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Robotically assembled brickwork

Manipulating assembly processes of discrete elements

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Abstract

Today, the advance of digital technologies, both on the side of conceptualisation of architecture and on the side of its production, enable information penetration across the whole process of making – from design to fabrication. This opens up new ways of thinking about architectural design and materialisation. Within the large family of computer controlled fabrication machines, industrial robots are especially well suited to be adopted for construction work, mainly because of their ability to perform variable assembly tasks. Although, so far applying robotic technologies in construction has mainly been viewed from an industrial engineering perspective, geared towards increasing productivity through automation without a link to the potentials for architectural design.

In the present work, potentials inherent in robotically controlled assembly processes are investigated from an architectural perspective, specifically focusing on the interrelation of design and fabrication. This is exemplified by the means of brickwork, which was chosen, because the relative small size of the single brick module and their generic geometry is well suited for a robotic assembly process. Further, the layering of bricks resembles one of the fundamental assembly processes in architecture and can easily be singled out as a well-defined subdomain of construction.

The robotic-based assembly processes and their corresponding design criteria are investigated through several physical experiments. The experiments combine both the design and engineering of a robotic fabrication process and, consequently, the application of the fabrication process on a design task.

The aim is to define techniques and methodologies for robotic-based assembly processes of brickwork, where the architectural design evolves into the interplay between conceptual intention and the engineering of a robotic process. The work is built on the hypothesis that the synchronisation of design and making can instigate novel design solutions for brickwork and is essential to leveraging new architectural potentials.

Zusammenfassung

Der Einsatz digitaler Technologien in der Architektur – von der Konzipierung einer architektonischen Idee, bis hin zu ihrer baulichen Ausführung – ermöglicht heute eine nahtlose Durchdringung von Informationen über den gesamten Herstellungsprozess. Dies erlaubt es, die Verbindung zwischen dem architektonischen Entwurf und dessen Materialisierung neu zu denken. Für die Umsetzung computergesteuerter konstruktiver Bauprozesse eignen sich insbesondere Industrieroboter, vornehmlich durch ihre Eigenschaft, unterschiedlichste Assemblierungsaufgaben auszuführen. Bisher stand bei dem Einsatz von Robotern im Bauwesen hauptsächlich die Mechanisierung manueller Prozesse im Vordergrund. Das Bestreben war dabei primär, eine Produktivitätssteigerung durch Automatisierung zu erreichen. Die Wechselbeziehung zu Konstruktion und Gestaltung eines Bauteils wurden dabei weitestgehend vernachlässigt.

In der vorliegenden Arbeit werden die inhärenten Potentiale roboterkontrollierter Assemblierungsprozesse aus einer architektonischen Perspektive und unter besonderer Berücksichtigung der Korrelation zwischen dem Akt des Entwerfens und dem Akt der Produktion untersucht. Beispielhaft wird dies anhand von Mauerwerk aufgezeigt. Neben der Tatsache, dass das Aufschichten von Ziegelsteinen eines der fundamentalsten Assemblierungsprozesse in der Architektur darstellt, eignet sich Mauerwerk auf Grund der relativ geringen Grösse des einzelnen Ziegelmoduls und dessen generischer Geometrie besonders für eine roboterbasierte Fabrikation.

Über eine Folge physischer Experimente werden roboterbasierte Assemblierungsprozesse sowie korrespondierende Gestaltungskriterien entwickelt und analysiert. Die Experimente verbinden jeweils den Entwurf und Konstruktion eines roboterbasierten Assemblierungsprozesses und dessen Anwendung innerhalb einer Entwurfs- und Bauaufgabe.

Ziel ist es, Techniken und Methoden für einen roboterbasierten Assemblierungsprozess für Mauerwerk zu identifizieren, wobei der architektonische Entwurf sowohl die konzeptionelle Gestaltung eines Bauteils als auch die Entwicklung eines kongruenten physischen Roboterprozesses umfasst. Im Zentrum der Arbeit steht somit die Hypothese: dass durch die wechselseitige Synchronisierung des Entwurfs- und Herstellungsprozesses neue konstruktive Potenziale und Ausdrucksformen im Mauerwerksbau entwickelt werden können.

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This work has only been made possible due to the support and involvement of many people throughout the years and to whom I would like to express my thanks:

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1 INTRODUCTION

1.1 Background and Motivation

This thesis develops novel methodologies and techniques for a singular robotic-based fabrication process for facing brickwork that integrates digital design with the physical assembly process. As subject matter, brickwork is especially well suited to investigate the relation between advanced architectural design and robotically controlled assembly processes. Brickwork is composed out of identical discrete elements of relative small size, i.e. bricks. Therefore, bricks can easily be handled in an automated robotic processes and as such automating brickwork by the means of robots has already been subject to research in the 1990s.[1]

The last couple of years have seen a renewed interest to apply robotic systems to construction work and the fabrication of architectural elements. This engagement is characterised by a shift in focus: from engineering-oriented towards a design-oriented approach. The former approaches robotics in construction predominantly from a managerial mindset, with the aim to automate the building process. Accordingly, the main objective is to increase productivity and to achieve a greater control of on-site construction work.[2] Robotic systems are meant to mimic and, ultimately, replace manual construction processes. Further, due to the attempt to apply industrialised methods to construction work, the processes are primarily geared towards efficiency and standardisation.[3]

In contrast, the recent interest of architects and designers in robotics is characterised by a different approach, which concentrates on the inherent variability of robotic systems and how this can be implemented already at an early stage of the architectural design process. This approach is supported by changing technical and economic conditions. Both in terms of initial costs and controllability of robotic systems, which have become

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[1] See Section 3.2.

[2] For a list of the main drivers for automating building processes in the first attempts to apply robotics to architecture and construction in the 1980s and 1990s see W. Poppy, "Driving forces and status of automation and robotics in construction in Europe," *Automation in Construction* 2, no. 4 (1994).

[3] Though efforts of automation are also argued with relieving workers from strenuous and hazardous work, it is the low productivity of construction work compared to other manufacturing industries, namely the automobile industry, that can be identified as the main driver of automation in construction. See for example C. Balaguer and M. Abderrahim, "Trends in Robotics and Automation in Construction," in *Robotics and Automation in Construction*, ed. C. Balaguer and M. Abderrahim (In-Teh, 2008), 2-4.

much more accessible over the last decade.[4] Today, by directly engaging with the machines, architects and designers apply robotic systems not only as means for automation of construction work, but for design exploration.[5]

Given, that this involvement with robotics in the field of architectural design is relatively new, the question of *if* and *how* an in-depth engagement with robotic processes expresses itself in the design and what overall impact this has on architecture is not yet answered. Such an involvement can affect the way we conceive architecture, in the case of this thesis the techniques and methods to digitally design brickwork, as well as the performance of the resulting architectural objects (e.g. in regards to construction, statics, building physics, aesthetics etc.).

While the term robot has a broad denotation that covers a large spectrum from simple machines for automation to intelligent acting autonomous apparatuses, this dissertation focuses specifically on applying 6-axis articulated arm robots – commonly referred to as industrial robots – as a means to the form giving of architectural artefacts (Figure 1).[6] Industrial robots are well established and robust machines, intended to perform material handling and diverse fabrication tasks. They offer three articulations for the positioning of the arm in space and three more to position its hand. But, industrial robots are *not* intelligent devices and only as complex as their respective control programmes.

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[4] See Section 2.4.

[5] This reinterpretation adopting industrial robots for architectural design and production was spearheaded by Gramazio Kohler Research at ETH Zurich, see F. Gramazio, M. Kohler, and J. Willmann, eds., *The Robotic Touch - How Robots Change Architecture.* (Zurich: Park Books, 2014). A further indication of the increased interest in robotics in the realm of architecture can be seen in the fact that the 32nd Annual Conference of the Association for Computer Aided Design in Architecture devoted a whole session to robotic constructions. See *ACADIA 12: Synthetic Digital Ecologies*, 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) (San Francisco: 2012). 2012 also saw the first international conference on robotic fabrication in architecture, art, and design in Vienna. See S. Brell-Cokcan and J. Braumann, eds., *Rob|Arch 2012: Robotic Fabrication in Architecture, Art and Design* (Vienna: Springer, 2013).

[6] The ISO (8373:2012) defines robots very generically as, “actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks.” The more specific term industrial robot comprises all robots applied to industrial applications. See ISO 8373:2012. “Robots and robotic devices - Vocabulary,” (2012). Since the majority of industrial robots are 6-axis articulated arm robots, these terms are used synonymous.

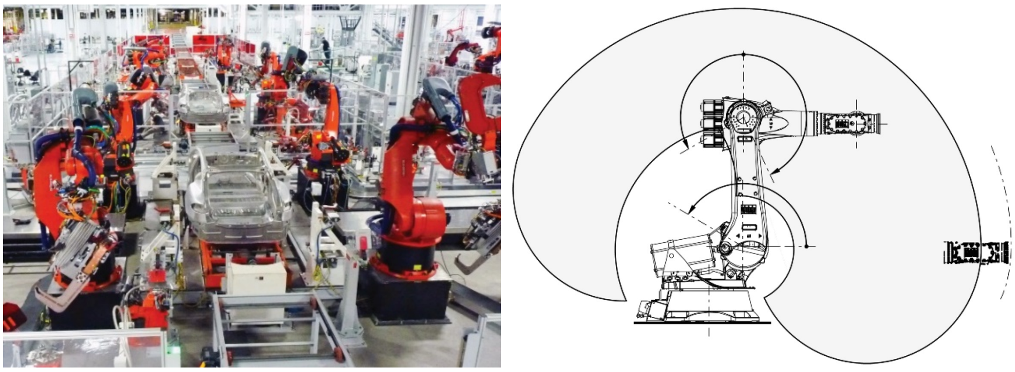

Figure 1. (left) Typical robotic assembly line at Tesla Factory; (right) Scheme of 6-axis articulated arm robot.

Since they are programmable machines, certain analogies can be drawn between industrial robots and computer numerically controlled (CNC) fabrication tools, such as routers, mills, or laser-cutters that have been adopted in the architectural realm over the last two decades. Digitally controlled fabrication machines – combined with digital design tools – allow for a direct transfer of design information to the fabrication of architectural artefacts. The potential for a seamless information flow permits the designer to gain greater control over the fabrication process, up to providing the data to explicitly define each fabrication step. This close coupling of the process of design and making is seen as a promise to narrow or even close the fabrication gap existing between the formulations of a design intent and its physical execution. A gap usually existing between the traditional medium of the architect, the drawing, which is restrained in the amount and quality of information it can convey, and the final physical outcome, which relies on the interpretation of the builders.[7] Further, digital fabrication machines can produce complex and unique components with only minimal or no additional expenses to standard components. Accompanied by the computational power of the digital design tools to easily create complex geometries or to create variability and differentiation through scripting, digital controlled fabrication machines can thus facilitate the production of non-standard[8] designs in an automated process.

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[7] This should by no means reduce the value of the medium of drawing in the process of creating architecture. As Robin Evans argues, the separation between drawing and building also holds great generative power for architecture. See R. Evans, "Translations from drawing to building," in *Translations from drawing to building and other essays*, AA Documents (London: Architectural Association, 1997).

[8] The term *non-standard* relating to architecture is used in reference to how something was made, as outlined by Mario Carpo: "In its simplest definition, non-standard production means the serial reproduction of non-identical parts". As such, items of a series although all different from another share a common "algorithmic matrix" in their geometrical definition, but also in the way they are produced, i.e. on the same machine using the same tools. In contrast to standardised mass production, non-standard production opens the potential to produce architectural objects that are specific to a given project. For example, they can respond to external parameters specific to a certain location, or can be optimised in form and material usage according to structural requirements. See M. Carpo, "Tempest in a Teapot," *Log*, no. 6 (2005). On the aspect of differentiation and variability in an automated design and construction process, see also M. Carpo, *The alphabet and the algorithm*, Writing architecture (Cambridge, Mass.: MIT Press, 2011).

However, beyond that industrial robots also exhibit specific features, which distinguish them from common CNC-machines. Within this thesis, following characteristics of industrial robots are of particular importance: 1) their universal nature, 2) their suitability for different assembly tasks, and 3) the ability to work in a 1:1 constructive scale.

The universal nature denotes the possibility to apply industrial robots to a multitude of diverse tasks. Their programmability does not only refer to the digital control of its movement and actions, but beyond that to the definition of the actual physical fabrication process. In contrast to CNC-machines the latter is not predefined, but dependent on the tool the robot is equipped with. These tools, so called *end-effectors*, can be highly specific and unique for a particular fabrication process. They can be designed to perform a physical material manipulation, but also to gather information, for example by probing, scanning, or measuring. As such, an industrial robot is a generic tool that constitutes a multitude of different fabrication machines in one (Figure 2).

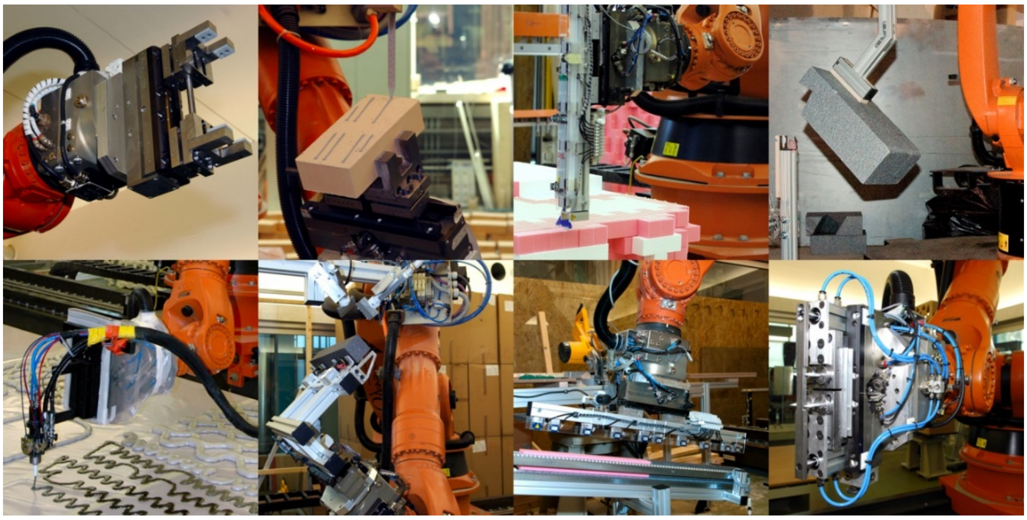

Figure 2. A variety of different custom designed end-effectors attached to the same robotic arm performing a variety of different processes.

