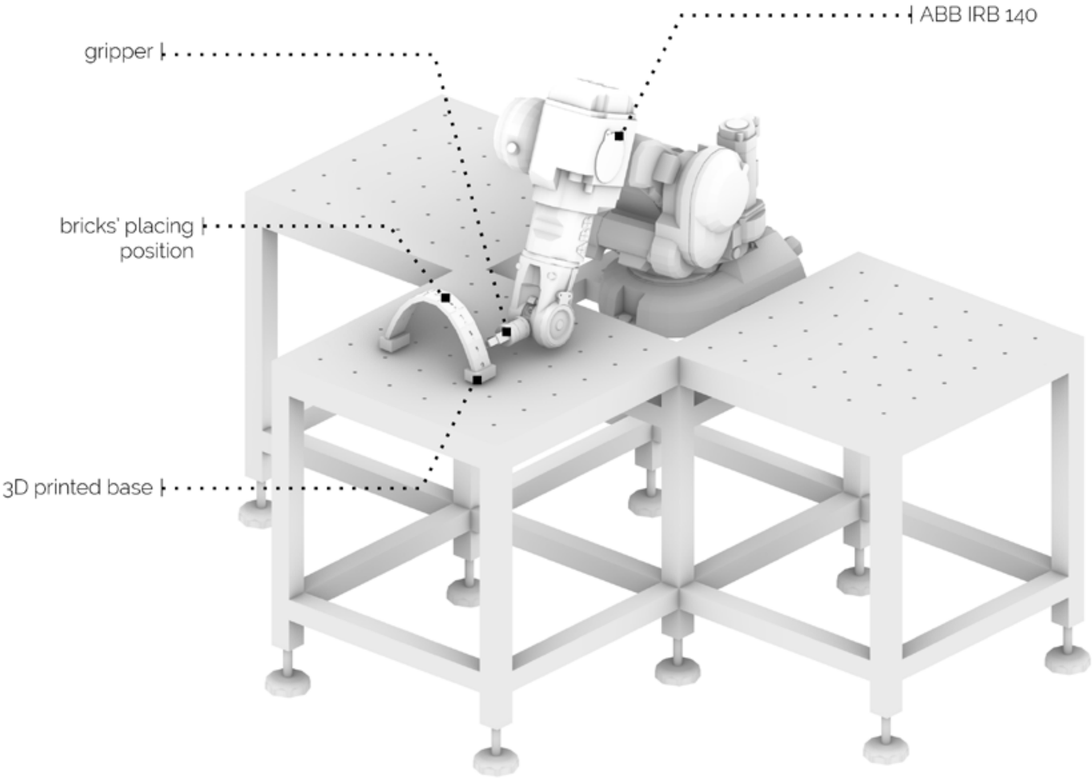


Figure 46: experiment 2 - robotic station setup _ source: author

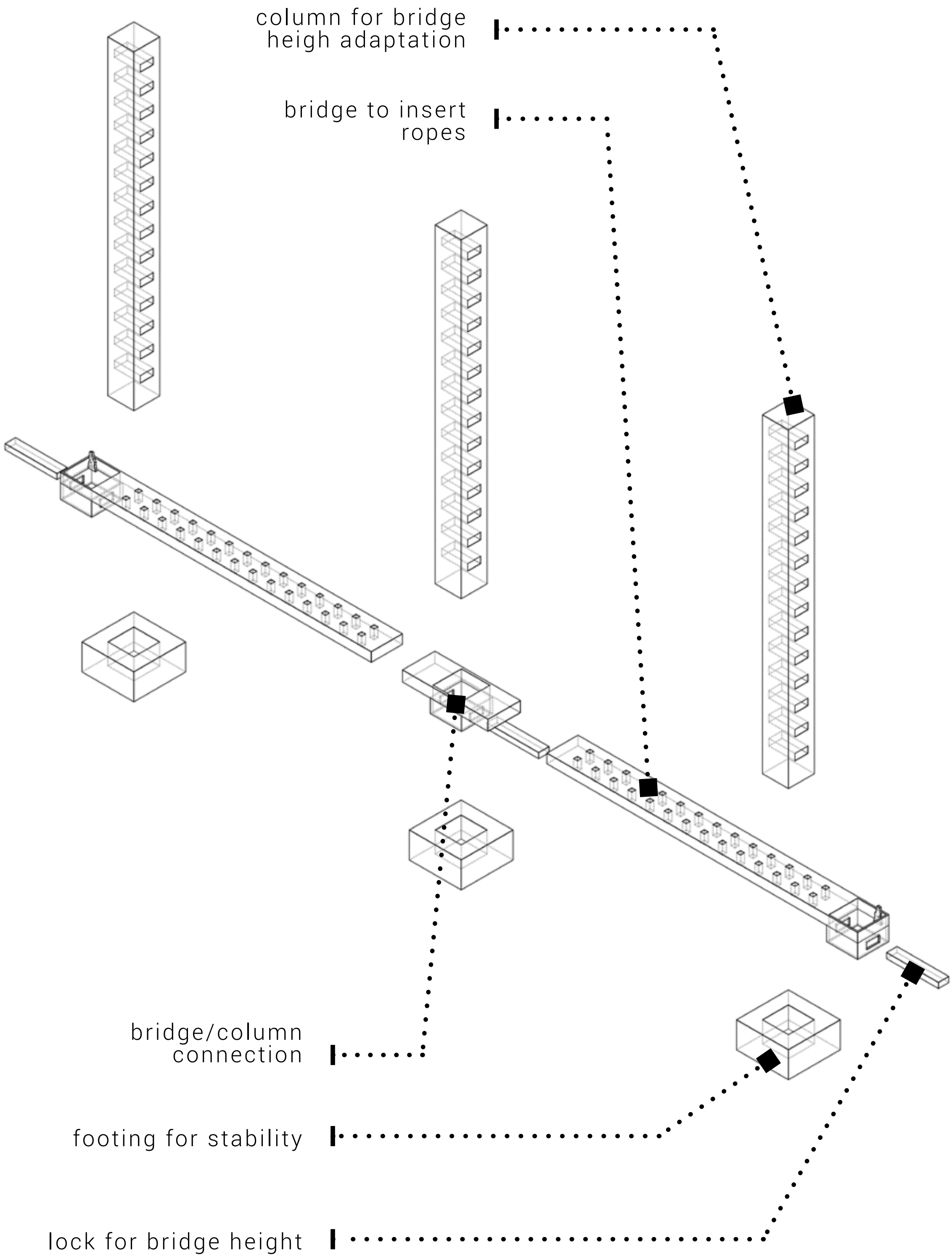
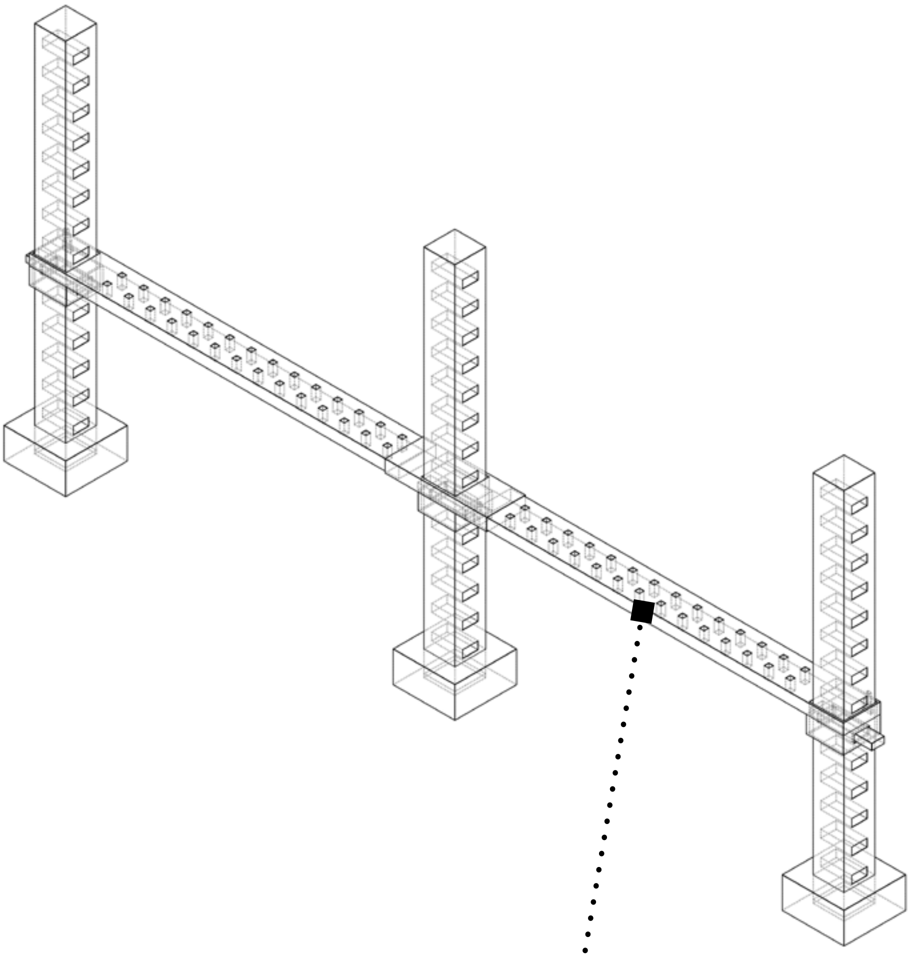


Figure 47: rope hanging tool breakdown _ source: author

Weight hanging tool breakdown



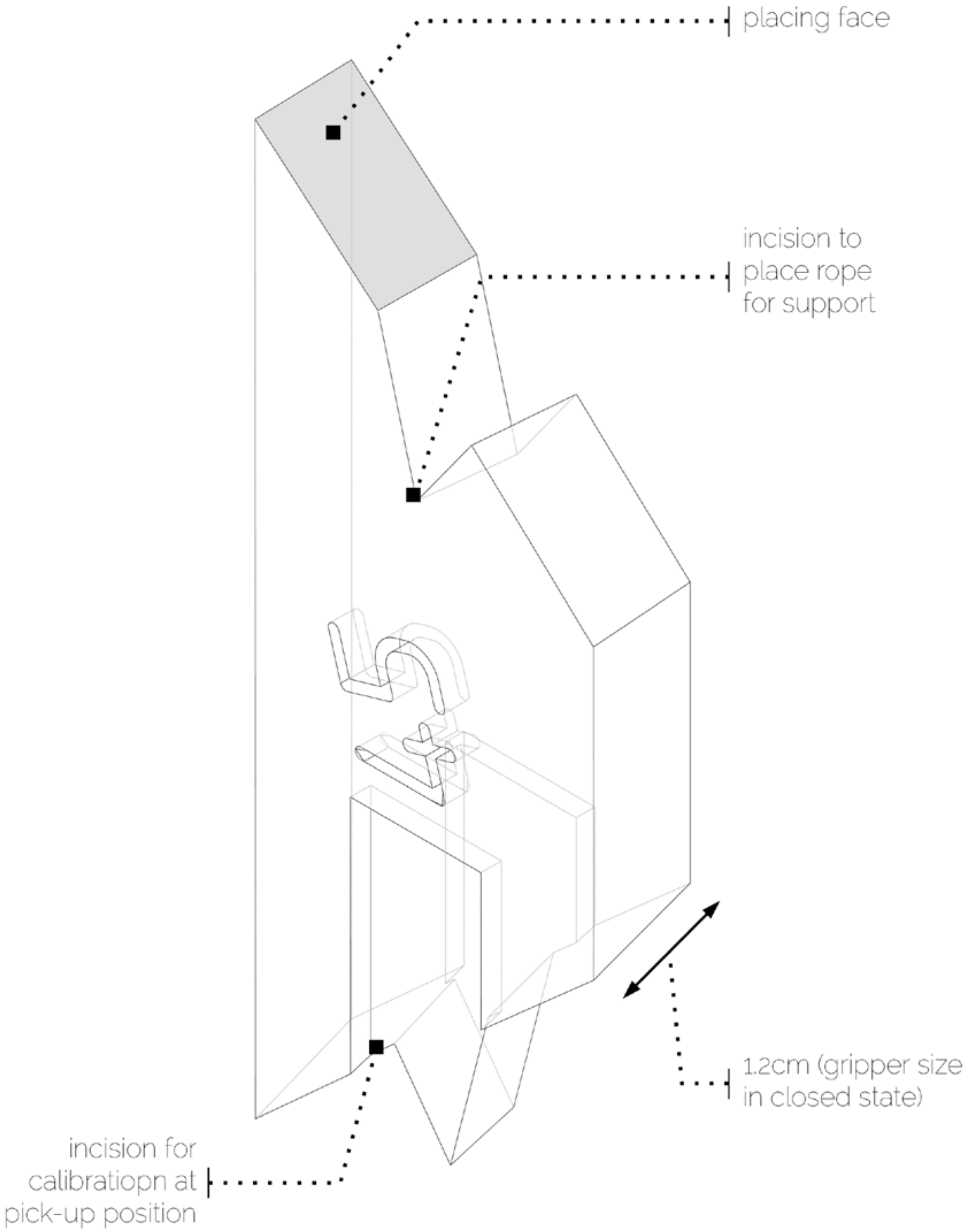


Figure 48: brick topology breakdown _ source: author

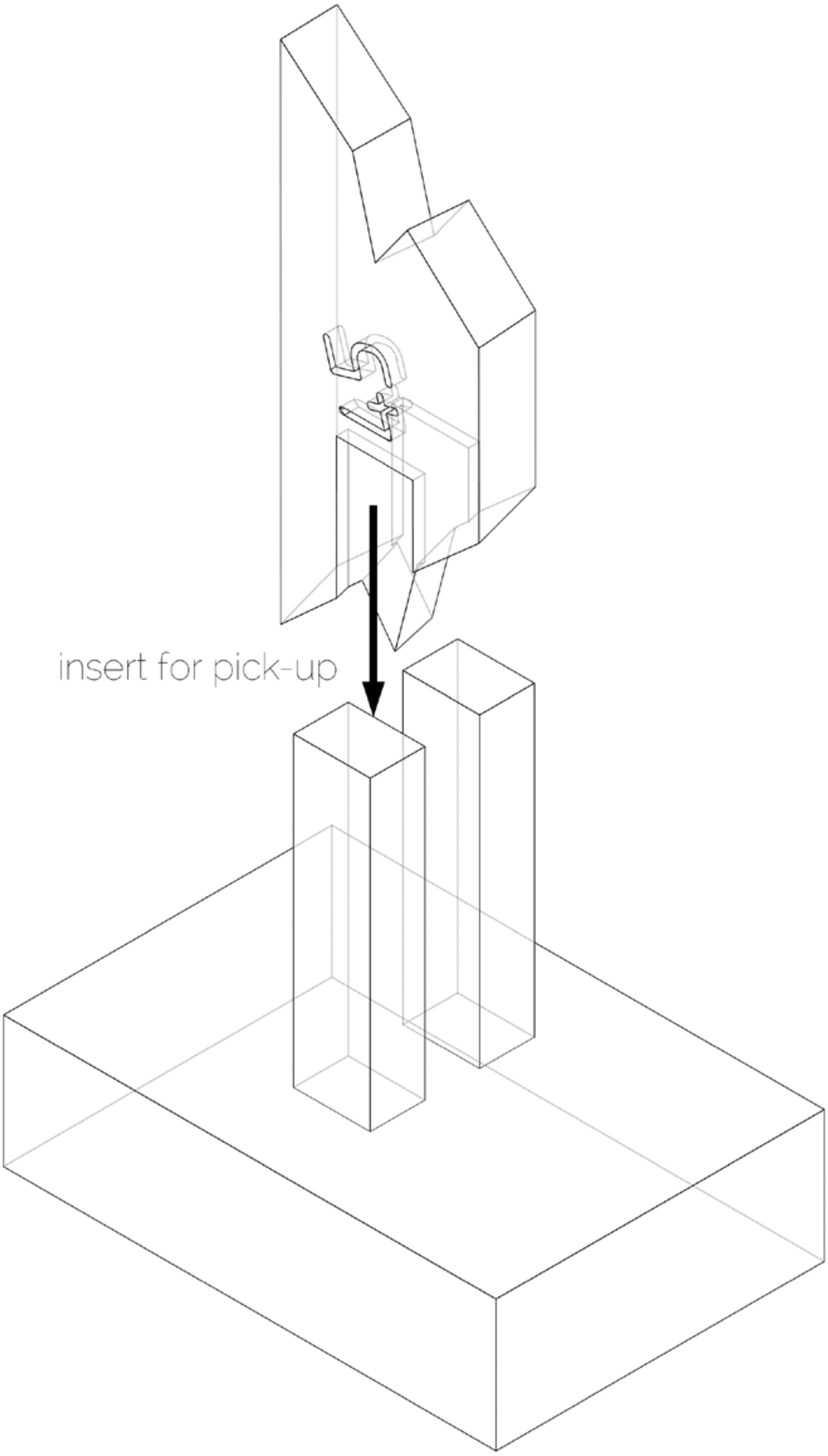
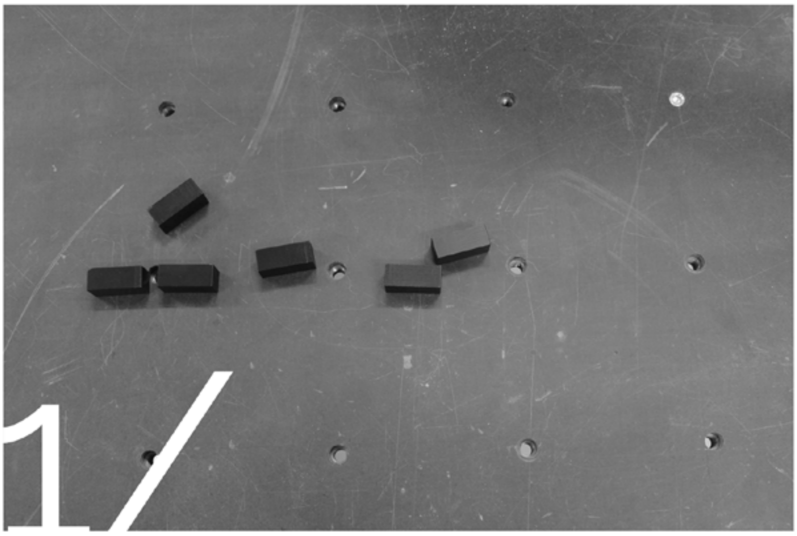


Figure 49: brick holder _ source: author

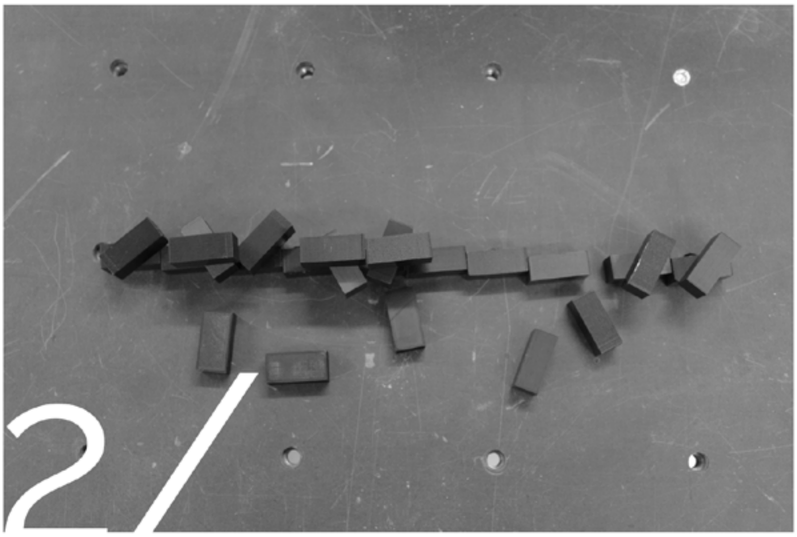
- Adjusting brick placement on table (inadequacy of a few cm between model and reality)
- Adjusting tool rotation by 90° (tool frame orientation wrong on simulation)
- Bricks sticking to the gripper
- Inexact positioning and brick movement with gripper opening