In consequence, industrial robots can also be applied to mimic existing CNC-machines. In fact, a great number of projects in architecture apply robotic fabrication in that way. Examples are the *Surfacing Stone*[9] project (Figure 3), where an industrial robot was applied for water jet cutting of marble, or the *ICD/ITKE Research Pavilion*,[10] constructed at the University of Stuttgart in 2010, where a robot was applied as a milling

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[9] The project can be viewed online: http://www.gsd.harvard.edu/#/projects/surfacing-stone-1.html (accessed: April 15, 2015).

[10] See M. Fleischmann and A. Menges, "ICD/ITKE Research Pavilion: A case study of multi-disciplinary computational design," in *Computational Design Modeling*, ed. C. Gengnagel, et al. (Berlin: Springer-Verlag, Berlin/Heidelberg, 2011).

tool. Although, these projects represent interesting and sophisticated investigations in material, fabrication technology, and constructive systems, they do not foster the inherent capacities of robotics in an architectural design and fabrication process. Even though, industrial robots were applied for fabrication, these processes could equally be performed applying available 5-axis machine tools (Figure 4).[11]

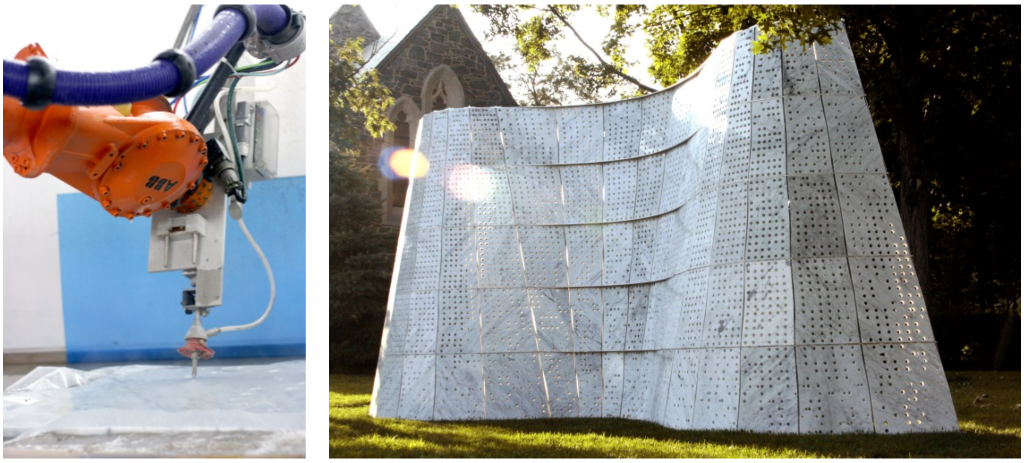

Figure 3. Surfacing Stone: (left) robot applied as a water jet cutting machine; (right) wall assembled out of individually formed and perforated marble plates.

Figure 4. ICD/ITKE Research Pavilion: (left) robotic milling of plywood plates; (right) assembly of planar plywood plates to a bending-active system.

In contrast, the potential of industrial robots lies in ability to realise custom processing techniques and assembly sequences. Apart from explicitly defining the control data of the fabrication process, the material manipulation itself can be designed. Thereby, the

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[11] This assumes that for instance a 5-axis router would feature a similar working envelope compared to the reach of the robotic arm.

definition and engineering of a project-specific fabrication process can become part of the overall design process and in consequence is subject to design decisions. As a result, industrial robots provide the opportunity to follow fabrication processes outside the given framework of common CNC-machinery.

The second aspect that distinguishes industrial robots from most CNC-machines is that the kinematics of the robotic arm lends itself particular well to assembly tasks.[12] Therefore, within the family of digitally controllable machines industrial robots are especially well suited to be adopted for construction work: a typical building process is mainly composed out of assembly tasks and construction can generally be described as the assembly of different parts and materials.[13] CNC-machines on the other hand – having their origin in the automation of machine tools – are geared towards the production of components, mainly through applying cutting or deformation processes. Though, in order to form a constructive system, these components still need to be assembled.[14]

While CNC-machines are already widely applied to manufacture parts and components for construction, both standard and individual components down to the lot size one,[15] exploiting the programmability of an industrial robot to create flexible, non-standard assembly processes for the production of architecture has now come into the focus of research and is gaining momentum.[16]Although, the efforts of adopting robotic systems for construction work in the 1990s built upon this specific characteristic of an industrial robot as an assembly tool, exploiting its digital controllability for architectural expression already in the design stage was not part of the agenda. On the contrary,

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[12] Industrial robots were initially developed for the handling of parts, in an effort to replace factory workers. This explains their evolution towards a kinematic system that in its physical structure resembles the human arm. In its structure, the links and joints of an articulated robot can be mapped against the anatomy of the human body, i.e. torso, chest, shoulder, upper arm, elbow, forearm, and wrist. The human hand itself is then represented by the end-effector. See G. S. Hegde, *A Texbook of Industrial Robotics* (Laxmi Publications, 2006), 21-22. For an in-depth comparison of industrial robots and humans, see S. Y. Nof and V. N. Rajan, “Robotics,” in *Handbook of Design, Manufacturing and Automation* (John Wiley & Sons, 1994), 271-75.

[13] In an interview with Ingeborg M. Rocker, Greg Lynn points towards the importance of assembly within architecture and how it was overlooked in the first wave of digital architecture: “Architecture has a disciplinary history and responsibility to express parts-to-whole relationships and hierarchy. At first, because we were amateurs, we didn’t express this and instead buildings were proposed as seamless monolithic hulking masses.” See I. M. Rocker, “Calculus-based form: an interview with Greg Lynn,” *Architectural Design* 76, no. 4 (2006): 90. In contrast, industrial robots now allow transferring digital design information into physical assembly processes.

[14] Digital control of CNC-machines now allows realising non-standard designs, where every single component is different, which can make the assembly task quite challenging, especially for a large quantity of components, which are all potentially uniquely shaped.

[15] Within the building industry subtractive processes are predominant, mainly the variety of CNC-tools applied in wood machining. See, for example, C. Schindler, “Ein architektonisches Periodisierungsmodell anhand fertigungstechnischer Kriterien, dargestellt am Beispiel des Holzbaus” (Ph.D., ETH Zurich, 2009). For a brief overview of process specific digital fabrication machines in manufacturing see for example B. Kolarevic. “Designing and Manufacturing Architecture in the Digital Age.” In *Architectural Information Management, 19th eCAADe Conference Proceedings*. (Helsinki, 2001), 117-23.

[16] This is a completely different approach from the research in robotics for construction of the 1990s, where the focus was on automating existing processes. Research in applying robots for assembly in architecture, in contrast to predominantly subtractive processes of CNC-machines, is pioneered by the group of Gramazio Kohler Research at ETH Zurich, of which the author was part of since 2006, see for instance M. Kohler, F. Gramazio, and J. Willmann, “Die Operationalität von Daten und Material im digitalen Zeitalter,” in *Positionen zur Zukunft des Bauens: Methoden, Ziele, Ausblicke*, ed. S. Hofmeister and C. Hellstern (München: Edition DETAIL / Institut für int. Architektur-Dokumentation, 2011).

building systems and design standards were derived to best meet standardised robotic assembly processes.[17]

Combined with their universal nature, robotically controlled assembly processes can establish a close link between non-standard design and contemporary building practice. Potentially, they allow for an explicit control over the construction process, by 1) enabling to define a specific physical assembly process, and 2) controlling the execution of this process by the means of digital design data. For example, instead of introducing differentiation and complexity in the individual component that form a whole, differentiation and complexity can now be introduced through the digital control of the assembly process. This unique situation in architectural practice opens up new ways of thinking about architectural design and materialisation and it sets the basis for the experimental investigations of this dissertation.

1.2 Thesis

The relevance of investigating robotic assembly processes of brickwork builds upon the hypothesis that the synchronisation of digital design and robotic assembly processes can instigate novel design solutions and is essential to leveraging new and partly unattended architectural potentials that put forward fundamental principles of construction and materiality. This is particular the case when dealing with a large number of discrete elements such as, for example, bricks.

Architecture is a material practice that manifests itself in physical reality. A conceptual design and the technology applied for its conversion into reality are intrinsically tied to one another. Therefore, the formal expression of an architectural product cannot be thought independent but is likewise determined by its material qualities and the processes applied to manufacture it.[18] In other words, architecture is a result of a process synthesizing both design and making. Though, throughout the evolution of architecture as a profession, beginning in the Renaissance, the intellectual process of design and the physical process of giving form grew more and more apart.[19] Industrialisation, which

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[17] See for instance, T. Bock, "Robot-oriented design" (paper presented at the 5th International Symposium on Robotics in Construction, Tokyo, Japan, June 6-8 1988).

[18] Semper formulates three integral aspects that define form in architecture: purpose, material and manufacturing process, G. Semper, *Der Stil in den technischen und tektonischen Kuensten, oder praktische Aesthetik*, 2nd ed., vol. 1 (München: Bruckmann, 1878), 7-9.

In his paper "Style in Design" Herbert Simon follows a similar notion, when he argues that "style can arise from three sources: the direct specifications of the final object, the nature of the process used to manufacture it, and the nature of the process used to design it," H. A. Simon, "Style in Design," in *Second Annual Environmental Design Research Association Conference - EDRA TWO*, ed. J. Archea and C. Eastman (Pittsburgh, Pennsylvania: Dowden, Hutchinson & Ross, Inc., 1970), 1.

[19] See, for example, J. Hill, "Building the Drawing," *Architectural Design* 75, no. 4 (2005): 13-21.

provided architecture with the concept of modularisation and mass-produced standardised components, further widened this gap.

As previously discussed, the advance of digital technologies – both on side of conceptualisation of architecture in the form of digital design tools, and on the side of production in the form of computer controlled fabrication tools – today enable again a closer connection between design and making. Thereby, adopting industrial robots with their unique characteristics is of specific interest for architecture. As programmable, universal assembly machines they can enable the direct control of the building process. It is this ability that allows for the creative and explorative part of making to instigate the architectural design process.

By addressing practical, methodological and theoretical obstacles to robotic assembly processes in architecture, this thesis aims to develop fabrication techniques, as well as establish corresponding design criteria and methods for non-standard brickwork that synchronise digital design with a robotic assembly process. Thereby, this thesis can pave the way for the exploitation of potential applications in the field of automated manufacturing of non-standard brickwork.

1.3 Methodology

1.3.1 Brickwork as subject matter of investigation

For several reasons brickwork is especially well suited to investigate the architectural potential of a robotically controlled assembly process. First, on a technical level, brickwork describes a self-contained subdomain of construction, the process can easily be overlooked and singled out for automation.[20] Also, the parts assembled are mainly of the same size and material and are of dimension and weight which can be handled by a robot. For this reason, automating brickwork by means of robots has already been subject to research in 1990s (see Section 3.2).[21]

Second, and of greater relevance, are the characteristic features of the brick as a universal building module for architecture. While many specialised components already predefine one single position for assembly, the simple geometry of a brick allows for a

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[20] See J. Laukemper, *Automation im Mauerwerksbau: Voraussetzungen, Verfahren, Wirtschaftlichkeit*, ed. P. D.-I. G. Drees, vol. 33, Schriftenreihe des Instituts für Baubetriebslehre der Universität Stuttgart (Stuttgart: expert verlag, 1992).

[21] The most developed robotic bricklaying systems can be found with J. Andres, T. Bock, and F. Gebhart, “First results of the development of the masonry robot system ROCCO: a Fault Tolerant Assembly Tool,” in *11th ISARC International Symposium on Automation and Robotics in Construction* (Brighton, England1994). and G. Pritschow et al., “A mobile robot for on-site construction of masonry,” in *IEEE/RSJ/GI International Conference on Intelligent Robots and Systems (IROS)* (Munich1994).

high degree of freedom in its relative placement, which permits realising versatile building forms.[22] In addition, due to its relative small dimension the necessary amount of bricks to create a greater, purposefully shaped whole soon exceeds a critical mass. In a traditional design and assembly process this leads to abstraction. Brickwork is generally defined through its outlines, with the position of the individual bricks described in an easily penetrable logic in form of a repetitive bond. Here, where the complex relation of a large amount of members has to be handled, a digital controlled design and assembly processes gains advantage over the human based processes, because it enables a targeted control of positioning each individual brick in space.

1.3.2 Techniques and methodologies for robotically assembled brickwork

The above outlined subject matter consequently requires a multidisciplinary approach that covers the fields of information technology, robotics, and architecture. However, each individual field cannot be followed in disciplinary depth within the scope of this research. As a consequence, it is the intention to identify how related aspects of information technology (i.e. computers and their ability to store, manipulate, and transmit data) and robotics (the ability to process data and transfer it into physical procedures) can be integrated into the domain of architecture, and ultimately, to benefit the design and building process. The aim is to define techniques and methodologies for robotic-based assembly processes of brickwork that are mutually informed by conceptual design intention and the engineering of the assembly process itself. Thereby, information technology plays a crucial role, since to achieve this, digital tools are necessary that integrate design knowledge with the control of a robotic fabrication process. Thus, the full potential of robotic-based fabrication processes can be exploited down to the smallest constituent element of an assembly.

The proposed techniques and methodologies build and expand upon precedent robotic solutions for automating brickwork. Especially, it suggests a combined authoring strategy for both the architectural design and the assembly process. Since the thesis is based on the premise that the process of making is a constituent factor of architecture and that by informing the design with the knowledge of making innovative and novel

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[22] Although, it must be acknowledged that many of the very expressive brickwork examples in history were realised by cutting the generic brick module into individual shapes to fit the design. This is especially true for gauged brickwork; see for example G. Lynch, *The History of Gauged Brickwork*, ed. A. Oddy, Butterworth-Heinemann series in Conservation and Museology (Oxford: Butterworth-Heinemann, 2007). Still, also through complex placement of the generic brick module a vast variety of expressive forms can be created. A prominent example is the Church of St Peter in Klippan, by Sigurd Lewerentz, where brick is used on the walls, ceiling, and floor, but also the altar and pulpit. Lewerentz stipulated that no brick should be cut, which results in irregular bonds and in parts large joints. See P. Blundell Jones, “Sigurd Lewerentz: Church of St Peter, Klippan, 1963–66,” *arq: Architectural Research Quarterly* 6, no. 02 (2002). Such an approach can be greatly facilitated by adopting a robot for assembly.

design solutions can emerge, the formalisation of building knowledge and how this is transferred are central points of investigation.