FIX 01

Fixing tape inside the gripper

- Brick position shifting with gripper opening
- Robot cables moving previously placed bricks



FIX 02

- Laying down double-faced tape to stabilize bricks at placing position
- Taping the cables closer to the robotic arm

- Bricks overlaping

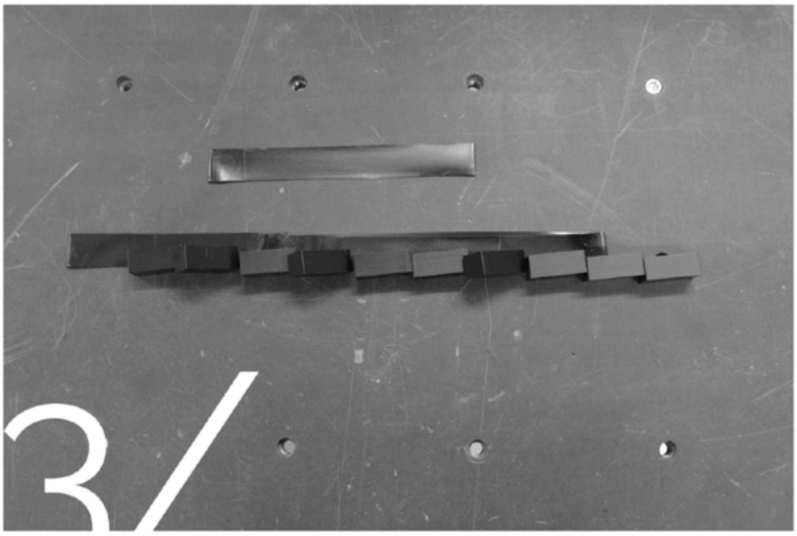


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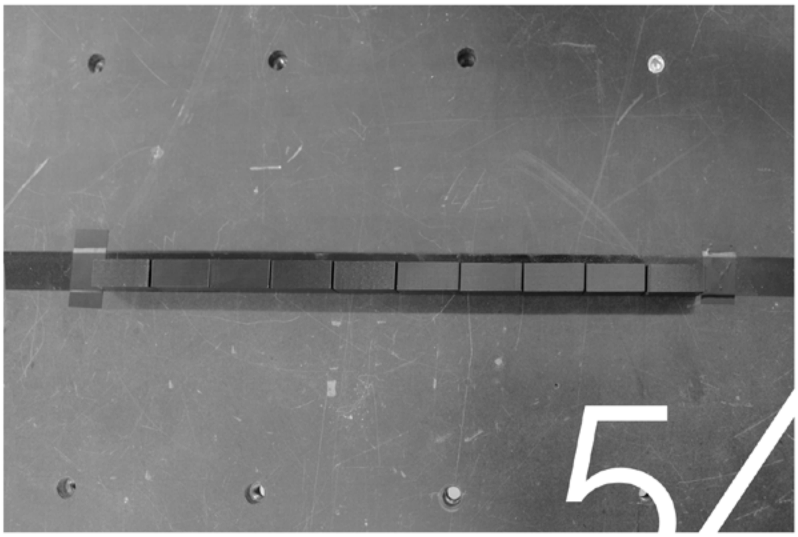
Figure 50: robot calibration process _ source: author

c. robotic assembly

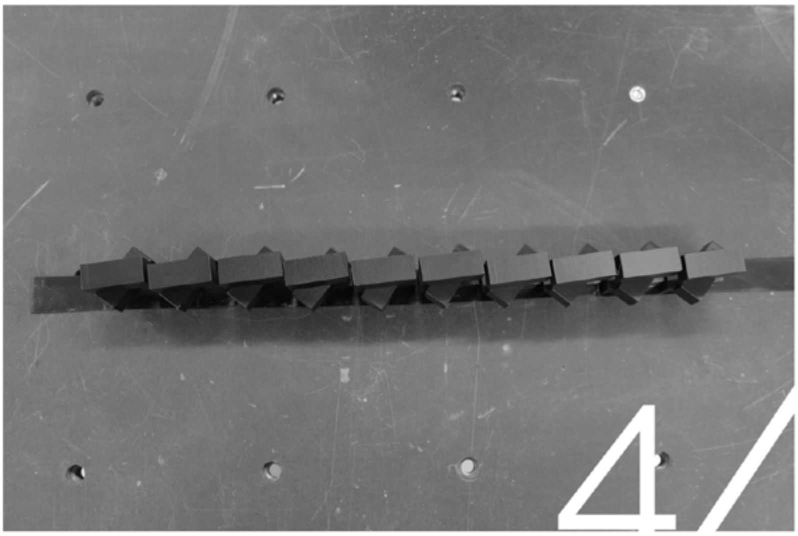
robot calibration



Good enough!