1.3.3 Experiments on non-standard robotic brickwork assemblies

Physical experiments constitute the core of the presented research work. The validity of the proposed robotic-based process and its corresponding design criteria and methodologies can only be investigated through physical application and, ultimately, through scrutiny of the architectural artefacts that result from such a process. As subject matter of investigation, the proposed techniques and methodologies are applied to the design and robotic assembly of brickwork. The experiments combine both the design and engineering of a robotic assembly process and, consequently, the application of the assembly process on a design task. Thereby, the interrelation of design and fabrication can be validated and further explored. Moreover, the experiments can be used to identify advanced design strategies that incorporate the potential of the robotic assembly process.

The physical investigations are divided into three experiments, 1) design and fabrication of non-standard wall elements, 2) design, fabrication, and installation of a bespoke façade, and 3) development and application of a completely automated fabrication unit for robotic assembly of brickwork *(ROB Unit)*. In their progression, each experiment is a further investigation and implementation of a robotic-based design and assembly process for brickwork. The applied techniques and methodologies are evaluated through the resulting architectural artefacts in regard to their formal expression and their constructive and structural qualities. Comparisons are drawn in relation to the respective conventional design and assembly process, as well as to predecessors of robotically assembled brickwork.

1.4 Structure of thesis

The thesis is structured in 6 Chapters. Following a general introduction on the renewed interest on applying robotics in architecture and construction, Chapter 2 recapitulates the application of robotics in construction so far and illustrates how these endeavours since the 1990s, which mark a peak in research and development in this domain, where mainly detached from architectural design processes.

Chapter 3 covers the assembly process of brickwork. On the one hand, it provides an analysis of the manual bricklaying process, focusing especially on the sequential process steps and the necessary tools applied. On the other hand, an overview of predecessors in the domain of robotically assembled brickwork is given. Thereby, similarities in the transfer towards a robotic process, but also the conceptual differences originating from the chosen approach, which combines the design and assembly process, are identified.

Chapter 4 presents the three experiments on robotically assembled brickwork. Within the experiments, both a robotic-based assembly process for brickwork and appropriate design strategies are developed, with the aim to synchronise the design and assembly process Thereby, the experiments build upon both the knowledge of the present principles and methods of the manual process, as well as the experiences of the robotic predecessors. Each experiment concludes in applying the process to a design task and the physical production of an architectural artefact. In their progression, the experiments build upon the respective previous findings, as well as increase the complexity of the architectural implementation, from the realisation of a single brick wall element, to a facing brick façade and the on-site production of an intricately shaped 100 m long, continuous brick wall.

Chapter 5 provides a discussion of the experiments and synthesises the characteristics of a synchronised robotic-based assembly and design process for brickwork, and further identifies their implication on brickwork design.

Finally, Chapter 6 presents the overall conclusion. It identifies the contributions, as well as limitations of the research and gives an outlook on future work.

2 ROBOTICS IN CONSTRUCTION

Even though, first attempts to apply robotics for construction work can be traced back to the late 1970s,[23] a coherent history of robotics in architecture and construction has yet to be developed. This chapter is a first attempt to close this gap. A historical overview is deemed necessary in order to embed precedent approaches, as well as to contextualise contemporary efforts. At the same time, the narrative presented here cannot be comprehensive. Given that this thesis is to a large part developed through physical experiments and physical application of a robotic assembly process at real-world scale, the focus is on applied research projects in the field, whereas purely theoretical work is omitted. The same applies to robots that are not directly applied to construction, but are deployed in the production of building materials or semi-finished products, an area, which compared to construction work itself, is already industrialised to large extend.

Further, from the numerous robot-related experiments emerging from architecture institutions over the last years, a great number remain small scale and in many cases the transfer towards an implementation in the construction industry is not yet pursued.[24] Therefore, this overview only highlights a selection of projects that are clearly dedicated to applying industrial robots to construction processes, and are thus of relevance to the present work.

Predecessors of robotic systems dedicated to the assembly of brickwork are discussed in a separate chapter (see Section 3.2).

Finally, it is important to note that the history of robotics in architecture and construction also features disruptions and does not at all follow a linear progression towards a

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[23] The Japanese pioneered the field of robotics in construction, with records of a first official research project from 1978, which is the earliest to date. An outline of Japanese efforts in the field can be found in Y. Hasegawa, “A new Wave of Construction Automation and Robotics in Japan” (paper presented at the 17th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 2000).

[24] This should by no means devalue these experiments. In addition to the aforementioned projects (see Section 1.1), an extensive overview of the range of current research and experiments can be obtained with the proceedings of recent conferences that include numerous robot related work. See for example, F. Gramazio, M. Kohler, and S. Langenberg, eds., *Fabricate: Negotiating Design and Making* (Zurich: gta-Verlag, 2014), W. McGee and M. Ponce de Leon, eds., *Robotic Fabrication in Architecture, Art and Design 2014* (Springer International Publishing, 2014), and D. Gerber, A. Huang, and J. Sanchez, eds., *ACADIA 2014 Design Agency*, 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) (Los Angeles: 2014).

predefined outcome.[25] In fact, a successful implementation of robotics in the field of architecture and construction cannot yet be foretold.

2.1 The advent of universal fabrication machines

The term *robot* was first coined by the author and playwright Karel Čapek in his drama *R.U.R.* or *Rossum's Universal Robots* in 1921.[26] Later in the 1940's Isaac Asimov, another science fiction author, laid out the field of *robotics* in his writing.[27] His view of the robot as a benevolent machine, put into the world to serve human kind and ease man's daily struggle is regarded to have "influenced the origins of robotic engineering."[28] Outside of science fiction, partly inspired by Asimov's writing, it was the goal to conceive machines to carry out a specific task substituting manual labour, which was especially hazardous, hard, and exhausting. In the beginning, the development was mainly on industrial robots, primarily built to substitute man on particular industrial manufacturing tasks.

The ISO (8373:2012) defines industrial robots as "automatically controlled, reprogrammable, multipurpose manipulator[s], programmable in three or more axes, […] for use in industrial automation applications".[29] Therefore, simplified expressed, an industrial robot is a machine that can perform movements, but is itself not equipped to perform a specific manufacturing task. An industrial robot can only be utilised in

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[25] For example, a survey amongst specialists in the field of automation and robotics in construction published 1994 lists, because the research in a higher degree of automation in the construction industry is connected to high costs, potential advances in the field are in many cases only developed in theory. The implication being that the practical implementations often do not meet the pre-established expectations. Further, the survey suggests that in several cases research in the field is rather driven by the availability of research money, than the actual needs of the industry. W. Poppy, "Driving forces and status of automation and robotics in construction in Europe."

[26] However, it was allegedly Karel's brother, the artist and poet Josef Čapek, that first invented the term, see F. Gramazio, M. Kohler, and J. Willmann, *The Robotic Touch - How Robots Change Architecture.*, 110. *Robot* derives from the Czech word *robota,* which means *compulsory labour*. Accordingly, the robots in Karel Čapek's play resemble artificial humans that are appointed for slave work, rather than mechanical machines. However, in their conception they follow the idea of a universal device that can substitute human work force. K. Čapek, R.U.R. - Rossum's Universal Robots, (Adelaide: University of Adelaide, 2014), http://ebooks.adelaide.edu.au/c/capek/karel/rur/index.html. Accessed April 15, 2015. Though the idea of robotics, "to build obedient and tireless machines, capable of doing man's boring and repetitive work," can be traced back to 350 B.C., J. N. Pires, *Industrial Robots Programming Building Applications for the Factories of the Future*, 1st ed. (New York: Springer, 2007), 2-8.

[27] The first use of the word *robotics* is generally attributed to Asimov, who first used the term in the short story *Runaround* published in 1942 and later collected in *I,Robot*, I. Asimov, *I, Robot* (London: Panther Books, 1968). Robotics refers to the technology dealing with the design, construction and operation of robots. In addition, in this story the famous three laws of robotics are explicitly laid out for the first time. The laws follow the purpose to obtain reliable control over semiautonomous apparatuses and as a *Gedankenexperiment* have been a common reference for robotics and information technology in the context of artificial intelligence, see R. Clarke, "Asimov's laws of robotics: implications for information technology-Part I," *Computer* 26, no. 12 (1993); R. Clarke, "Asimov's laws of robotics: Implications for information technology. 2," *Computer* 27, no. 1 (1994).

[28] R. Clarke, "Asimov's laws of robotics: implications for information technology-Part I." Clarke expresses Joseph Engelberg's – who together with George Devol is considered one of the fathers of industrial robots – fascination with Asimov's writing as a teenager as an influence in developing the first industrial robot. The same point is made by Wesley Stone who, argues the first industrial robot was a merge of technological ingenuity and a vision originating from the world of science fiction, L. S. Wesley, "The History of Robotics," in *Robotics and Automation Handbook* (CRC Press, 2004).

[29] ISO 8373:2012, "Robots and robotic devices – Vocabulary."

combination with end-effectors that enable the robot to perform specific material manipulations, as well as peripheral devices such as sensors, external tools or additional external axes. Together they comprise an industrial robot system. Industrial robots can be understood as universal fabrication machines that can be adapted to perform a broad range of material manipulation. In their generic nature, they are comparable to computers, with the difference that operations are performed on physical entities instead of on information. George Devol, who applied his invention of a *Programmable Article Transfer* for a patent in 1954 – which is considered being the first patent for an industrial robot, termed the object of his invention as *universal automation* and draws a direct analogy to computers.[30] The first commercial computers from Remington Rand (UNIVAC) and IBM had just become available a few years earlier.[31] Where the computer is a *universal machine* for office work – and nowadays almost all aspects of our lives, the former equals for fabrication: a general-purpose machine (Figure 5).

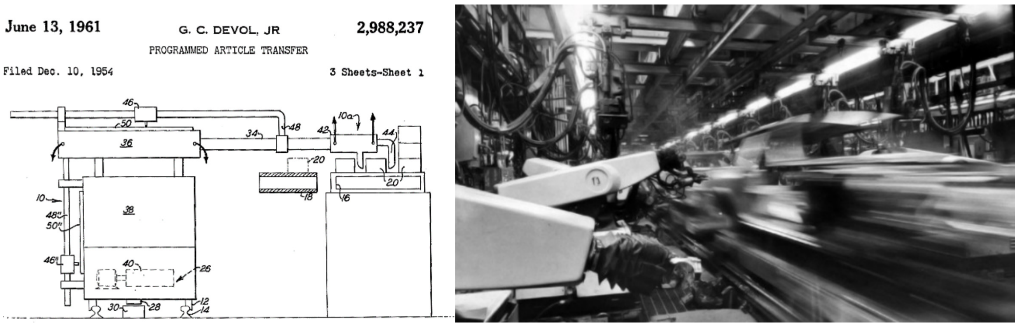

Figure 5. (left) Schematic drawing of Devol's universal automation machine; (right) Unimate robots working on an assembly line at Generals Motor's Vega plant, Lordstown, Ohio, 1972.

Together with Joseph Engelberger, Devol founded the robotic manufacturing company *Unimation.* They developed the first industrial robot, *Unimate,* which went to work for General Motors in 1961 extracting and separating parts of a die-casting machine. Soon after, Ford Motor Company applied the *Unimate* for spot-welding, which became a primary application for robots, as these jobs were particularly exhausting and hazardous

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[30] In the patent description Devol writes, "Universal automation, or 'Unimation,' is a term that may well characterise the general object of the invention. It makes article transfer machines available to the factory and warehouse for aiding the human operator in a way that can be compared with business machines as an aid to the office." G. C. Devol. Programmed Article Transfer. United States Patent 2,988,237, filed 10th December 1954, and issued 6.13.1961. The term universal automation, also relates to Turing's universal machine, which again illustrates Devol's conceptual proximity to computers. A. M. Turing, "On Computable Numbers, with an Application to the Entscheidungsproblem," *Proceedings of the London Mathematical Society* Series 2-42, no. 1 (1937).

[31] Actually, Devol was responsible for developing magnetic storage technology at Remington Rand. Although, Eckert-Mauchly Computer Company, a subsidiary of Remington Rand, developed the UNIVAC, it is likely that Devol was involved in one way or the other in the development of the UNIVAC. For computers as business machines, see M. Campbell-Kelly and W. Aspray, *Computer: a history of the information machine*, 2nd ed. (Westview Press, 2004), 93-115. The close analogy drawn between industrial robots and computers can also be seen due to the fact, that computers or business machines were mainly understood as an electronic means of automation at that time, as indicated by T. Haigh, "The chromium-plated tabulator: institutionalizing an electronic revolution, 1954-1958," *Annals of the History of Computing, IEEE* 23, no. 4 (2001).

for workers.[32] These first industrial robots were limited to perform simple recurring operations. They were by far not as sophisticated as the humanoid robots envisioned by Čapek and Asimov. And, although future generations of industrial robots evolved constantly, mainly in regards to mechatronics, their assignments within industrial automation processes remained the same as characterised in their initial use: performing repetitive recurring operations.[33]

In the 1970s, articulated arm robots as we know them today emerged. Influenced by Victor Scheinman's design of the so-called *Stanford Arm*[34] from 1969 – a robotic arm with six degrees of freedom controlled by a standard computer – ASEA presented the IRB-6 robot in 1973. The IRB-6 featured an anthropomorphic design and its movements mimicked that of a human arm.[35] It was the first serially produced microcomputer-controlled all-electric industrial robot. It allowed continuous path motion, whereby applications that are more sophisticated, like, for example, machining and arc welding became possible.[36] KUKA followed with their *FAMULUS* model in the same year, the first robot with six electromechanical driven axes (Figure 6).

Figure 6. (left) Puma Robotic Arm, a further developed version of Scheinman's Stanford Arm by Unimation and General Motors, which was launched commercially in 1979; (right) KUKA FAMULUS.

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[32] See J. F. Engelberger, "Historical Perspective and Role in Automation," in *Handbook of Industrial Robotics (Second Edition)*, ed. Y. N. Shimon (New York: Wiley, 1999).

[33] This might also be due to the fact, that robots entered an industrialised and economic environment, which was already characterised by a high division of labour, employing low-skilled workers. On the one hand, this fostered the implementation of industrial robots, on the other hand, it limited the utilisation of robots for more flexible and challenging applications.

[34] V. D. Scheinman, "Design of a Computer Controlled Manipulator" (Ph.D., Stanford University, 1969).

[35] The human arm served as a model for the robot design, meaning its links and joints relate to the anatomy of the human body, i.e. torso, chest, shoulder, upper arm, elbow, forearm, and wrist. Thereby, increasing the dexterity of the robot arm in comparison to other kinematic models, for example Cartesian robots with only translatory axis. See G. S. Hegde, *A Texbook of Industrial Robotics*, 21-22.

[36] See M. Hägele, K. Nilsson, and J. N. Pires, "Industrial Robotics," in *Springer Handbook of Robotics*, ed. B. Siciliano and O. Khatib (2008), 967.

The industrial robot industry quickly gained momentum and manufacturing was automated in a large scale in the 1980s; the biggest customers being the automobile (welding applications) and the electronics industries (assembly applications). Today, the estimated operational stock of industrial robots lies between 1.3 and 1.6 million.[37]

Although, the basic concept of the articulated arm robot has not dramatically changed since then, there have been significant advances in the field of industrial robotics from the 1970s to today (Figure 7).[38]

Figure 7. The KR 6 R900 sixx is part of the KUKA AGILUS family, which was introduced in 2012. Its kinematic design is noticeably similar to the robot models introduced in the 1970s, shown in Figure 6.

To a large part, these can be attributed to an improvement in speed, accuracy, and weight.[39] Further, different kinematic configurations were introduced, which were more suitable for specific operations, or, for example, allowed for a more efficient usage of floor space.[40] In the 1990s, new applications accrued in the food and pharmacy

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[37] IRF, "World Robotics 2014 Industrial Robots," (Frankfurt am Main: International Federation of Robotics (IRF), 2014). The estimate results from annual supply figures and the assumption of an average service life of 12 years per robot.

[38] However, some argue that original expectations (partly fuelled by science fiction) were not met. To a certain extend this can be attributed to the huge market demand. Norberto Pires summarises, that the "robotic evolution was not as fantastic as it could have been". He indicates that since the available technology was sufficient to satisfy the customers' needs, the continuous research developments did not always reach industry. J. N. Pires, *Industrial Robots Programming Building Applications for the Factories of the Future*, 6. Engelberger goes as far as to state that "the commercially available technology is not remarkably different from what existed 20 years ago," see J. F. Engelberger, "Historical Perspective and Role in Automation."

[39] An important milestone in this respect is the first direct-drive robotic arm build by Asada and Kanade at Carnegie Mellon University in 1981, see H. Asada and T. Kanade, "Design of Direct-Drive Mechanical Arms," *Journal of Vibration, Acoustics Stress and Reliability in Design* 105, no. 3 (1983). In 2006 KUKA presents its lightweight robot, which features a weight-to-payload ratio of 1:1. The robot builds upon the research of the German Aerospace Centre (DLR), see G. Hirzinger et al., "DLR's torque-controlled light weight robot III – are we reaching the technological limits now?" (paper presented at the IEEE International Conference on Robotics and Automation, 2002).

[40] In 1978, the first SCARA robot was created by Hiroshi Makino at the Yamanashi University in Japan, which was filed for a US patent in 1980. The simplicity of its four-axis design combined with its low-cost made the SCARA very popular for small-scale assembly tasks. See H. Makino and N. Furuya, "Selective Compliance Assembly Robot Arm (SCARA)" (paper presented at the 1st International Conference on Assembly Automation ICAA, Brighton, March 25-27 1980). In 1985, KUKA introduces a z-shaped robot arm. Contrary to the common parallelogram design, this configuration saves floor space in manufacturing settings.

industries, which called for a higher flexibility in robotic control programmes. It became necessary to handle variations in product size, shape, and rigidity. This was partly achieved through integrating sensors, vision guidance, and force feedback combined with techniques of artificial intelligence. Another solution to make robotic processes more "intelligent" is through realising man-machine interaction and integrating a human operator into the control loop.[41]

Despite these efforts, the existing use of industrial robots is mostly limited to repetitive tasks in a controlled manufacturing environment that can be programmed in advance. This is also due to the fact that the automobile industry is still the biggest customer and therefore a driving force behind the development of robotic machinery.[42] Thus, most industrial robots are adapted to fulfil the needs of a high volume market in respect to delivering a high reliability and productivity. Implementing flexible manufacturing processes though, still comes at a high cost.[43] Integrating and programming robotic systems is complex and time consuming.[44] Therefore, the application of industrial robots for small lot sizes or one-of-a-kind production is, in most cases, economically not feasible. Consequently, although conceived as highly flexible machines, today, industrial robots are not applied as such.[45]

2.2 History of robotics in architecture and construction

The application of industrial robots as a means to increase productivity through automation was also of interest in the building industry.[46] The first traceable research

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[41] An overview of the state of the research in robotics can be found in E. Garcia et al., "The evolution of robotics research," *Robotics & Automation Magazine, IEEE* 14, no. 1 (2007).

[42] In 2013 the automobile industry's share of total supply of industrial robots was about 39%, see IRF, "World Robotics 2014 Industrial Robots."

[43] See T. Brogårdh, "Present and future robot control development – An industrial perspective," *Annual Reviews in Control* 31, no. 1 (2007).

[44] Although it must be acknowledged that programming robotic systems has become much easier, from manually teaching the first *Unimate* and storing its individual axis position for later playback, towards methods of Cartesian interpolation and tools for offline programming.

[45] In the last couple of years, promising attempts have been made to address the shortcomings of traditional industrial robots. New emerging companies like *Universal Robots* and *Rethink Robotics*, aim at offering robotic arms that are, more flexible, and easier to program than traditional products. One of the major advantages being that these robotic arms are safe to work alongside humans. Thus, elaborate safety measures, which limit flexibility of robotic system and increase complexity, become obsolete. KUKA, for example, follows a similar approach with its lightweight robotic arm *LBR iiwa*. A major restriction of these systems is that both reach and payload of the arms are limited. When applying industrial robots to construction these are decisive factors. See for example, C. Fitzgerald, "Developing baxter" (paper presented at the IEEE Conference on Technologies for Practical Robot Applications (TePRA), 22-23 April 2013) and W. Knight, "Smart Robots Can Now Work Right Next to Auto Workers," MIT Technology Review, http://www.technologyreview.com/news/518661/smart-robots-can-now-work-right-next-to-auto-workers/ (accessed April 15, 2015).

[46] Thomas Bock and Silke Langenberg characterise the introduction of robots to construction as part of an attempt to rationalise and industrialise the building industry, which set in much earlier. This attempt was driven by an increased demand for housing after the First World War in the 1920s and 1930s and facilitated to an even higher degree in Europe during the post-war boom years between 1950 and 1970. With the 'robot boom' in general manufacturing in the 1970s, applying robots to construction seemed the logical next step. T. Bock and S. Langenberg, "Changing Building Sites: Industrialisation and Automation of the Building Process," *Architectural Design* 84, no. 3 (2014).

into construction robots started 1978 in Japan as a joined project between universities, robot manufacturers, and general contractors and was financed by the *Japan Industrial Robot Association*.[47] Since then, applying robotics and automation in construction has been a continuous subject of interest.[48] The evolution of the domain of robotics in construction can be closely aligned to the history of the *International Association for Automation and Robotics in Construction* (IAARC), which was founded in 1990. Specifically, the proceedings of their annual symposia, the *International Symposium on Automation and Robotics* (ISARC), which already originated in 1984, give a comprehensive overview of the research devoted to robotics in architecture and construction.[49] Generally, robotics in construction can be divided into the two large fields of civil infrastructure (e.g. road, tunnel, and bridge construction, mining, earthwork, etc.) and house building.[50] Within the scope of this thesis, this Section gives an overview of the developments of robotics applied to the latter.

In contrast to the programmable manufacturing machines that originated from tooling machines, industrial robots were primarily conceived as handling and assembly tools. Applied to construction work this meant that research efforts were geared towards substituting the human worker on site. Japanese companies and universities led R&D activities in robotics and construction with a noticeable boom in the late 1980s and early 1990s.[51] This was on the one hand due to the country's special economic situation, as well as supported by the unique structure of the Japanese building industry. Large construction firms were vertically integrated, often incorporating manufacturing. Organising manufacturing of components and construction could thus be more easily linked and organised. Notably, David Gann mentions in this context that competition between construction firms in Japan was mainly technological driven, opposed to solely price-based as in most other countries. Thereby, investment in R&D seen in proportion to construction output was double in Japan than compared to other industrialised countries during the 1980s and 1990s.[52] Further, Japan's restrictive foreign workers policy generated an active need for increasing productivity in construction due to skilled labour shortage and an aging workforce. Robots were conceived to perform specialised tasks, such as distributing materials, fitting equipment to ceilings, setting interior walls, welding structural steel members, painting, and many more.[53]

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[47] See Y. Hasegawa, "A New Wave of Construction Automation and Robotics in Japan."

[48] See A. Warszawski and R. Navon, "Implementation of Robotics in Building: Current Status and Future Prospects," *Journal of Construction Engineering and Management* 124, no. 1 (1998), and more recently T. Bock, "Automatisierung und Robotik im Bauen," in *Wendepunkt(e) im Bauen - Von der seriellen zur digitalen Architektur*, ed. W. Nerdinger (München: Edition Detail, 2010).

[49] All ISARC proceedings from 1984 onwards can be accessed digitally through the IAARC website: http://www.iaarc.org/pe_publications.htm (accessed April 15, 2015).

[50] C. Balaguer and M. Abderrahim, "Trends in Robotics and Automation in Construction."

[51] See Y. Hasegawa, "A New Wave of Construction Automation and Robotics in Japan."

[52] D. M. Gann, *Building innovation complex constructions in a changing world* (London: Telford, 2000), 197-98.

[53] Noteworthy are the first application of a construction robot in 1988. The machine successfully painted a façade area of 95,400 m^2, while automatically avoiding glass and openings, S. Sakamoto, "Mechanical planning and actual test results of a robot for painting the exterior walls of high-rise buildings," *Advanced Robotics* 5, no. 4 (1990) and S. Terauchi et al., "Development of exterior wall painting robot capable of painting walls with indentations and protrusions" (paper presented at the 10th International Symposium on Automation and Robotics in Construction (ISARC), Houston,

In 1984, *Shimizu Construction Company* – one of Japan's largest construction firms – applied a robot to construction for the first time. The so-called *Shimizu Site Robot-1* (SSR-1) performs the spraying of fireproofing (Figure 8).[54] While the SSR-1 demonstrated the feasibility of applying a robot for on-site construction work, the test case also revealed certain barriers for adopting industrial robots to construction work. On the one hand, the size and weight of the SSR-1 was too large to be transported in a lift, thus manoeuvring it through doorways or allocating it to different floors of a building proved difficult. On the other hand, the control of the SSR-1 was complex and operators had to be thoroughly trained. Further, acquisition costs at the time were relatively high.[55]

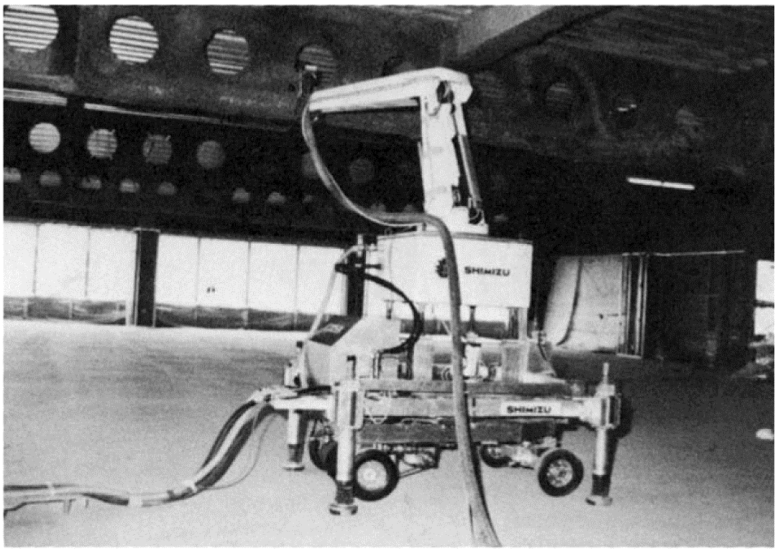

Figure 8. Shimizu Site Robot-2 (SSR-2). The successor of the SSR-1 featured a position sensor to detect the distance from the robot arm to the steel beam as its main advancement.

While the SSR-1 was based on a commercially available articulated arm robot[56], in most cases, the development focused on custom robotic devices optimised to perform a single

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USA, 24-26 May 1993). An example of a robot performing welding tasks is presented by N. Fukuhara et al., "Development of a robot system for large assembly welding of steel columns," *Welding International* 6, no. 10 (1992) and the distribution of material is demonstrated by T. Honda et al., "A material-handling system in the building site" (paper presented at the 9th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 1992). A system for interior finishing is introduced by K. Nanba et al., "Development and application of the light weight manipulator for interior finish work" (paper presented at the 13th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 1996).

Finally, an overview of different robots and automated machines in construction in Japan can be found in L. Cousineau and N. Miura, *Construction Robots: The Search for New Building Technology in Japan* (Reston, Va.: ACSE Press, 1998).

[54] T. Yoshida et al., "Development of spray robot for fireproof cover work" (paper presented at the 1st International Symposium on Automation and Robotics in Construction (ISARC), Pittsburgh, USA, 1984).

[55] R. Kangari and T. Yoshida, "Prototype Robotics in Construction Industry," *Journal of Construction Engineering and Management* 115, no. 2 (1989).

[56] The SSR-1 and its two successors applied a Trallfa spray-paint robot mounted on a mobile platform, T. Yoshida et al., "Development of spray robot for fireproof cover work." Trallfa, a Norwegian company, already developed spray-paint robots in the late 1960s. The company was taken over by AESA 1986, which later became ABB.

specific task. One of the more prominent examples that came to a widespread use in Japan is that of a mobile robotic device dedicated to surface finishing of concrete slabs.[57] Research departments of different construction companies were developing such devices in parallel. Examples are the *Mark II*,[58] the *SurfRobo*,[59] and the *FLATKN*.[60] As a matter of course, these specialised machines lacked the flexibility to be applied to different construction tasks, other than their predefined process. In addition, the *FLATKN* does not work autonomously, but is controlled via remote control (Figure 9).

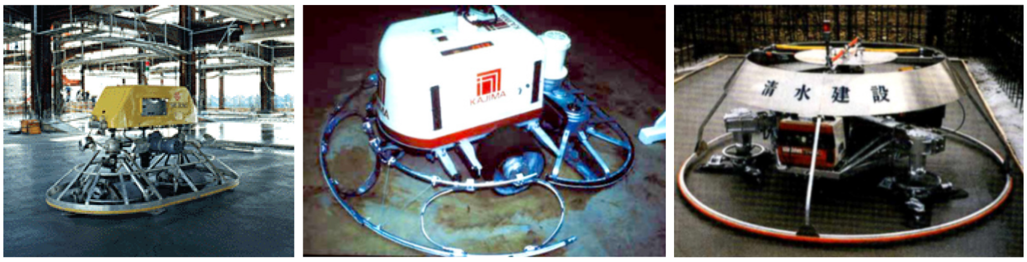

Figure 9. Concrete finishing robots. (left) SurfRobo by Takenaka Cooperation; (middle) Mark II, also known as Kote-King, by Kajima Corporation; (right) FLATKN by Shimizu Corporation.