FIX 04

Lower brick distancing to 1mm
Rotate the tool's frame a few
mm in compensation



- Distance between bricks too high
- Brick orientation slightly shifted

FIX 03

Give some error margin in the bricks
positions by distancing them by 2 mm

digital simulation

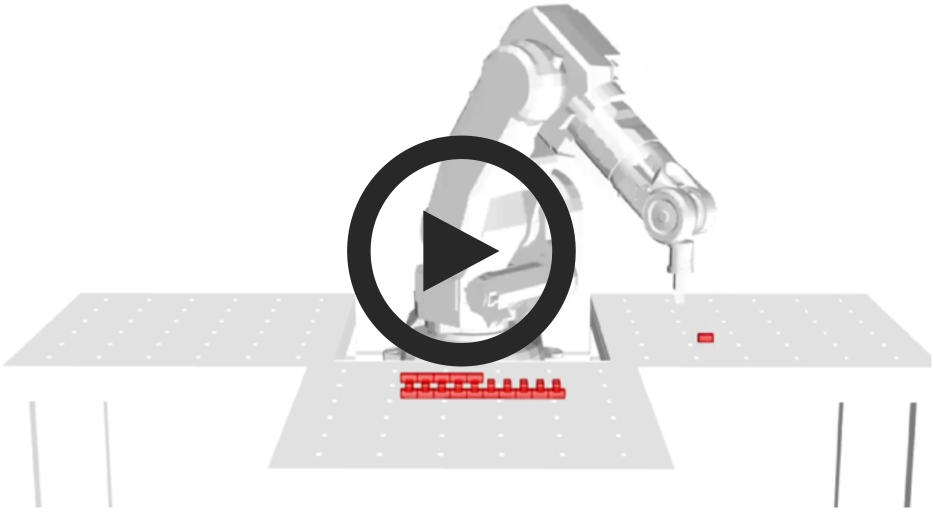


Figure 51: brick wall test - motion planning simulation
source: author

CLICK SCAN

physical experiment

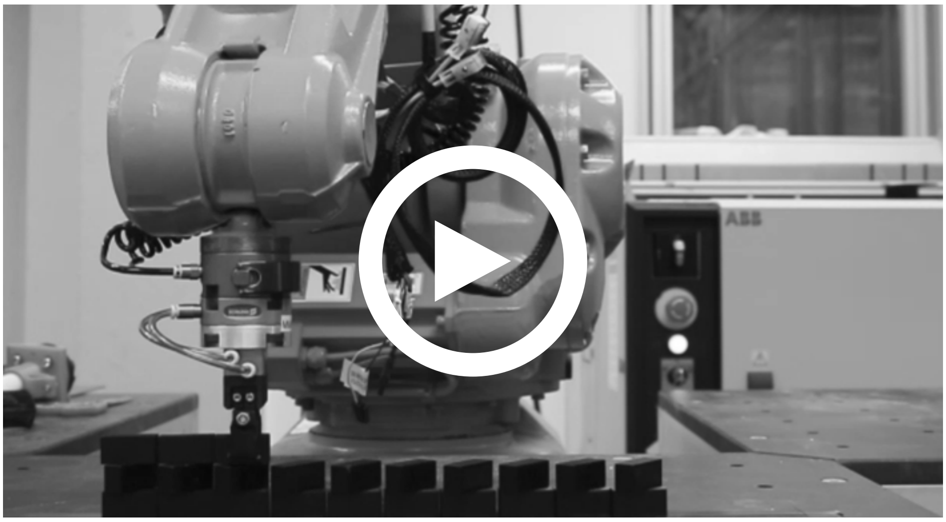


Figure 52: brick wall test - physical experiment
source: author

CLICK SCAN

digital simulation

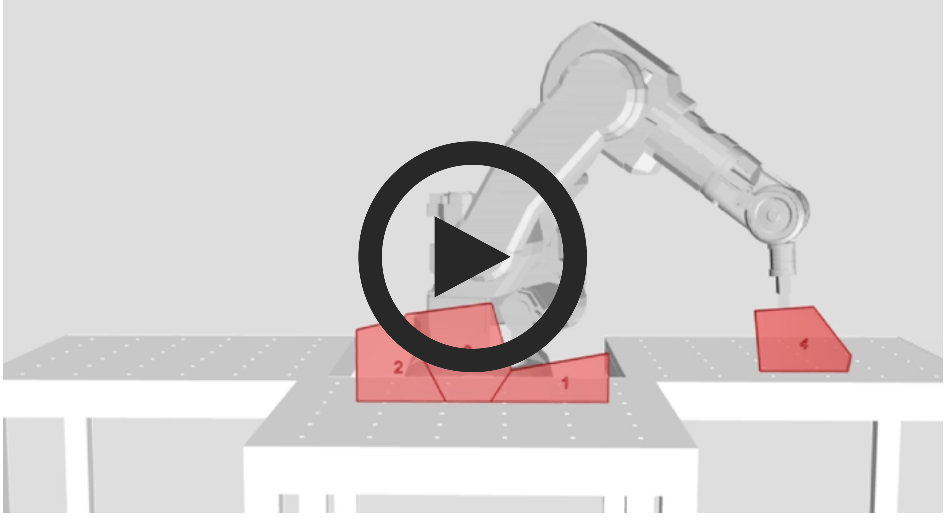


Figure 53: voronoi wall test - motion planning simulation
source: author

CLICK SCAN

physical experiment

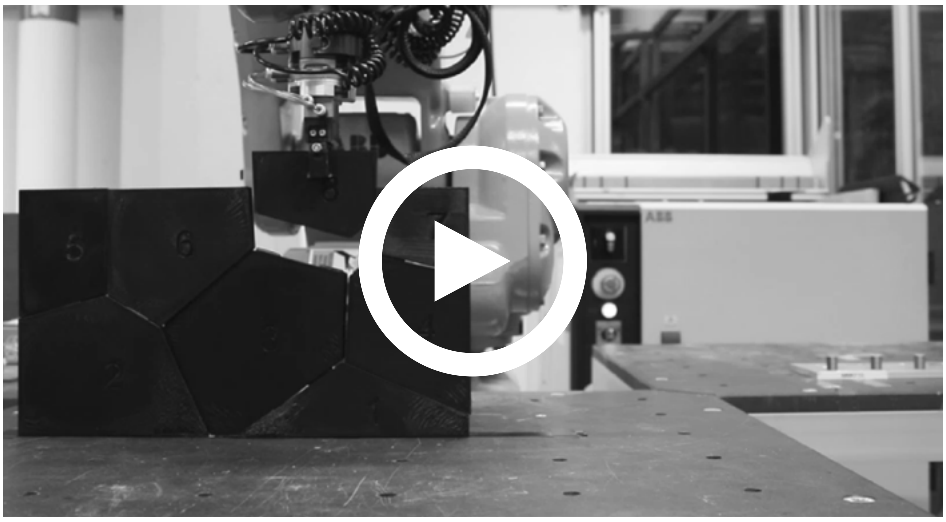


Figure 54: voronoi wall test - physical experiment
source: author

CLICK SCAN

digital simulation

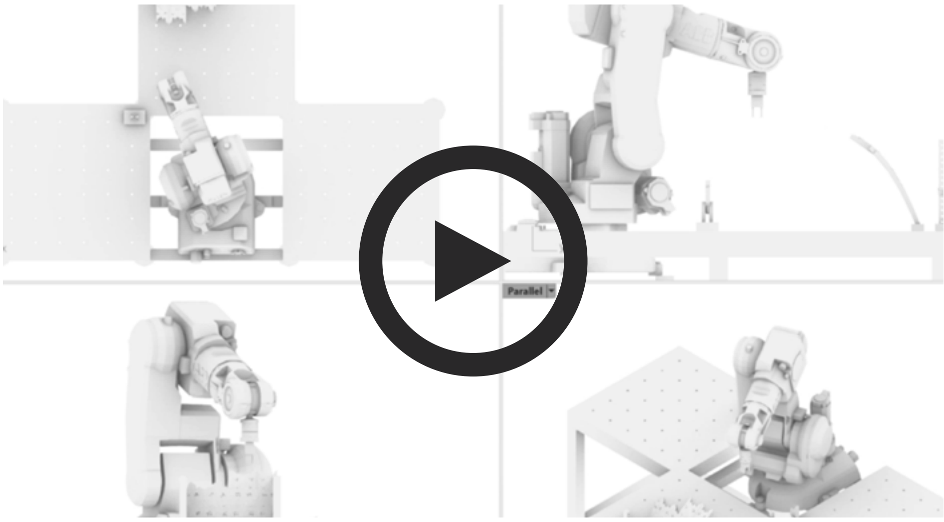


Figure 55: hanging weight - motion planning simulation _ source: author

CLICK SCAN

physical experiment - dry fit

Figure 56: hanging weight - physical experiment - dry fit source: author

CLICK SCAN

physical experiment - tape

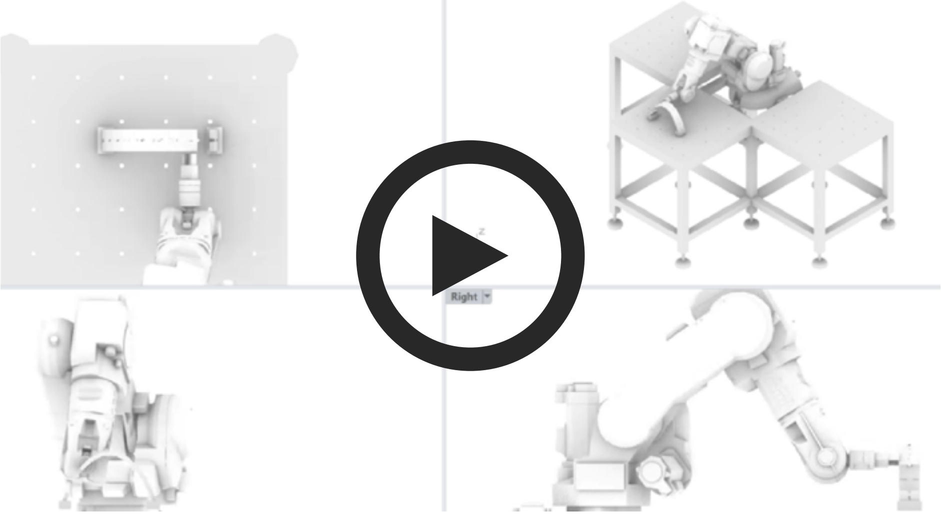
Figure 57: hanging weight - physical experiment - tape source: author

CLICK SCAN

physical experiment - modeling clay

Figure 58: hanging weight - physical experiment - modeling clay _ source: author

CLICK SCAN

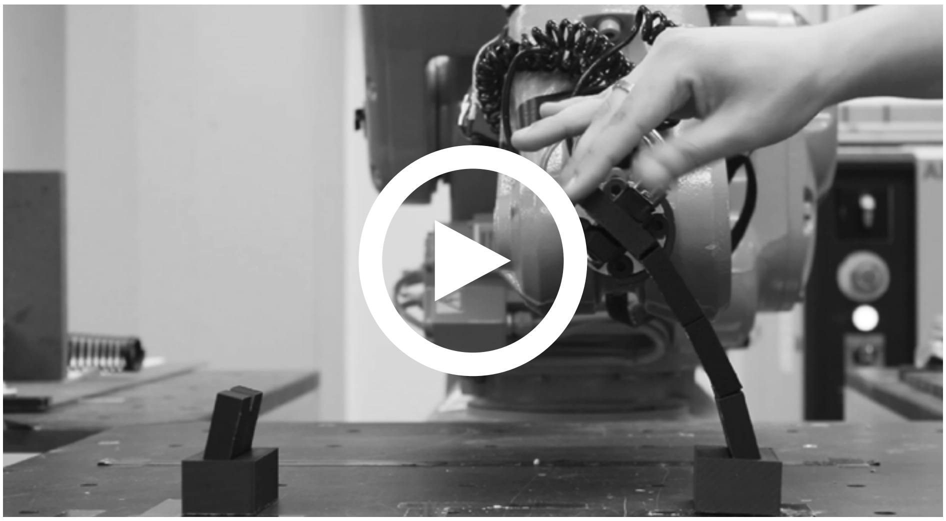


digital simulation

Figure 59: place and hold - motion planning simulation
source: author

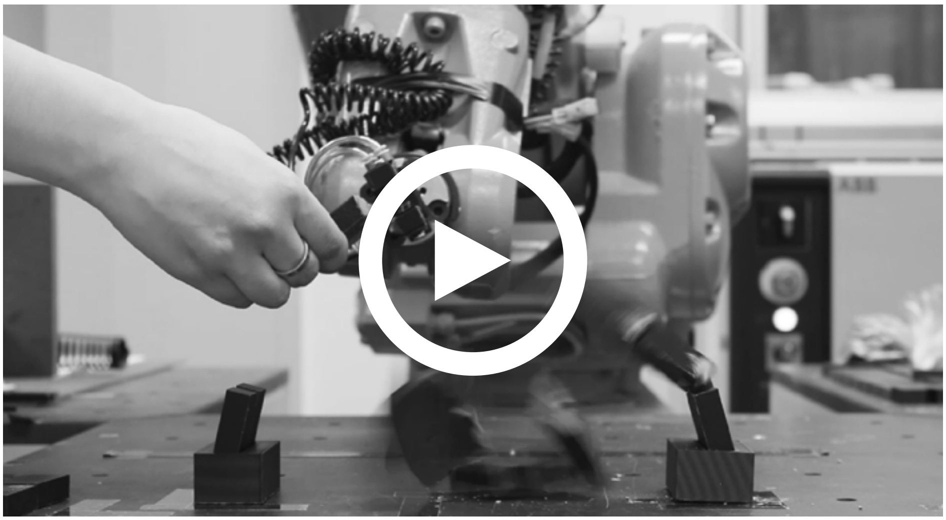
CLICK SCAN

Figure 60: place and hold - physical experiment - dry fit
source: author



physical experiment - dry fit

CLICK SCAN



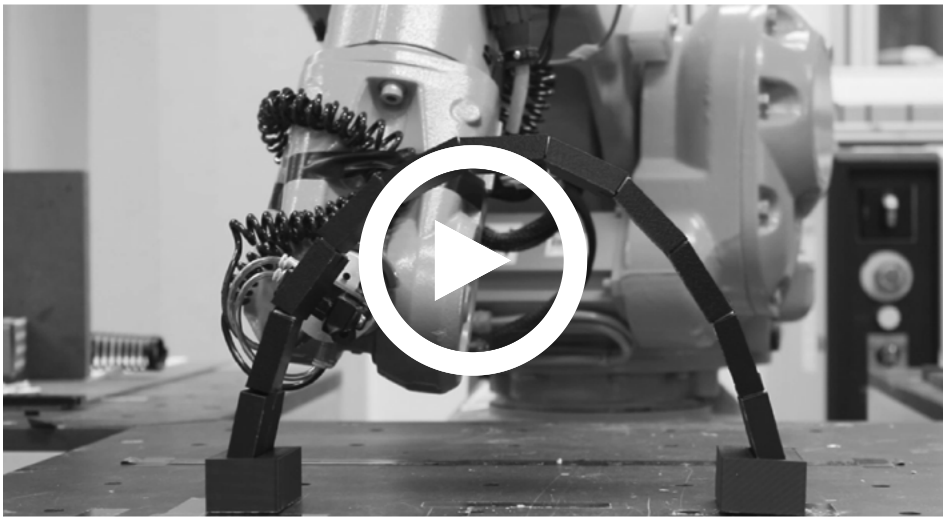
physical experiment - fast setting clay

CLICK SCAN

Figure 61: place and hold - physical experiment - fast setting clay _ source: author

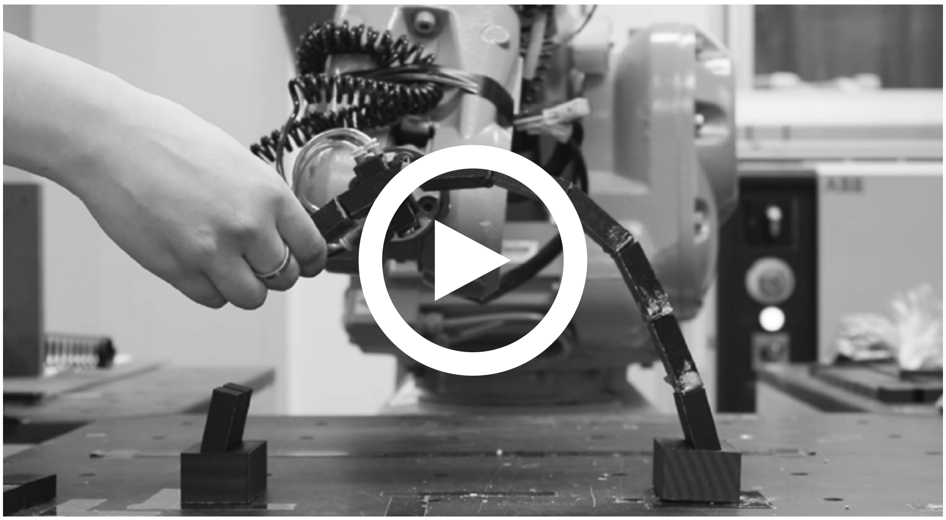
Experiment 2 – Place and hold

Figure 62: place and hold - physical experiment - tape source: author



CLICK SCAN

physical experiment - tape



CLICK SCAN

physical experiment - moldable rubber

Figure 63: place and hold - physical experiment - moldable rubber _ source: author

D. experimentation outcomes

a. Key findings

The experiments were aimed at exploring how robots can be used to facilitate building geometries that traditionally require a lot of formwork. Those explorations have led to the following findings:

- Integrating automation into the act of construction can heavily impact on the geometry to facilitate the logistics. This can be either avoided by changing the setup around, hidden during the finishing stages of the building (like a uniform mortar layer), or it can be considered part of the building and left as a testimony to how it was built (e.g., rammed earth walls).

- The imbrication system helped tremendously with the assembly process, not only by creating solidarity between the pieces but also by calibrating their placement;

Experiment 1

- The weighted rope system presents some difficulties, such as removing the rope from the brick below to support the newly placed brick, which causes to destabilize the rest of the brick “columns” while moving the rope up.

- It is also difficult to maintain binding agents in place, as the rope scrapes them away during the removal process;

- The tool to maintain the weights has to be studied carefully to avoid collisions with the robot during placements;

- Upon the gripper's release, the bricks' angles shifted to accommodate the compression enacted by the supporting weight, which augmented the error margin. This might be less problematic with heavier materials, but in the context of our experiment, the impact was too significant;

- However, despite these difficulties, the overhang achieved using this system makes it interesting enough to keep exploring by diversifying some of the parameters (topology, materiality and weight, different binders, a studied approach to the placement angle of the weights...)

Experiment 2

- The placing angle and coordinates of the bricks were inexact, and while trying to align with the robot does provide a good guide, it was still lacking precision, which could build up very easily in the case of more complex structures (more pieces or different angles);

- While the robot did provide a stable support while holding the bricks, during the manual support time the instability and tremor often cause the structure to collapse. The binding agents did help manage that aspect by providing some buffer;

- The stability reached quite promptly after starting the experiment makes it by far the most promising.

b. Room for improvement

The next step for this exploration would be to integrate the materiality and weight aspect. While early on in the process the thesis had to develop a research aim and angle (robotic assembly), material remains a very impactful parameter for compression-based structures, and while these experiments allowed to have a good outlook on certain areas, these were mostly related to the process, and not the object in itself.

While the second experiment offers great prospects in robot x human collaboration in the building process, it could also be an interesting development to have two robots alternate laying the bricks, making them engage in both assembly and support.

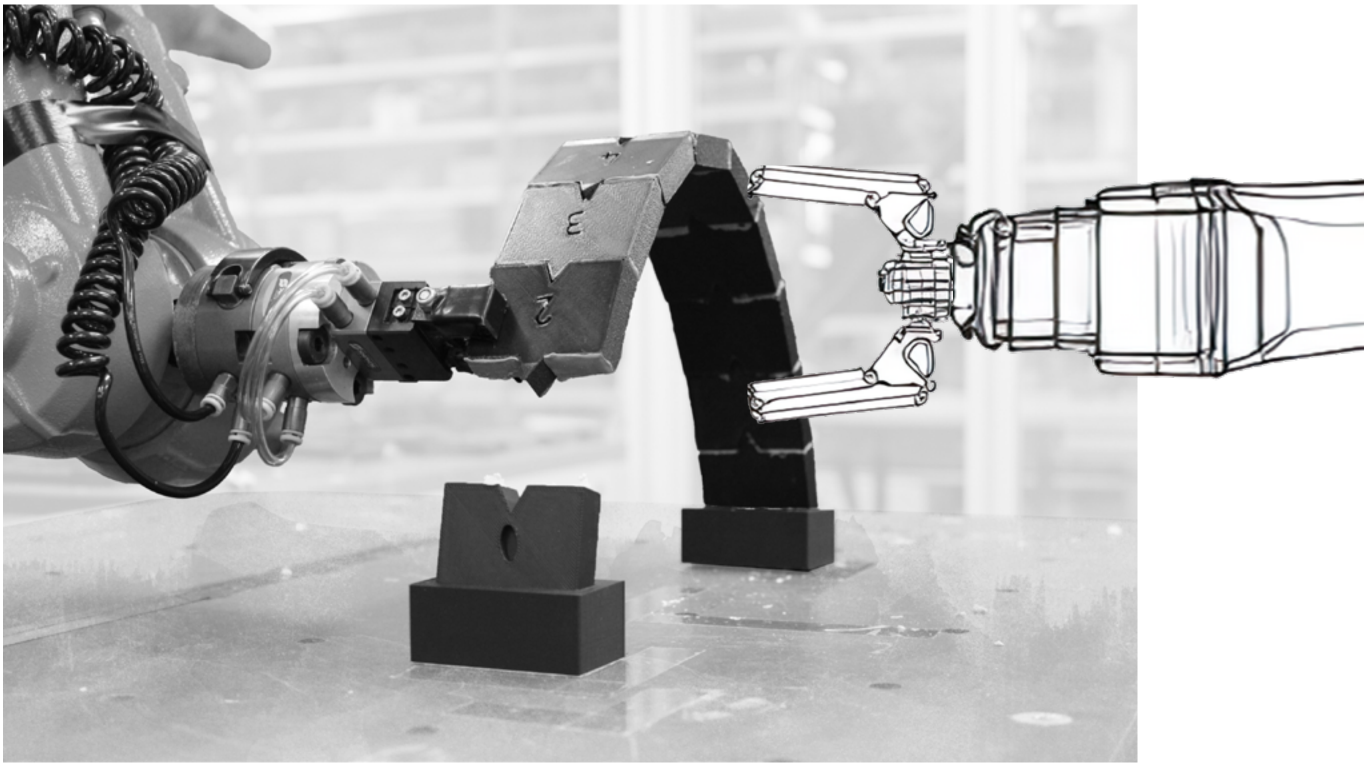
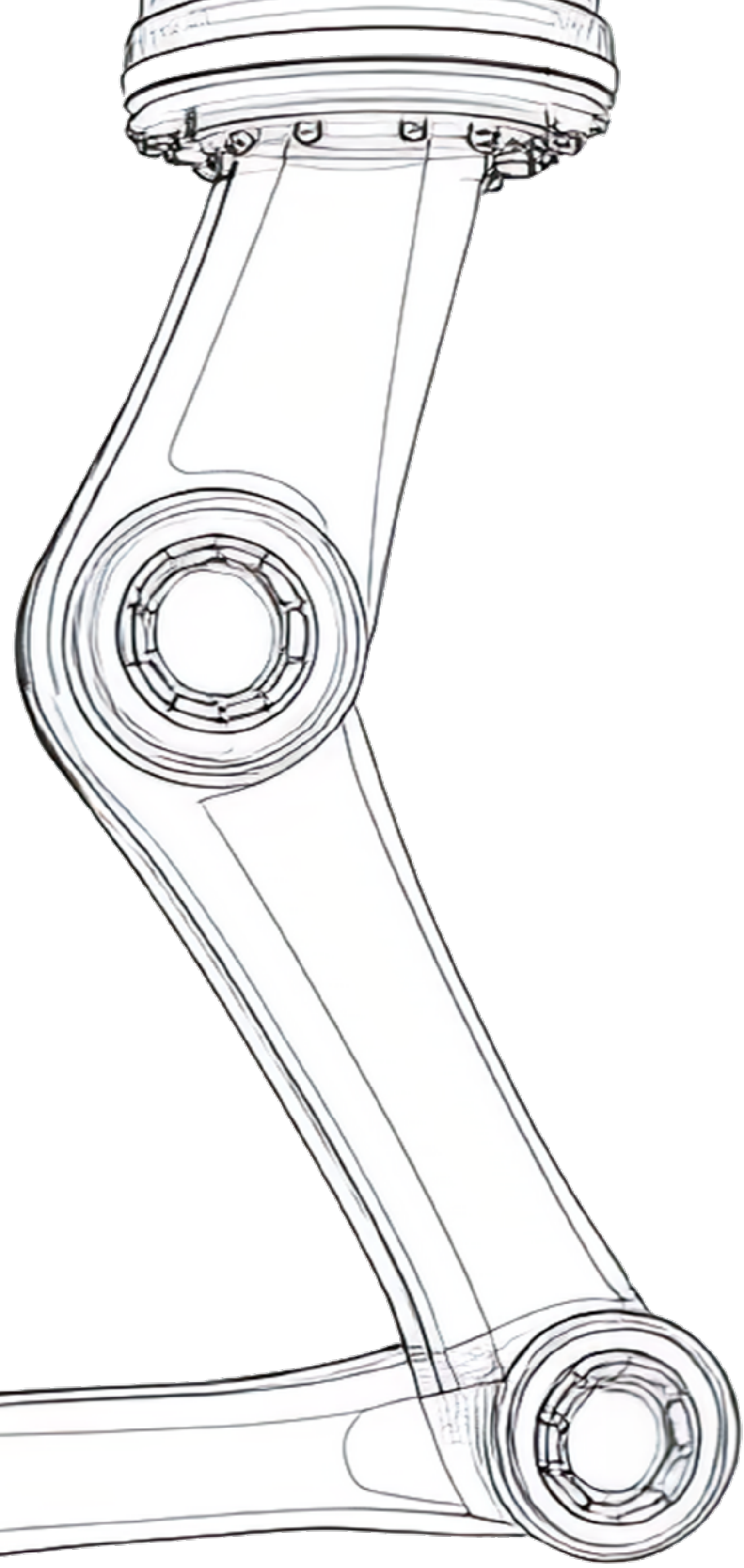