Actually, tele-operated apparatuses account for the majority of robotic devices applied to construction.[61] These can, on the one hand, make use of the increased lifting capability of the machine versus a human worker. On the other hand, they have the advantage of exploiting sensory information from the human operator, which often proves to be too difficult to automate, especially in an uncertain environment like a construction site. However, at the same time, because these machines are still operated manually, they escape the advantages and potentials arising from a digitally controlled process (Figure 10).

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[57] Y. Kajioka and T. Fujimori, “Automating Concrete Work in Japan,” *Concrete International* 12, no. 6 (1990).

[58] N. Tanaka et al., “The Development of the ‘Mark II’ Mobile Robot for Concrete Slab Finishing,” in *CAD and Robotics in Architecture and Construction* (Springer US, 1986).

[59] K. Kikuchi, S. Furuta, and T. Imai, “Development and the result of practical works of concrete floor finishing robot,” in *5th International Symposium on Robotics in Construction (ISARC)* (Tokyo, Japan1988).

[60] R. Kangari and T. Yoshida, “Prototype Robotics in Construction Industry.”

[61] M. Taylor, S. Wamuziri, and I. Smith, “Automated construction in Japan,” *Proceedings of the ICE - Civil Engineering* 156 (2003).

Figure 10. Example of a tele-operated robot, the so called Mighty Hand by Kajima Corporation.

Besides single-purpose construction robots, integrated construction automation systems were developed, with the aim to create a factory-like situation on the construction site. Thereby, the difficult challenges arising from working in an unstructured environment with sometimes changing site conditions, common to on-site construction, could be minimised. In these systems, the currently constructed floor is assembled using a temporarily covered working platform. The working platform provides automated material handling systems, as well as a controlled and weather protected construction environment, in which robots can perform diverse construction tasks, such as, for example, material manipulation or welding. Although it must be noted, that not all construction tasks are automated. According to construction progress the platform can be raised to complete the next floor. In 1991, Shimizu Construction Company put a real scale prototype for an automated high-rise construction site in operation. Their so-called *SMART* system features an automated welding of steel frames, placing of prefabricated concrete floor panels, as well as placing of interior and exterior wall panels.[62] Other Japanese construction companies, like Obayashi,[63] Maeda,[64] and Taisei developed similar systems (Figure 11).[65] Common to all is, that in order to achieve a high degree of automation, these system are greatly dependent on standardisation and prefabrication. The wall panels processed by the *SMART* system, for instance, feature special joints and are specifically designed for robotic construction.[66] In addition, the working platform

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[62] Y. Miyatake, Y. Yamazaki, and R. Kangari, “The SMART System Project: A Strategy for Management of Information and Automation Technology in Computer Integrated Construction” (paper presented at the 1st International conference, Management of information technology for construction, Singapore, 1993).

[63] K. Hamada et al., “Development of automated construction system for high-rise reinforced concrete buildings,” in *IEEE International Conference on Robotics and Automation* (Leuven1998); T. Wakisaka et al., “Automated construction system for high-rise reinforced concrete buildings,” *Automation in Construction* 9, no. 3 (2000); H. Miyakawa et al., “Application of automated building construction system for high-rise office building” (paper presented at the 17th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 2000).

[64] M. T. Salim, “Bringing an old concept into the future: The Maeda MCCS Analysis” (paper presented at the CIB IAARC W119, Munich, Germany, 24th October 2012).

[65] S. Sakamoto and H. Mitsuoka, “Totally Mechanized Construction System for High-Rise Buildings (T-UP System),” in *Automation and Robotics in Construction Xi*, ed. D. A. Chamberlain (Oxford: Elsevier, 1994).

[66] J. Maeda, “Development and Application of the SMART System,” ibid.; Y. Yamazaki and J. Maeda, “The SMART system: an integrated application of automation and information technology in production process,” *Computers in Industry* 35, no. 1 (1998). Another major challenge proves to be the logistics and the need for just-in-time delivery of construction material.

constraints the vertical configuration of the building and thereby limits the freedom of architectural design, for example, the possibility to react to surrounding conditions.

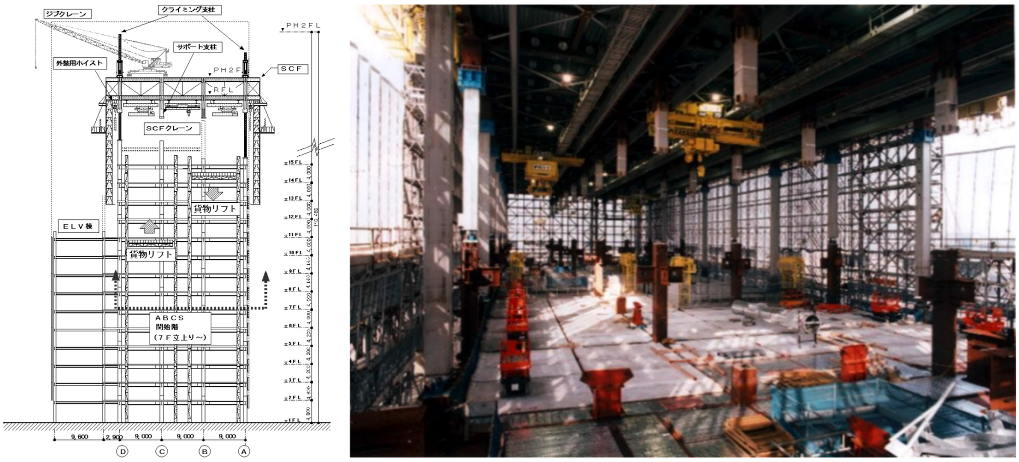

Figure 11. "Automated Building Construction System" (ABCS) by Obayashi Corporation: (left) Cross section of ABCS system applied to a 26 story office building. The system was applied for all standard floors from the 7th floor upwards. The uppermost floor is enclosed by a so called "Super Construction Factory" (SCF); (right) View inside the SCF, which establishes a controlled environment for the automated construction work like material transport and welding.

European examples of an integrated approach towards robotics and automation in construction are the *Future Home*[67]and the *ManuBuild*[68] research project. These EU funded research projects ran from 1998 to 2002, and from 2005 to 2009 respectively. The primary goals were to improve productivity, quality, and safety, and finally to achieve a reduction of construction costs. Thereby, ICT plays a crucial role in integrating the complete building process from design to management and construction. The research was driven by the paradigm of industrialisation and design is geared towards a prefabricated kit of standard components that are suited for robotic assembly.[69] Although receiving substantial funding, these projects have not yet made a noticeable impact on the building industry.[70]

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[67] C. Balaguer et al., "FutureHome: An integrated construction automation approach," *Robotics & Automation Magazine, IEEE* 9, no. 1 (2002).

[68] T. Bock, "The Integrated Project ManuBuild of the EU" (paper presented at the 23rd International Symposium on Robotics in Construction (ISARC), Tokyo, Japan, 2006).

[69] J. Neelamkavil, "Automation in the Prefab and Modular Construction Industry," in *The 26th International Symposium on Automation and Robotics in Construction (ISARC 2009)* (Austin TX, USA, 2009).

[70] On the contrary, after four years of development, *ManuBuild* industry partner NCC from Sweden launched *NCC komplett* in 2006, a platform based industrialised housing system, but already decided to discontinue the system in 2007, when it became obvious that anticipated cost reductions would be impossible to achieve. NCC's investment in the system was around 1 billion Swedish Crowns, which equals over 100 million Swiss Francs. On *NCC komplett* see T. Bock, "The Integrated Project ManuBuild of the EU."; NCC, "NCC Annual Report 2006," (Solna, Sweden 2006), 11. The discontinuation is reported in NCC, "NCC Annual Report 2007," (Solna, Sweden 2007), 25.

2.3 Limits of first generation robotics in construction

In the first phase of robotics in construction, which reached its peak in the 1990s, over 200 different prototypes of robotic solutions have been developed especially for the construction industry and tested on building sites.[71] This number includes various mechatronic devices, ranging from entirely autonomous machines, to tele-operated apparatuses. As a restriction to this number, it has to be considered that not all of these machines perform tasks that are stringently necessary for construction, as for instance painting. Nevertheless, with few exceptions in Japan, nearly none of these developments could establish themselves in the industry or pass a prototypical stage. Here, Carlos Balaguer and Mohamed Abderrahim correctly identify the main barriers for robotics and automation in construction in the "nature of the work environment".[72] As already discussed, the environment on a construction site is highly unstructured. Further aggravating factors are that building construction features a low-level of standardisation and involves dealing with large tolerances compared to traditional industrial manufacturing.

However, in general the concepts applied to other manufacturing based industries were directly transferred to the building industry. Typically, the automobile industry is seen as an archetype.[73] This analogy ignores the substantial differences in the product (i.e. a building versus an automobile). First, there is a difference in scale. Whereas the working envelope of an articulated arm robot can easily encompass the final product of an automobile, this is not possible in building construction. This is accompanied by the fact that, on average, in construction much heavier objects have to be handled.[74] In consequence, construction robots either had to be mobile, facing numerous additional challenges (e.g. issues of perception and orientation), or the solution was to automate the building process as a whole as integrated construction automation systems.

Secondly, apart from different technological challenges, there are significant structural differences between manufacturing and construction. The main difference being that the building industry is mainly project-based. Every building is one of a kind, designed for a special purpose on a particular site and meeting a client's special demands.[75] In

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[71] T. Yoshida, "A Short History of Construction Robots Research & Development in a Japanese Company" (paper presented at the 23rd International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 2006).

[72] C. Balaguer and M. Abderrahim, "Trends in Robotics and Automation in Construction," 1.
This is also one of the reasons why in recent years research has focused more on service robotics that allow for a greater human-robot interaction.

[73] S. Kieran and J. Timberlake, *Refabricating architecture how manufacturing methodologies are poised to transform building construction* (New York: McGraw-Hill Companies, 2004), xi.

[74] In fact, reach and payload of articulated arm robots are directly related to the needs of the automobile industry, since they form the biggest customer.

[75] On the specifics of the building industry see for instance, D. A. Turin, "Construction and development," *Habitat International* 3, no. 1-2 (1978)., S. Groák, *The idea of building: Thought and action in the design and production of buildings* (London: E & FN Spon, 1992), 121-29. Looking at the house building industry in North America and Australia, Harris and Buzzelli argue that instead of being insufficient and having to learn from other industries, such as the automobile industry, the house building industry is very successful role model in adapting to a "fluid and unstable

addition, it involves various actors ranging from architects to contractors and suppliers, which are very rarely coordinated. Further, the building industry shows a relative lack of large capital-intensive companies, but is mainly comprised out of small to medium-sized enterprises (SME) that are reluctant towards large investments.[76]

In summary, the first generation of robotics in construction were mainly targeted towards increasing productivity and the focus was set upon accomplishing a monetary benefit through the usage of automated machines. In many cases, established manual operations were directly translated into an automatic process – with the aim to save labour, reduce costs, and obtain quality control in production. However, the resulting highly specialised robotic systems were not able to adapt to specific building challenges and limited the overall design space, while being far too expensive and not affordable for companies of the building industry. The flexibility to react on different design situations, flexibility inherent in robotic systems, was lost.[77]

Moreover, a common approach to react on this inflexibility of the machines was to further constrain the architectural design and adapt it to the limits of the robotic construction system.[78] In addition, Frans van Gassel and Ger Maas argue that it were primarily process engineers that executed such R&D efforts. This compassed the special expertise of professional builders and architects in the construction of buildings and its direct relation to the architectural design process. Ultimately, architecture is a highly complex matter and a good understanding of the work processes necessary to construct a building is essential. The implicit knowledge of the architect and builder on the sequence of construction, how elements are joined and fitted to form a whole, need to be thoroughly taken into account.[79]

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economic environment". R. Harris and M. Buzzelli, "House Building in the Machine Age, 1920s-1970s: Realities and Perceptions of Modernisation in North America and Australia," *Business History* 47, no. 1 (2005). Arguably, vendors of prefabricated houses try to adopt economy of scale to their advantage making use of concepts of standardisation as well as mass customisation. However, to a large extend a productivity increase is achieved through a vertical integration of the building process from planning to execution, without making use of automation in the construction process.

[76] J. Barlow and R. Ozaki, "Achieving Customer Focus in Private Housebuilding: Current Practice and Lessons from Other Industries," *Housing Studies* 18 (2003).

[77] See S. Obayashi, "Problems and effects of automation and robotization" (paper presented at the 9th Intnternational Symposium on Automation and Robotics in Construction, Tokyo, Japan, 6-8 June 1992).

[78] See for instance T. Bock, "Robot Oriented Design," *Architectural Product Engineering* (1988); A. S. Howe, "Designing for automated construction," *Automation in Construction* 9, no. 3 (2000).

[79] F. v. Gassel and G. Maas, "Mechanising, Robotising and Automating Constrcution Processes," in *Robotics and Automation in Construction*, ed. C. Balaguer and M. Abderrahim (In-Teh, 2008).

2.4 Design potential of bespoke robotic construction processes

The last couple of years have witnessed a renewed interest in the field of robotics in construction.[80] During the first phase, it had been predominantly engineering disciplines that formed the field. In contrast, today, the disciplines of architecture and design introduce a fundamentally different perspective. In 2005, ETH Zurich installed the first laboratory equipped with an industrial robot within an architectural context.[81] Other architecture institutions around the world soon followed and started to invest in robotic infrastructure.[82]

Research focus is not set on imitating and automating manual construction processes, but to transform and rethink construction in concert with digital tools (i.e. both the robot as a digital controlled fabrication machine and advanced digital design).[83]

During the 1980s and 1990s, engineering research was to large part concerned with developing the robotic machine itself (specialised to perform a single construction task). Now, the versatility of *standard* industrial robots is exploited to perform explicit construction tasks that follow specific design intentions.[84] These tasks range from assembling discrete elements like bricks – the subject matter of this thesis – to material-centric construction processes such as, for example, robotic slipforming concrete.[85]

This fundamentally different approach has been facilitated by changing surrounding circumstances and accessibility of the technologies involved. On the design side, architectural practice is no longer imaginable without the aid of information technology.[86] Especially, CAD/CAM today allows for a seamless connection between design data and fabrication data, to directly control production machines. Thereby, allowing for differentiated designs in an automated process and making fabrication technology in general much more accessible for the designer. On the other side,

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[80] Soon after its peak in the 1990s, R&D on robotics in construction declined. A main reason being the crisis of the *bubble economy* in Japan. The country was one of the driving forces behind developing robotic solutions for the building industry. Additionally, the failure of establishing any of the robotic developments in the industry left the important stakeholders disillusioned, realising that their expectations were too high. Eventually, both these aspects lead to strongly reduced investment in research activities. See C. Balaguer and M. Abderrahim, "Trends in Robotics and Automation in Construction," ibid.