Figure 64: place and hold - last state of robotically supported stability before arc completion _ source: author



c. From lab to life

This experiment was designed as a first step of the robotic simulation of a construction process. Taking it out of the laboratory conditions and into real-life applications would necessitate reconsidering many parameters that were either limited or facilitated by the lab conditions. The nature and position of the robot would have to be considered for every different use case. This factor would be closely linked to the material used and the general shape of the vault. While a lighter material is less favourable for using weight to provide more stability in compression during the building process, it is ideal for exploring options of lighter robotic solutions such as drones, which liberates the process from a significant amount of constraints in motion planning. As for heavier and denser materials, they could provide the necessary stability and strength needed for building stronger structures, but they would require more powerful and possibly stationary robotic systems. These systems would need to handle the heavier load and would likely need more complex planning to move around the materials. Additionally, using these robots would need careful planning for energy use and operation, as heavier materials would need more power and precise control to ensure both safety and efficiency in the construction process.

03 / application

s & implications

A. use cases

From exploring historical building practices (see Annex 1) to solving placement logistics and robotic motion logic, the transition might seem significant, but it is not. This exploration is far from being purely a technical and technological prowess. Instead, it is deeply rooted in the architectural tradition where architects were also master builders, creating a full circle between innovative building practices and the integral role architects played in the construction process historically.

The next chapter, explores ideas for situations where formwork-free vaulting can be relevant and useful, accompanied by some diagrammatic images to illustrate these scenarios. Following this, a deeper discussion ensues about the role of the architect and their crucial contribution to cultivating a more diverse urban landscape, promoting a sustainable built environment, and facilitating challenging architectural endeavors.

The background drawings for the diagrams are AI-generated using Adobe Firefly, as a way to create a physical context for the applications. The vaulting solutions were modeled using Rhinoceros and Grasshopper.

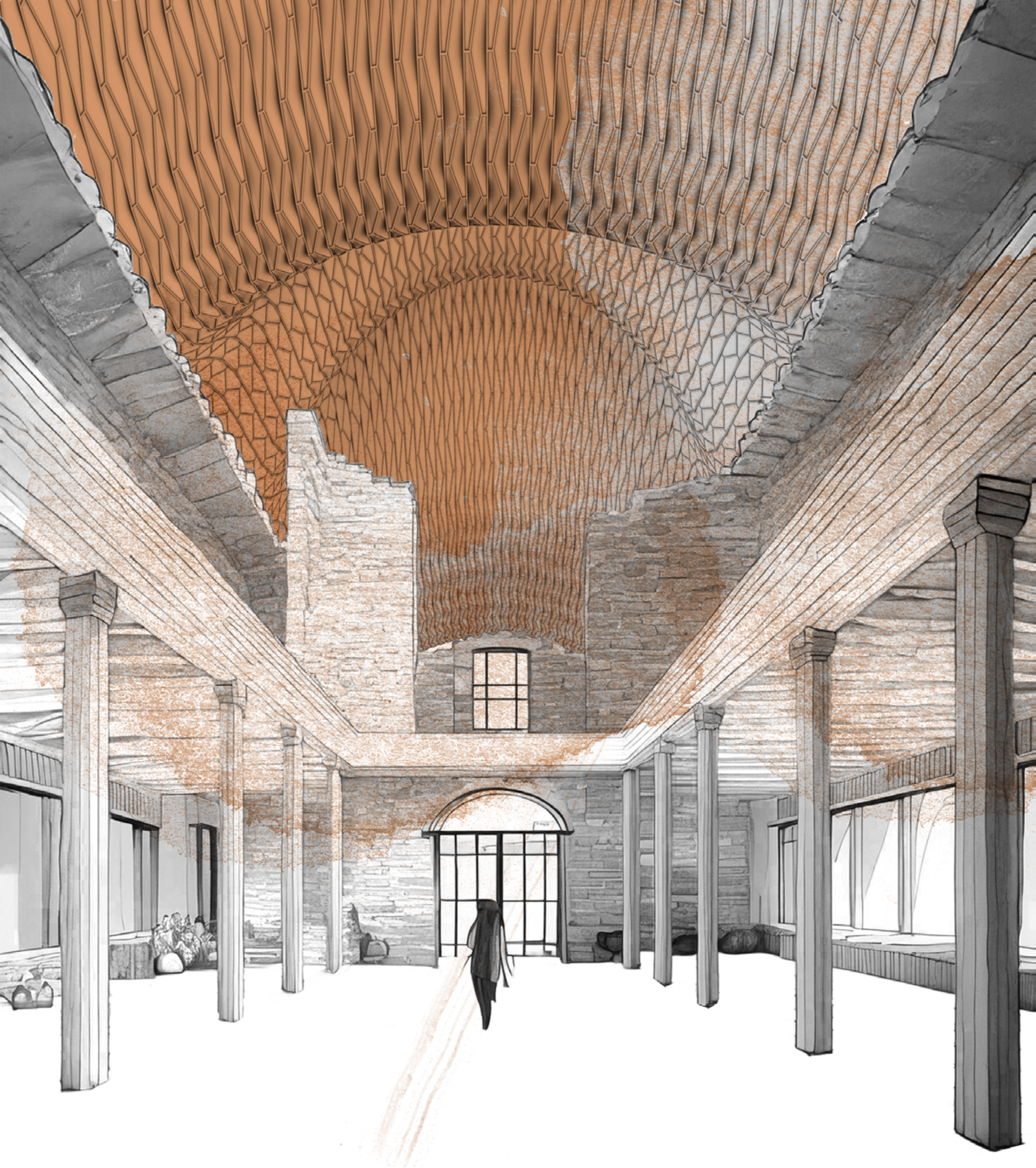


Figure 65: use cases - low-impact intervention _ source: author

a. Low-impact intervention

Interventions on historical buildings can range from relatively tricky to nearly impossible, depending on the condition and conservation of the structural skeleton. In some cases, placing formwork can be impractical due to the potential damage it could cause to the structure. In those situations, having a system that doesn't rely on direct vertical support could expand the possibilities for the project significantly.

Figure 66: use cases - form and efficiency _ source: author

b. Form and efficiency

In connection with the previous situation, avoiding formwork can be crucial when working in busy spaces, such as main streets or official buildings, where cutting public access for months until the construction is completed is not feasible. In such cases, a formwork-free solution could be ideal.

The diagram also plays with the concept of the second experiment, suggesting using drones to temporarily hold the last brick in place while waiting for the next brick to be picked up from a remote location. The mechanical features required for these machines would need to be developed by mechanical engineers.