[81] F. Gramazio, M. Kohler, and J. Willmann, *The Robotic Touch – How Robots Change Architecture*, 107.

[82] Among many others the Harvard Graduate School of Design (http://www.gsd.harvard.edu/inside/cadcam/), Carnegie Mellon University (http://www.cmu-dfab.com/), the Southern California Institute of Architecture (http://www.sciarc.edu/portal/about/resources/robotics_lab.html), and the University of Stuttgart (http://icd.uni-stuttgart.de/?p=4052) installed robotic fabrication laboratories.

[83] T. Bonwetsch, F. Gramazio, and M. Kohler, "Digitales Handwerk – Digital Craft," *Graz Architecture Magazine* 6 (2010).

[84] M. Bechthold, "The Return of the Future: A Second Go at Robotic Construction," *Architectural Design* 80, no. 4 (2010).

[85] E. Lloret et al., "Complex concrete structures: Merging existing casting techniques with digital fabrication," *Computer-Aided Design* 60 (2015).

[86] L. Iwamoto, *Digital Fabrications – Architectural and Material Techniques*, Architecture Briefs (New York: Princeton Architectural Press, 2009), 5-6.

industrial robots are on the verge of becoming a public domain. Compared to the 1990s, today the worldwide installation of industrial robots has more than doubled, while at the same time the average price of a robot unit fell to a third of its equivalent price (Figure 12).

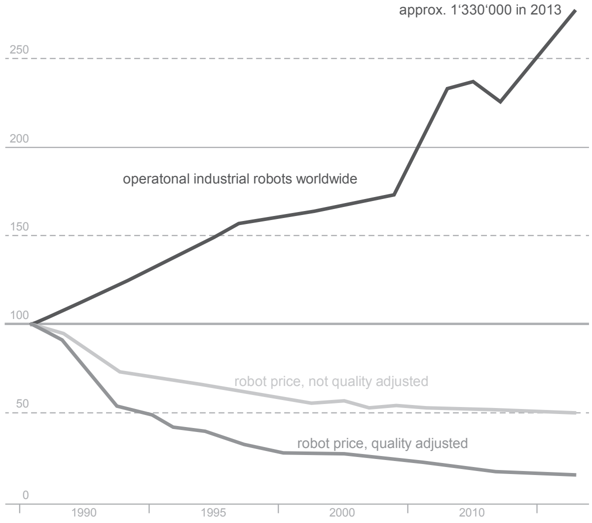

Figure 12. Development of stock of operational industrial robots worldwide compared to robot prices in the time period 1990-2013, index 1990=100. The quality adjustment includes the performance improvements of industrial robots in comparison to the index value.

The performance-to-cost ratio improved as robot manufacturers today integrate off-the-shelf personal computer technology and consumer software in their controllers, as well as in programming and control software. Advanced controls and inverse kinematics for instance, allow moving the robot in various coordinate systems simply by defining a point in space, instead of having to define the rotary angle of each axis oneself. This is accompanied by increased performance parameters such as speed, load-weight ratio, and immensely improved mean time between failures.[87]

This “second go at robotic construction”[88] is therefore not a direct continuity of previous endeavours. It is far less a technological development of automated construction machines. Rather, the increased accessibility allow industrial robots to become an experimental tool in architecture that enables the investigation of bespoke, digital

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[87] See M. Hägele, K. Nilsson, and J. N. Pires, “Industrial Robotics,” 969. A further indicator that industrial robots are now considered a reliable and robust technology is the fact that also within the engineering discipline research focus in the domain of robotics in construction has shifted from the development of specific hardware towards *soft robotics*. The term *soft robotics* comprises the robotic software, but also the integration of on-site sensory data acquisition and processing, security and the overall process control. See C. Balaguer, “Soft robotics concept in construction industry,” in *World Automation Congress, 2004.* (Seville, 2004).

[88] M. Bechthold, “The Return of the Future: A Second Go at Robotic Construction.”

controlled material and construction processes, as well as appropriate digital design methods.[89]

Among the large number of robot related projects that emerged over the last years in the architectural domain, the *In-Situ Robotic Fabrication (DimRob)* project is exemplary.[90] On the one hand, it is decisively concerned with construction, whereas in many other projects the robotic arm is applied to surfacing and patterning processes, or the fabrication of components.[91] On the other hand, it combines challenges arising from working on-site – thereby addressing some of the predominant obstacles of the first phase of robotics in construction, with adaptive building strategies for non-standard in situ fabrication.

DimRob is a prototype mobile construction unit, consisting of a standard industrial robot arm attached to a mobile base. As such, it bears resemblance to the SSR-1 (see Section 2.2). However, instead of being limited to a specific task (i.e. fireproofing), it is a generic platform, allowing for a diverse range of robotic-based construction processes. Further, it is specifically designed to work and manoeuvre on a construction site. Meaning, that in weight and dimension it can pass standard door openings and does not exceed load limits of floor slabs. Also, it integrates sensor technology to enable localisation and repositioning of the robot, as well as to adapt to surrounding conditions and material tolerances.

However, due to its prototypical development, *DimRob* has not yet reached the level of maturity, whereas a productive and economical implementation on a construction site still awaits proof. Moreover, besides issues of site and material logistics that should not be overlooked when introducing robotics to a construction site, suitable applications, where an on-site robotic system can add value to the construction process, still need to be identified. Nevertheless, *DimROB* demonstrates a promising trajectory for future on-site robotic construction (Figure 13).

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[89] Accessibility is prerequisite in order to investigate robotic fabrication from an architectural perspective. With shifting the focus from robotic problem solving to exploring the place of robotics within a culture of making and construction in architecture, the current approach rather expands on the disciplines engagement with advanced digital design and digital fabrication techniques. See for instance, B. Kolarevic, ed. *Architecture in the Digital Age – Design and Manufacturing* (New York: Spon Press, 2003). However, the robot adds to the concept of digital fabrication, mainly due to its openness to perform different processes, which sets it apart from specialised CNC-machines.

[90] V. Helm et al., "In-Situ Robotic Construction: Extending the Digital Fabrication Chain in Architecture," in *Synthetic Digital Ecologies: Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, ed. J. K. Johnson, M. Cabrinha, and K. Steinfeld (San Francisco, 2012).

[91] A. Picon, "Robots and Architecture: Experiments, Fiction, Epistemology," *Architectural Design* 84, no. 3 (2014).

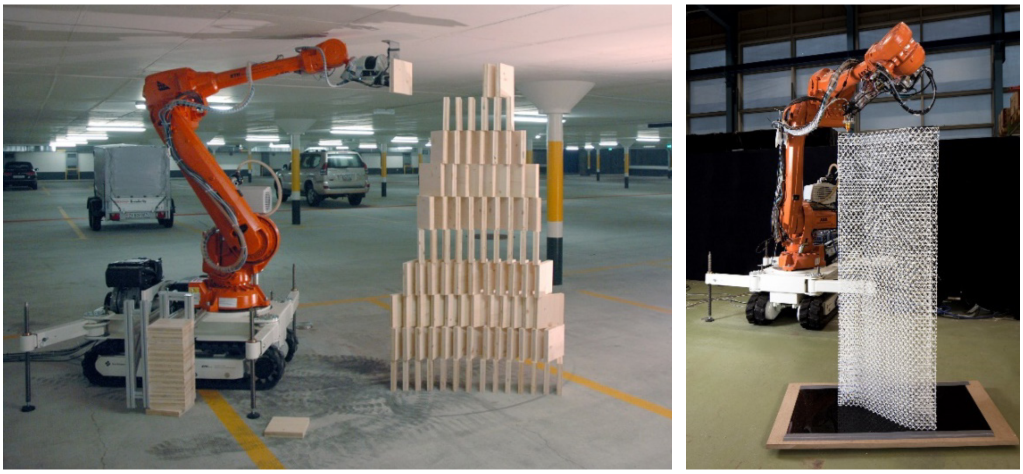

Figure 13. DimRob performing different fabrication processes: (left) assembling discrete wooden elements; (right) Prototypical mesh-mould process extruding thermoplastic polymers.

A first potential application of the *DimRob* platform is the research into robotic extrusion of spatial meshes that can act as concrete formwork and reinforcement.[92] Here, the advantages of a robotic process are seen in the ability to create complex spatial formwork that allow for non-standard concrete constructions. The in-situ fabrication bears the potential to adapt to local conditions in real time and permits a continuous process. Therefore, for example restrictions in size that might apply for prefabricated elements do not apply. The research is still at a fundamental level. A major challenge and a prerequisite for a future application of the process, is to replace the currently applied thermoplastic polymer for extrusion with a much stronger filament. Only then can the mesh be structurally activated to also take on the function of reinforcement (Figure 13 right).

2.5 Impact of robotics in architecture and construction to date

Industrial robots where initially conceived as universal fabrication machines, but they are seldom applied as such. This is due to complexity of programming, as well as the existing structures of the industries in which they are deployed. The normal case of

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[92] N. Hack et al., “Mesh-Mould: Robotically Fabricated Spatial Meshes as Concrete Formwork and Reinforcement,” in *Fabricate: Negotiating Design & Making*, ed. F. Gramazio, M. Kohler, and S. Langenberg (Zurich: gta-Verlag, 2014).

operation for industrial robots is within mass production processes, where in a one-time set-up the robot repeatedly performs the same operation.[93]

In the first phase of applying robotics to construction work, versatility was further limited by introducing specialised robotic machines. These resemble a closed system and in general could only be applied to the specific construction task they were designed for. Robotics in construction was mainly approached as a technical problem with the aim to increase productivity. The concept to automate construction work was either to mimic the manual process, or to reengineer the processes to suit robotic systems. However, both specialised machines and standardised robotic construction systems proved to limit the design potential and the adaptability of the systems to different building challenges.

The renewed interest in robotics in construction originating from within the field of architecture is based on an approach, where the robot enables the investigation of distinct construction and material processes. Instead of robotic construction leading to further standardisation, many of the experiments and research projects that have emerged over the last years in this field display the high degree of spatial and structural differentiation that can only be achieved by a digitally controlled robotic process. At the same time, certain shortcomings of former attempts are addressed. For example, the integration of sensory information and adaptable robotic construction processes aim at overcoming barriers of material tolerances and unstructured environments common to construction sites.

However, in regards to industrial implementation, these new developments are still at an early stage. So far, robots have only had a very marginal impact on the building industry.[94] Clearly, the main question for the future will be if robotic automation can add value to the construction process. Comparing the first phase of robotics in construction with current projects hints at the fact that merely automating established construction processes with the aim to substitute human workers will not be sufficient. On the other hand, robotic construction might establish itself, where the amount of members and structural complexity exceed the capabilities of a human. Therefore, it can be expected that robotic solutions will not eliminate traditional manual processes, but complement them.[95]

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[93] It is a paradox that robots were initially conceived to substitute human labour and as such designed to imitate the dexterity of the human arm with its flexibility and possibility to guide a multitude of different tools, but in practice were limited to always perform the same repetitive single task. A reason might be, that industrial robots replaced human labour in a by this time already highly industrialised surrounding, where mainly unskilled workers only performed a limited number of simple tasks. Hence, the skillset demanded for by the robot was limited.

[94] The few applications that can be found are mainly in the domain of civil infrastructure (e.g. roadwork, tunnelling, and inspection of pipes).

[95] See also discussion in Section 5.

3 ROBOTIC BRICKWORK

Foremost, it is the potential for adaptation, which qualifies brickwork especially well for the intended research on how robotic processes might influence and change established architectural practices. The simple brick geometry and its relative small size allow assembling diverse building forms. Brickwork – probably the oldest artificially produced building material – can thus adapt to various architectural styles and requirements.[96] The circumstance that it is still common today to construct with bricks can be regarded as evidence of its versatile qualities.[97]

The brick module is the smallest entity in a larger constructive reference system. Due to the inherent constructive logic, but also due to the amount of bricks needed to create a greater whole that quickly exceed a critical mass, this reference system is often based on a regular grid.[98] It is expected that here the combination of advanced digital design methods with robotically controlled assembly processes can activate a much larger design space, by enabling the exploration and materialisation of a higher level of design complexity through a targeted positioning of each individual brick. Ultimately, brickwork lends itself particular well to applying robots, especially industrial robots that were developed mainly for the purpose of performing handling and assembly tasks. The basic construction process of brickwork consists of the repetitive assembly of discrete parts. The parts assembled are mainly of the same size and material and are of dimension and weight which can easily be handled by a robot. In traditional brickwork, the bricks are merely stacked on top of each other and bonded with mortar. The overall assembly acts as a compression-only structure. Thus, the robot is not challenged to assemble complex joints, which need to be resilient to tension forces. Being a self-contained subdomain of construction, brickwork can easily be singled out for automation and the single process steps necessary to construct a brick wall can be clearly laid out. Altogether, automating brickwork by means of robotic fabrication can be regarded less

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[96] See for example H. E. Kramel, *Backstein als Gestaltungselement*, Element (Zurich: Schweizerische Ziegelindustrie, 1984).

[97] The firing of bricks can be traced back to 4500 BC, see J. W. P. Campbell and W. Pryce, *Brick: A World History* (London: Thames & Hudson, 2003), 30. Today, bricks still hold a considerable market share. Alone, over 8 million cubic meter of bricks were produced 2012 in Germany, with facing brickwork accounting for around 10% of this amount. Assuming that facing brickwork is generally half a brick thick (115 millimetres) this equals over 6 million square meter of façade. See Statistisches Bundesamt, "Produzierendes Gewerbe – Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden," Fachserie 4 (Wiesbaden: Statistisches Bundesamt, 2013).

[98] Already for an average single-family house, the façade area equals 200 square metre, which again equals over 8'000 bricks (if one assumes 50% of the façade area to be penetrated with openings). It is evident that the design of such a brick façade and the communication of the design to the builder can only be managed with a set of standardised rules.

complex than for other architectural construction processes (e.g. concrete construction with the necessity to erect a formwork, insert reinforcement, etc.).[99]

While the robotic assembly of brickwork is the main area of investigation presented here, the material itself features unique aesthetic characteristics, such as colour, reflection, and tactile qualities.[100] For the observer, the single brick is a tangible entity that retains its readability also in the context of a larger assembly and is thus able to reveal the constructive logic behind. This aspect enables to scrutinise the resulting artefacts of robotically assembled brickwork also on an aesthetic level.[101] While the thesis touches upon these aspects, an in-depth exploration on the aesthetic implications of robotic brickwork would be a separate research and beyond the scope of the presented work.

This Section discusses the present principles and methods of the manual brickwork process, as well as predecessors of robotic automation solutions, and establishes the foundation for the physical experiments. At this point, it is important to point out that within the context of this work, brickwork will be discussed based on its application to the construction of walls and façades.

3.1 The handcraft brickwork process

Identifying fundamental principles and techniques of brickwork and transferring them to a robotic assembly process requires an in-depth understanding of the handcraft of bricklaying. As James Campbell correctly points out, a large part of techniques of bricklaying applied today have a very long history.[102] This includes the constructive rules that are applied, the tools used, as well as the brick itself. The relative small module size of a single brick relates directly to the repetitive handcraft process. The dimension and the weight of bricks are optimised for working manually on site: handling the bricks with one hand, while the trowel with the mortar lies in the other hand. Thereby, a single person is able to handle and place the bricks without the need for any additional

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[99] See J. Laukemper, *Automation im Mauerwerksbau*, 33., p. 7 and p. 156. In his study, Laukemper concludes that the prospects for success of applying robots for brickwork are favourable. Although, only for non-facing, on-site brickwork. For a further discussion on Laukemper, see Section 3.2.

[100] In his critical essay on the fascination of bricks, Dieter Hoffmann-Axthelm denotes these "romantic" qualities of brickwork – with its ability to provoke unique aesthetic impressions – as its only right of existence. Though, this reduction on the use of brickwork must be seen in the light of the discussion on Postmodernism in architecture. D. Hoffmann-Axthelm, "Der Mauerziegel: Eine Faszination und ihr Objekt," *ARCH+*, no. 84 (1986). Juhani Pallasmaa on the other hand embraces the phenomenological qualities of bricks that convey notions "of earth and fire, gravity and the ageless traditions of construction," which in his opinion can support an "architecture of sensory realism." J. Pallasmaa, "Hapticity and time: notes on fragile architecture," *Architectural Review* 207, no. 1239 (2000).

[101] For Joerg H. Gleiter brickwork is part of everyday human experience, and therefore, the results of a digitally controlled bricklaying process may connect, what he calls the "digitally sublime", with "practical aesthetics". J. H. Gleiter. "Das Digital-Erhabene." *Neue Zürcher Zeitung*, June 1 2013, 64.

[102] See J. W. P. Campbell and W. Pryce, *Brick: A World History*, 303. Although, it must be pointed out that this does not mean there is no potential for advancement.

machinery. Although brick dimensions differ worldwide, they remain in a comparable range. Besides exhibiting a size that can be easily gripped by the human hand, the length of the brick normally equals twice the width plus one standard joint to allow for good bonding (Figure 14).[103]

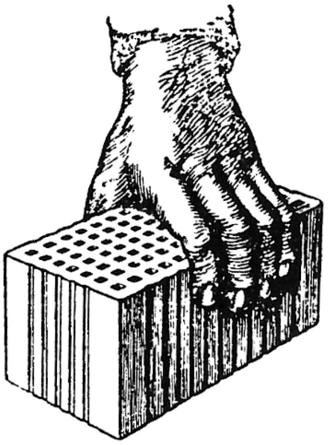

Figure 14. Hand gripping a brick. Traditionally, the width of a brick was chosen such that it could easily be gripped with one hand.

Until the beginning of the nineteenth century, bricks were fabricated manually and usually close to the building site. A high demand of bricks as building material for factories, as well as the new developed urban areas that accompanied industrialisation, boosted the development of brickmaking machines. The acceptance of the auger press developed by Carl Schlickeysen in 1854 and the circular kiln developed by Friedrich Hoffmann (patented in 1859) allowed for large-scale industrialisation of brickmaking (Figure 15).[104] Mechanisation in brick production combined with new and better means of transportation (i.e. railway) moved brickmaking away from the building site into the factory. Further, the mechanisation of brickmaking and its serial production supported the efforts of technical regulations and standard brick dimensions.[105]

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[103] See G. C. J. Lynch, "Bricks: Properties and Classifications," *Structural Survey* 12, no. 4 (1994). Before metrication of the bricks dimension, its measures were directly related to body measurements, for example, a Prussian brick had the length of a Prussian foot (~31 centimetres). In Germany, for example, metrication of brick measures were introduced in 1870 with the *Reichsformatziegel* (25 by 12 by 6.5 centimetres), which was replaced by the DIN standard 105 in 1952. See D. Hoffmann-Axthelm, "Der Mauerziegel: Eine Faszination und ihr Objekt."

[104] See W. Bender, "Popular errors in the history of brickmaking technology," *Zi Ziegelindustrie International - Brick and Tile Industry International* 59, no. 12 (2006). Bender observes, although Schlickeysen and Hoffmann are associated with the invention of these technologies, they both "merely" made the decisive contributions for these technologies to establish themselves. Rather than a revolutionary breakthrough, these machines were the result of successive, incremental change, building upon a vast number of entrepreneurs that invested in the design of brickmaking machines. I. B. Holley Jr., "The Mechanization of Brickmaking," *Technology and Culture* 50, no. 1 (2009).

[105] See F. Schumacher, *Das Wesen des neuzeitlichen Backsteinbaues*, Reprint der Originalausgabe 1920 ed., Callwey Reprints (München: Callwey, 1985), 95-99.

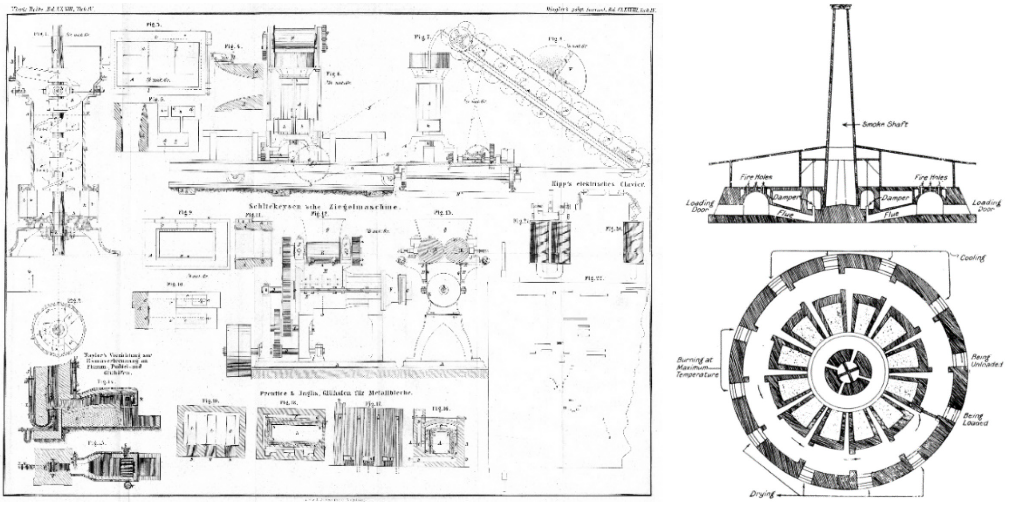

Figure 15. Industrialisation of brickmaking: (left) Schlickeysen press; (right) sectional elevation and plan of a Hoffmann kiln.

While brickmaking moved into the factory in the middle of the nineteenth century and can be regarded as completely industrialised,[106] bricklaying today – despite all efforts of mechanisation and automation – remains to a large part a manual process. Dependent on the quality demand of the work to be executed, especially if the aim is for an aesthetically appealing surface of facing bricks, bricklaying demands substantial knowledge and craft skills. The quality of the workmanship has a direct effect on the strength of the brickwork and its aesthetic appearance.

Exemplary, Gerard Lynch describes the skills and individual process steps necessary for bricklaying.[107] Foremost, he names three principal factors a bricklayer needs to respect, which are "level, plumb and bond."[108] On the one hand, the bonding of the bricks decides on how well the forces acting on the wall are distributed. At the same time, the bonding influences the brickwork's appearance by its distinctive joint pattern. While historically, proper and consisting bonding was a structural necessity to guarantee load bearing capacities, today facing brickwork is mainly reduced to cladding and bonding strength is of less importance. This results, for example, in a half-a-brick thick wall, which is consequently executed in a simple stretcher bond.[109] On the other hand, if level and plumb are lost, the centre of gravity of the wall shifts, meaning that the wall can carry less weight.[110] For common brickwork, bricks are laid out in courses on a bed

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[106] In contrast to the process of bricklaying, it is not uncommon to come across industrial robots in a factory set-up for brickmaking, see A. Kochan, "Robots help out with bricks," *Industrial Robot: An International Journal* 24, no. 2 (1997).

[107] G. Lynch, *Brickwork history, technology and practice*, vol. 1 (London: Donhead, 1994), 182-93.

[108] Ibid., 34.

[109] The reduction of facing brickwork to a simple cladding is largely owed to the fact that the regulations on thermal insulation have drastically increased over the last decades. Thereby, enlarging the necessary wall depth for a pure brick construction, which increases construction costs, while reducing usable floor space.

[110] W. Belz, *Mauerwerk Atlas*, 3rd ed. (München: Institut für internationale Architektur-Dokumentation, 1993), 87-88.

of mortar. According to Gerard Lynch, the laying of a perfect horizontal joint, the so-called “bed joint”, is a basic requirement for well-executed work.[111] Using a trowel the right amount of mortar is spread along the wall and trimmed along the faces. The next brick to be laid is then set into the mortar bed and gently glided into position. While applying slight pressure, the brick is adjusted to the correct height and positioned so that the front arris matches the lower brick. In doing so, surplus mortar pressing out underneath the brick is cut away with the trowel. To ensure that a wall is built up straight, the led has to be checked on a regular basis. A line spanned across the wall length acts as a visual guide for horizontal alignment, as well as for matching of the front arris. For applying vertical joints, so called “perpends”, the joining face of the brick to be laid is additionally buttered with mortar before being bedded. Here again, as Gerard Lynch emphasises, applying the right amount of mortar is crucial to achieve perpend joints of uniform thickness.[112] Finally, for facing brickwork the joints are evened out for weather protection and appearance with a rod.

Recapitulating the processes of bricklaying, it becomes clear that also the tools that support the craft of bricklaying are of relevance for this discussion. For the process described above, these are principally laying tools, as well as measuring and levelling tools. The tools applied have changed only little in the past 500 years.[113] The main laying tool is the trowel, which is used for all mortar handling steps. For levelling, a string is stretched along the course to guide and level of the laying process. Correct vertical and horizontal positioning of the wall is verified through a spirit level and plumb rule. Additionally, try square and bevel are applied to control angles, and measuring rules serve to check width and height of the brickwork (Figure 16).

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[111] G. Lynch, *Brickwork history, technology and practice*, 1, 182.

[112] Ibid., 190.

[113] Ibid., 143.

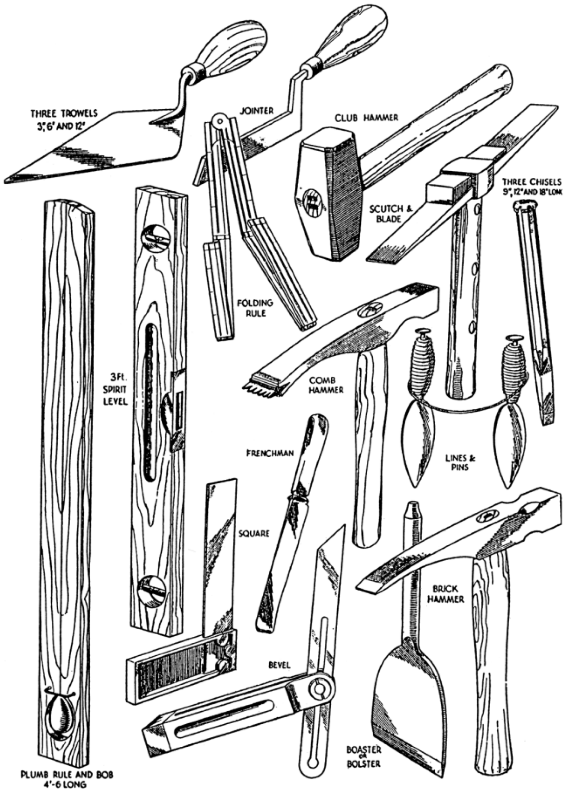

Figure 16. Overview of common bricklaying tools.

Finally, a practiced use of senses is essential for the bricklayer, who relies foremost on his visual perception.[114] A bricklayer needs a "good eye" to estimate how much mortar to take on the trowel and spread along the bricks to accomplish even joints, as well as setting the brick plumb and level. To do so he judges the brick edges against already set bricks and the guideline. Whereas parallel lines are easy for the eye to judge, angles deviating from 90 degrees become laborious, because they can only be accomplished using a special gauge. Hence, the bricklayer has to perform additional actions and placing the bricks takes considerably more time. Alongside visual skills, good sensory capacity in both arm and hand are needed to gently adjust the brick position and apply exactly as much pressure as necessary to create an adequate bond between the brick and the mortar. Additionally, also time has an effect. The mortar cures over time and the bricklayer must work at a constant speed to avoid the mortar curing before the brick is put in place, which would result in an insufficient bonding.

It is essential, to consider all these aspects, when developing a robotic assembly process for brickwork. Ultimately, the knowledge and necessary skills to assemble brickwork

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[114] As Gerard Lynch writes: "An experienced craftsman erecting a quoin would not check either plumb or gauge until it was at least five courses high, his expert eye being his guide in the judging of plumb and gauge. The level would be used only to confirm his skills." Ibid., 198.

has to be transferred into the mechanics and control of a machine, and therefore has to be made explicit (see Section 4).

3.1.1 Formalising knowledge of brickwork

Efforts to formalise knowledge of brickwork can be seen in the pattern books that emerged in the eighteenth century, which covered both construction rules and design details. Prior to this, knowledge of materials, their deployment in construction, the course of actions to follow, and the skill to perform, were mainly passed on verbally and through physical guidance by the craftsmen.[115] Therefore, knowledge of brickwork was seldom stored in explicit form like drawings or formulas, but in the product itself.[116] Learning the craft of bricklaying primarily involved copying and repetition. Craft skills and experience were valuable and intentionally kept secret, as exemplified by the guild system.[117]

Craft knowledge is often referred to as tacit knowledge, meaning knowledge that cannot be fully verbalised.[118] While, to a certain degree, the knowledge to execute skilful brickwork can be asserted to a tacit element acquired through practice, the rules of bricklaying though can be made explicit. Therefore, in former times the tacit knowledge applied in the craft of brickwork can be regarded to a large extend as knowledge "that could be articulated but happens not to be."[119]

Pattern books articulating building knowledge first emerged in England, following the famous example of Palladio's *Quattro Libri dell'Architettura* from 1570.[120] Depicting the sections, elevations, and details of a building in measured drawings, the pattern books were intended on the one hand, to give building owners an impression of the details proposed. On the other hand, architects and craftsmen used these books for educational and inspirational purpose. Over time, pattern books also included knowledge on material and construction rules. In the nineteenth century, textbooks specialised on a specific craft (e.g. bricklaying, carpenter) appeared. These handbooks on architecture and construction comprised all necessary knowledge for building and

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[115] For this reason, techniques of brickwork, like other crafts, only evolved slowly in a process of trial and error, where improvements occur sequentially. Lynch exemplifies this in the evolving craft of bricklaying in England during the medieval period. While important buildings were constructed by immigrant Flemish bricklayers, other brickwork of that time put up by local craftsmen exhibit random bonding of bricks. The structural need for bonding was only slowly understood. See ibid., 33-38.