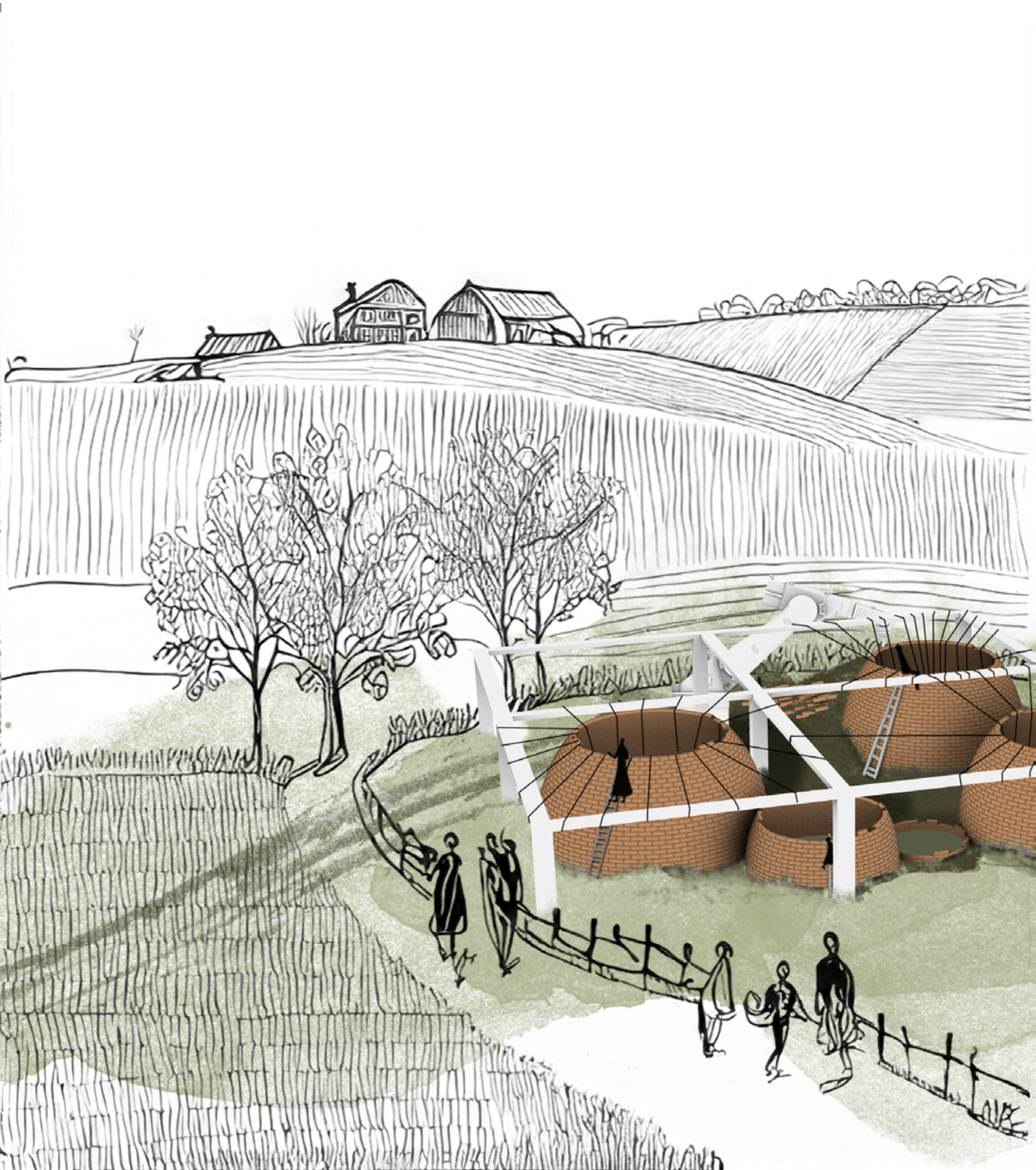


Figure 67: use cases - cultural and climate adequacy _ source: author

c. Cultural and climate adequacy

In his article “Designing like you give a damn - about what exactly? Exploring the ethics of ‘humanitarian architecture’,” Nikki Linsell discusses how the Maasai tribe returned to their traditional homes after humanitarian organizations built “modern” brick houses for them. When anthropologist Emma Crewe asked which houses they preferred, their response was: “**We may be Maasai but we are modern Maasai. Of course we want modern rectangular houses.**” (Linsell, 2014)

Vaulting has been omnipresent in various regions of the world throughout history, particularly in areas with specific climatic features. As explained in the first chapter, its climate mitigation qualities are undeniable. Over time, vaulting has evolved beyond a utilitarian form into a symbol, intertwined with familiarity, culture, and community practices.

In contemporary societies that have embraced industrial and standardized building methods, it is increasingly difficult to find workers skilled in constructing traditional non-standard buildings. Therefore, reinventing building practices by merging them with local materials and streamlining the processes to be time- and cost-efficient is crucial. This approach ensures that traditional forms remain competitive with standard building practices, preserving their unique qualities and cultural significance.

Figure 68: use cases - Remote locations and locally sourced materials _ source: author

d. Remote locations and locally sourced materials

Vaults have been constructed worldwide, using various materials such as light earth bricks, stone, and wood. This technique is therefore versatile enough to adapt to diverse contexts, utilizing local resources for construction instead of relying on transporting industrial products used in standard building practices.

In addition to significantly contributing to the sustainability of the built environment, this approach could revolutionize construction in remote areas with limited access to external resources due to geographical constraints and/or lack of infrastructure.

Moreover, it reinforces the communal independence and resilience in maintenance, as having locally available materials and standardized know-how can reduce the cost of repairs or reconstruction, such as in the event of natural disasters.

B. the multiple facets of design

a. Bridging form and material

Studying how materials behave and using that knowledge to build better structures offers several benefits. Exploring form to generate structure, as demonstrated through methods like graphic statics, we can create more efficient and effective construction processes. This approach mirrors the practices of traditional master builders who worked closely with materials to construct enduring buildings.

Louis Kahn's famous quote regarding what shape a material wants to embody illustrates the importance of respecting the preferences of materials in design. When architects consider these preferences, they can develop innovative construction systems that leverage the strengths of each material, thus diversifying the range of possibilities and alternatives to improve our building practices. While concrete itself isn't the absolute devil, the issue arises when standardized and industrialized building practices prioritize profit over sustainability.

Architects have a crucial role in moving away from standardized practices and exploring alternative materials and techniques. By incorporating these considerations into building design, architects can advocate for more sustainable approaches that prioritize the long-term environmental impact of structures. This shift towards diverse materials and techniques has the potential to promote more sustainable building practices and reduce the negative environmental effects of industrialized construction.

b. Plurality in architecture

Vaults found worldwide offer examples of how construction practices can reflect cultural diversity. Beyond their shapes and types, vaults hold ecological and cultural value rooted in traditional practices using local materials. These structures often excel in thermal performance, adapted to local climates. Culturally, vault typologies involve communal building and maintenance traditions, fostering community engagement without industrial intervention.

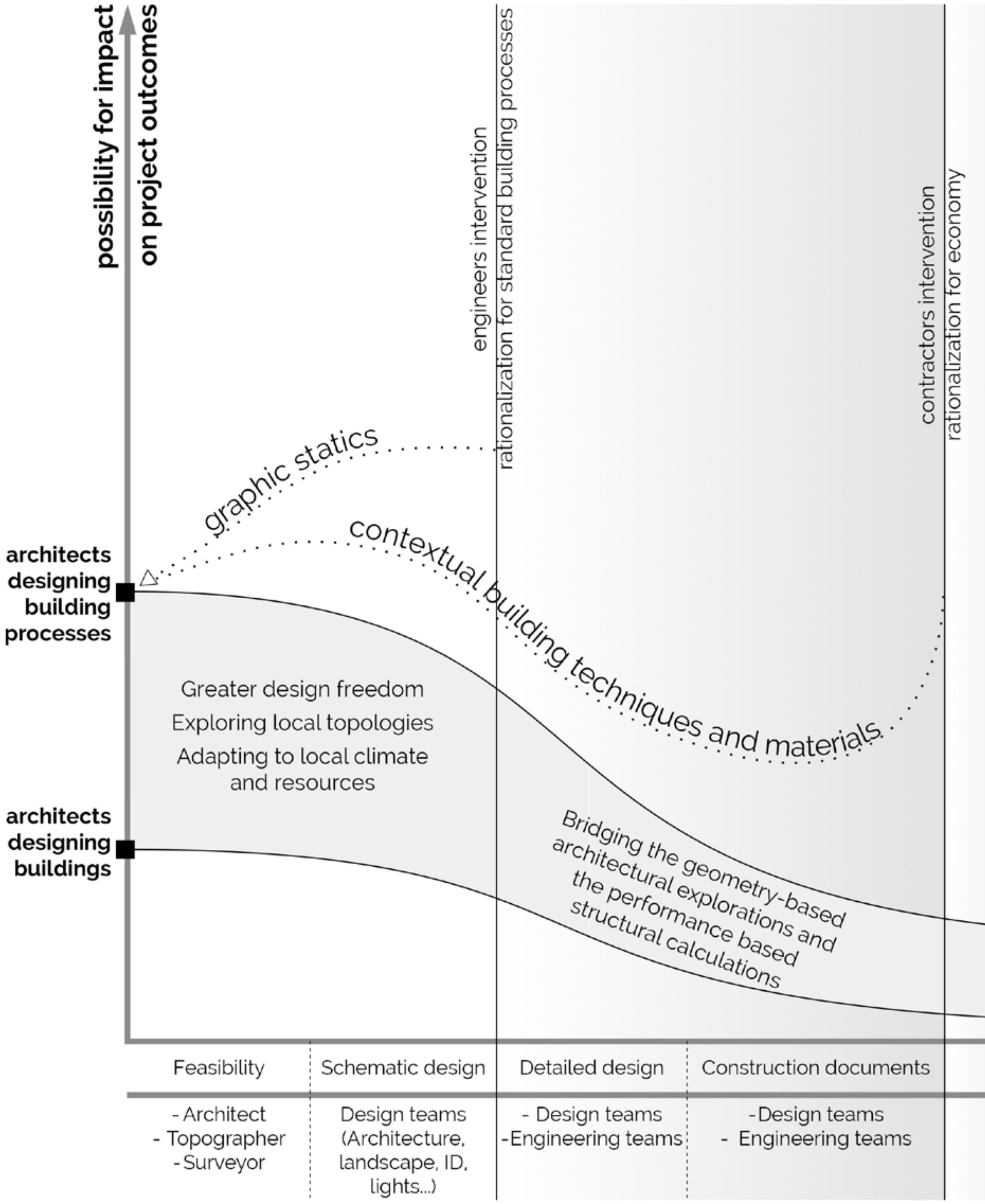
Emerging architects skilled in digital fabrication and assembly play a vital role in bridging cultural heritage with modern construction methods. Their sensitivity to space and culture, coupled with a willingness to explore, enables them to integrate new building practices as early as at the design stage. By streamlining traditional building processes with digital tools, architects can connect traditional techniques to contemporary construction, expanding their impact within the industry.

Introducing modernized rules to traditional building practices facilitates knowledge conservation and widespread use. By simplifying old techniques, we create an accessible framework for their adoption, challenging the default reliance on industrial methods. Accessibility is crucial, ensuring that innovations benefit all communities, particularly those with limited resources.

The aim is to find a middle ground between museifying communities and civilizations, and between stripping them completely off their specificities and imposing imported urban typologies on them. Modernity can take different forms, and that is why having the building practices evolve with societies is crucial to reach that equilibrium.

c. Architects and building processes

Architects are the first to intervene in a construction project. Furthermore, they are present throughout the whole process, and have to intervene at every stage and



collaborate with all other parties involved.

As the project advances, the chances for positive impact on the outcome (for any metric, eg. cost, efficiency, sustainability...) decreases. This underscores the architect's pivotal role in effecting change.

Integrating building processes with the act of design is the solution. By collaborating with the different stakeholders from the get-go, to integrate considerations for structure, material and cost optimization as the start of the design process, we gain huge potential for a true paradigm shift, to move towards better building practices and outcomes.

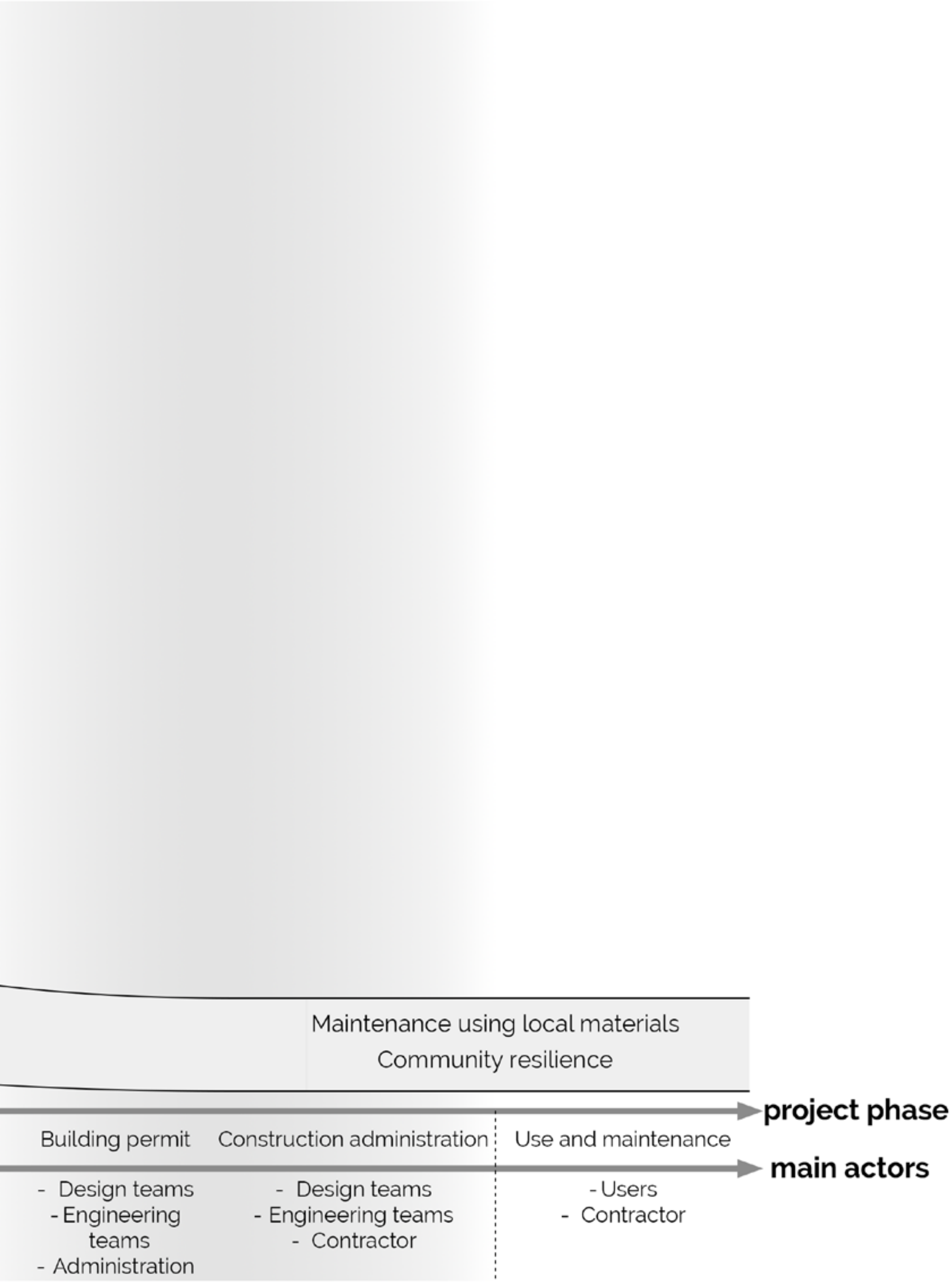
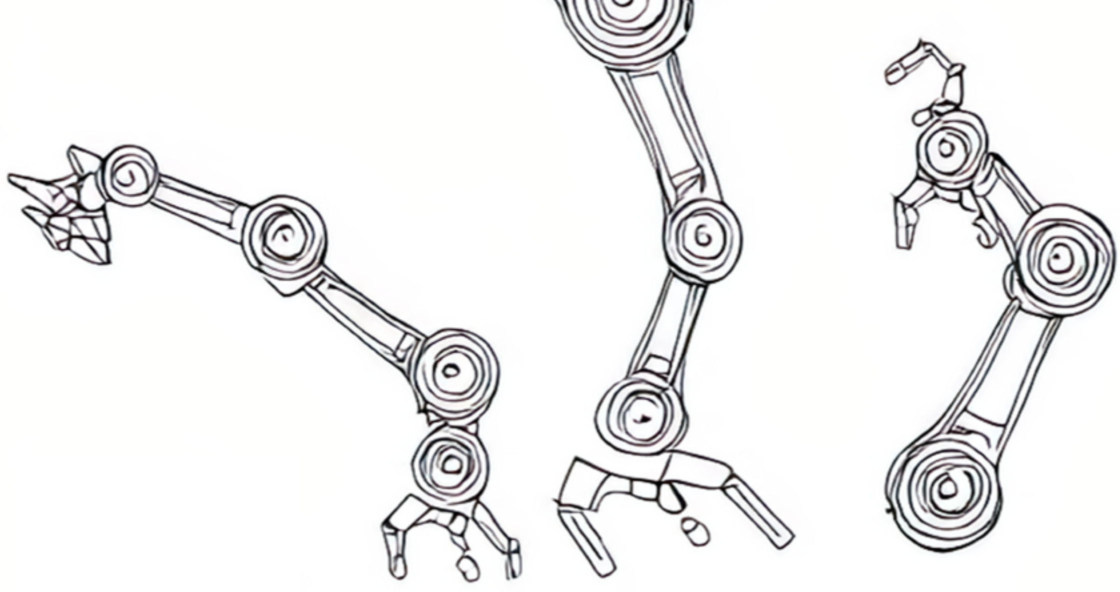


Figure 69: redefining the building process paradigm _ source: author

04

conclusion

conclusion

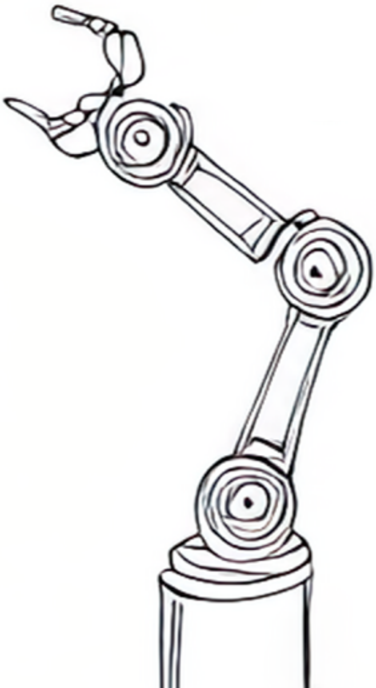


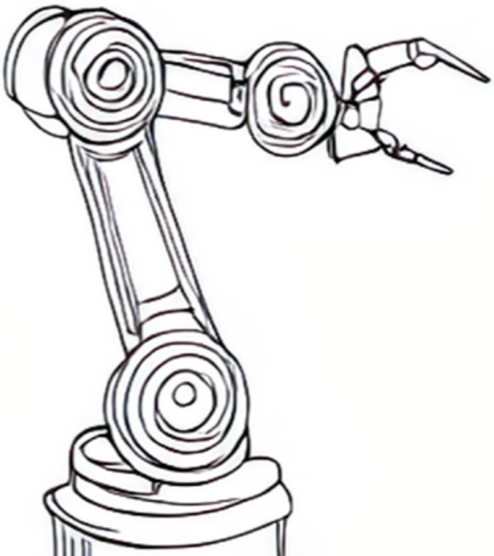
This thesis explores the integration of robotic assembly in the construction of formwork-free vaults, merging historical vaulting techniques with automation and digital fabrication. Various manual and robotic experiments were conducted to investigate the challenges and opportunities of this approach.

Manual experiments provided valuable insights into practical aspects of brick placement and motion planning, while robotic experiments highlighted the feasibility of different assembly methods and the importance of integrating material properties and weight considerations.

The potential of blending historical building practices with contemporary digital tools to create more sustainable and efficient construction methods was proved to be subsequent. By re-imagining building processes and exploring different architectural topologies, we can address the limitations of current industrialized building practices, which often prioritize cost and time efficiency over ecological and cultural considerations.

Robotic assistance can play a crucial role in preserving and evolving traditional construction methods, so that modernity could take a broader meaning tightly linked to context. Future research should focus on refining the robotic assembly process (human x robot VS robot x robot), exploring materiality, and expanding the realm of applications to include different architectural typologies and contexts.





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