[116] See R. Foque, *Building Knowledge in Architecture Case Studies* (Brussels: ASP Vub Press, 2010), 75.

[117] See A. R. J. P. Ubbelhode, "The Beginnings of the Change from Craft Mystery to Science as a Basis for Technology," in *A History Of Technology*, ed. C. Singer (Oxford: Clarendon Press, 1958).

[118] The idea of tacit knowledge was introduced by Polanyi in M. Polanyi, *Personal knowledge towards a post-critical philosophy* (Chicago: University of Chicago Press, 1958).

[119] Allan Janik continues to specifically cite the example of guilds: "Trade secrets typify this sort of tacit knowledge. Guild masters from time immemorial have been acutely aware of the ways in which their status, power and standard of living often depended upon keeping the tricks of the trade from the uninitiated." A. Janik, "Tacit Knowledge, Working Life and Scientific Method," in *Knowledge, Skill and Artificial Intelligence*, ed. B. Göranzon and I. Josefson, The Springer Series on Foundations and Applications of Artificial Intelligence (London: Springer, 1988), 54.

[120] See C. Davies, *The Prefabricated Home* (London: Reaktion Books, 2005), 117.

construction with a specific material in form of text and drawings and could be used as technical guidance for the skilled craftsman. The textbook of Wilhelm Behse first published in 1902, for instance, covers all aspects of bricklaying, including necessary mechanical tools and instructions on how to erect, for example, supportive formwork.[121] Besides figures and descriptive text Wilhelm Behse also includes formulas for instance for calculating the thickness of a wall under load (Figure 17).

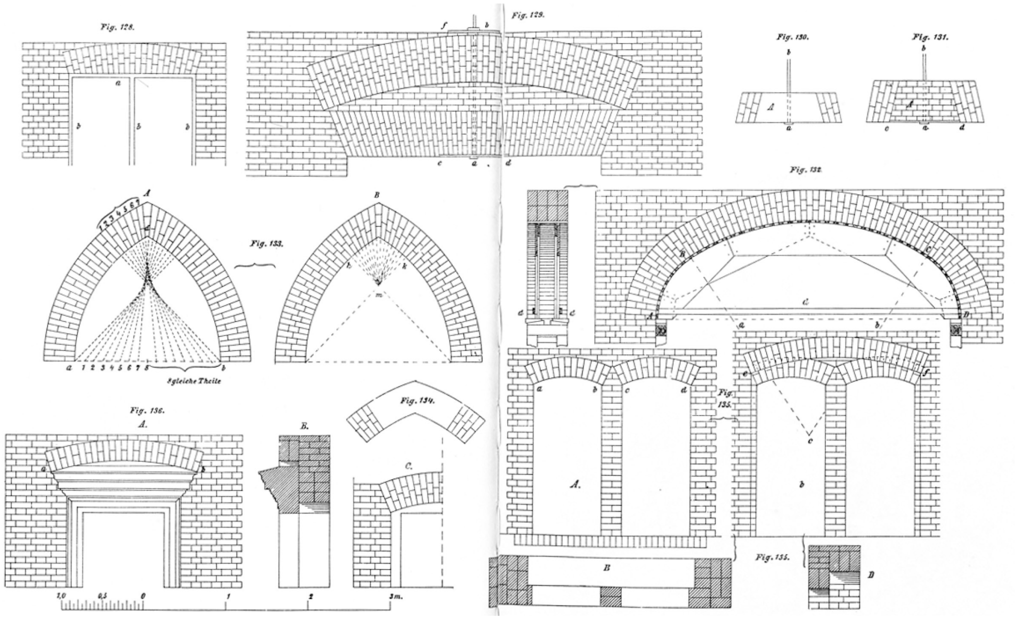

Figure 17. A plate depicting the correct method to set out arches in brickwork.

Today, various handbooks for construction adopt the transfer of knowledge and guide the architect and planner. While some are oriented towards the architect and cover constructive details as well as common brick bonds, others are oriented towards civil engineers, covering topics like dimensioning of brickwork, material properties, building physics, and applicable codes and norms.[122]

Although, pattern books can be regarded as a shift in referring to science as a foundation for technology, compared to "craft mystery"[123], it must be noted that pattern books, as well as contemporary handbooks for construction, can only cover a canon of accepted

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[121] W. H. Behse, *Der Maurer eine umfassende Darstellung der sämtlichen Maurerarbeiten* (1902; reprint, Hannover: Th. Schäfer, 1996).

[122] A handbook specifically focusing on brickwork is, for example, G. Pfeifer et al., *Mauerwerk Atlas*, 6 ed. (Basel: Birkhäuser, 2001). See also, A. Deplazes, *Constructing Architecture: Materials, Processes, Structures* (Basel: Birkhäuser, 2005). This handbook covers brickwork among various other materials and construction techniques. Engineering aspects of brickwork are presented, for example, by W. Jäger, *Mauerwerk-Kalender*, 38th ed. (Berlin: Ernst & Sohn, 2013).

[123] See A. R. J. P. Ubbelhode, "The Beginnings of the Change from Craft Mystery to Science as a Basis for Technology."

brickwork in a certain time period, and, naturally, they cannot convey the particular experience and tacit knowledge of the bricklayer. Gerard Lynch argues, for example, that pattern books led to a decline in variety of techniques and designs of brickwork, which led to "the erection of many fine buildings spoilt only by the repetition of detail."[124] This statement addresses the potential risk of a mechanised application of formalised knowledge. Further, it suggests that in order to introduce creativity, also in a digital designed and robotically assembled brickwork process there must be room for a tacit element. Whereby tacit knowledge is understood similar to Allan Janik, such that it is not so much about the limit of verbalising applied rules, but to master them.[125] Certain rules can then be varied and manipulated, thereby creating crafted variation and subsequently a bespoke result.

3.1.2 Design and execution of brickwork

Design of brickwork is today clearly separated from execution and the direct hands-on process of bricklaying.[126] Design is mediated through drawing.[127] Apart from capturing a design intention, technical drawings inform other parties involved in the building process on how to execute a design. This requires the knowledge of brickwork assembly to be translated and codified. The drawings are guided by handbooks of construction (see Section 3.1.1), as well as conventions and standards, in order to prevent misinterpretation. However, the translation from drawing to execution is not a direct one. Drawings are abstractions that necessarily need to leave out information.[128]

The conventional way for an architect to represent a brick wall in plan is to define its outer boundaries, without explicitly defining each single brick. Standard CAD-systems adopt this representation. For standard brickwork this information is sufficient. Given the bond type and the dimension of the brick unit, a mason with his implicit knowledge and experience can easily erect such a wall. Nevertheless, a common understanding of construction processes of brickwork between designer and craftsmen is necessary. Even if not depicting very single brick, a brickwork design (since it is assembled out of identical units) should respect modular co-ordination, for instance, the overall

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[124] G. Lynch, *Brickwork history, technology and practice*, 1, 51.

[125] A. Janik, "Tacit Knowledge, Working Life and Scientific Method."

[126] Prior to the 19th century, design and construction were often developed together on site. If not performing construction work himself, the architect or builder instructed the craftsmen through verbal or physical guidance. The architectural profession itself was "traditionally regarded as a craft, or close to the notion of craft." J. Pallasmaa, *The thinking hand existential and embodied wisdom in architecture* (Chichester: Wiley, 2009), 64.

[127] The advent of the drawing in the 15th century as an essential intellectual process for architectural practice started to separate the process of design from the physical making of a building. Ideas were now generated in drawings. Thereby the status of the profession of the architect was raised. Through a drawing, authorship could now be "assigned to the designer architect, instead of to the accumulated knowledge of different craftspeople. See J. Hill, "Building the Drawing," *Architectural Design* 75, no. 4 (2005): 14.

[128] Analysing primarily engineering drawings, Kathryn Henderson argues that no drawing, with what technique so ever, can capture hands-on understanding of how an assembly works. Drawings can never capture all aspects of design and function, as well as all the knowledge necessary to transform them into a physical real. "It is the tacit knowledge of the craftsperson – the practical epistemologies of eye, hand, and situated practice – that gets the job done." See K. Henderson, *On line and on paper visual representations, visual culture, and computer graphics in design engineering*, 35.

dimensions of a brickwork element should coincide with the unit size of the brick used and the size of the mortar joints respectively. Still, this over simplified representation of brickwork has its limitations. Especially, considering brickwork that might feature non-traditional bonding systems or non-planar geometries. Such non-standard brickwork is dependent on defining the position of every single brick in three-dimensional space and can hardly be communicated in a planar drawing.[129]

However, applying non-standard brickwork is an exception and today facing brickwork is mainly reduced to cladding, resulting in a half-a-brick thick wall, which is mainly executed in a simple stretcher bond. On the one hand, this is due increased requirements on the outer façade, i.e. in regards to water tightness and insulation.[130] At the same time, a decrease in skill of construction workers can be observed. Performing traditional techniques on site are considered very time consuming. Therefore, the application of traditional decorative bonds has declined in favour of simple stretcher bonds (Figure 18).[131]

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[129] The non-standard and irregular bonding of the brickwork for the Church of St Peter in Klippan, by Sigurd Lewerentz, for example, was not communicated through drawing, but execution was overlooked and adjusted on site by the architect himself. See P. Blundell Jones, "Sigurd Lewerentz: Church of St Peter, Klippan, 1963–66."

[130] See J. W. P. Campbell and W. Pryce, *Brick: A World History*, 290.

[131] See G. Lynch, *Brickwork history, technology and practice*, 1, 64.

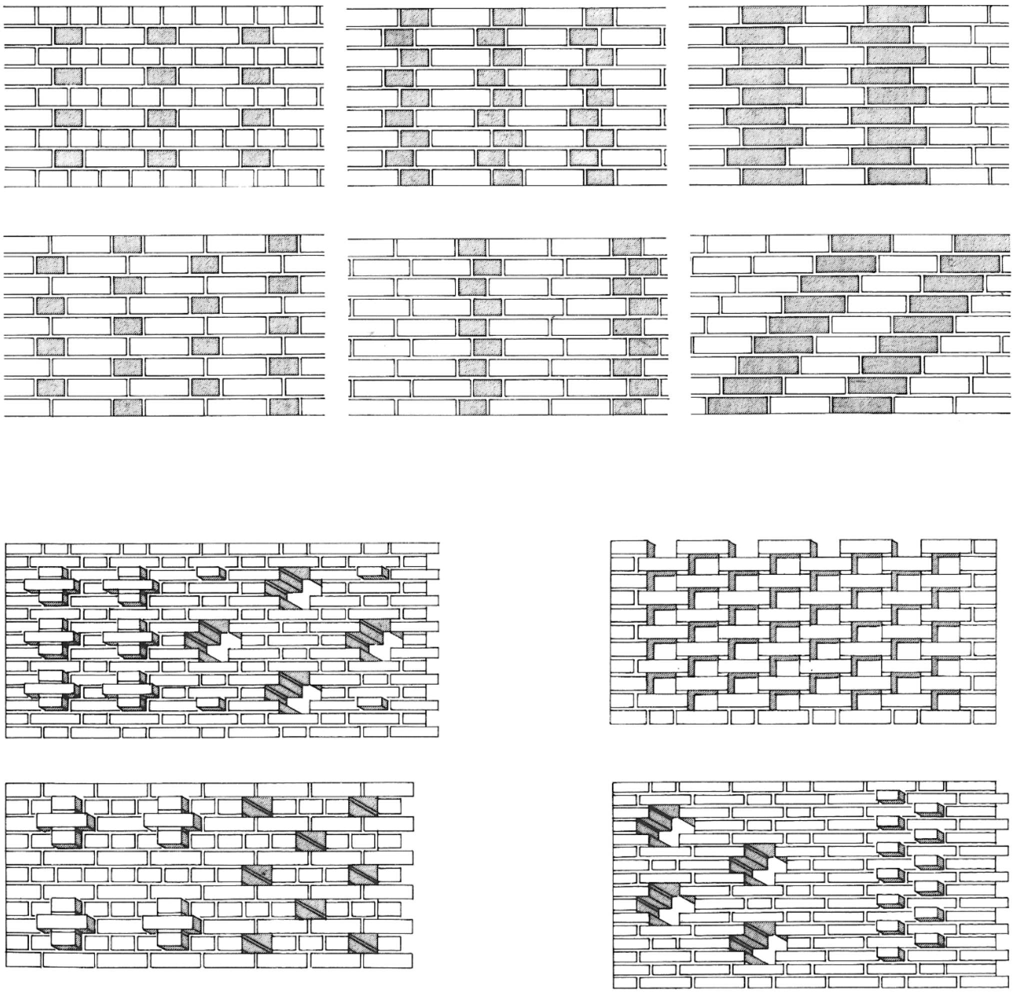

Figure 18. Examples of traditional decorative bonds.

While, the majority of facing brickwork is assembled manually on-site, the low productivity of bricklaying, compared to larger panel systems, stimulated efforts to introduce methods of industrialisation to brickwork assembly. Attempts of rationalisation can be seen in the prefabrication of brickwork panels, thus moving bricklaying away from the construction site and into the manufacturing plant. On-site work is thus reduced to the fitting of large panels. Prefabricating brickwork panels raises the problem of transportation. And, brickwork is unable to absorb tension forces, thus it has to be additionally reinforced in order to prevent failure of the brickwork during transportation and lifting. The bricklaying itself, however, is still performed manually, but in a protected environment (Figure 19).[132] The predecessors in robotic brickwork

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[132] For an overview of prefabrication of brickwork in Switzerland see G. Zenobi and P. Reinshagen, *Vorfabrikation mit Backstein*, Element (Zurich: Schweizerische Ziegelindustrie, 1973).
Attempts to automate the bricklaying process itself are discussed in Section 3.2.

can be understood as a continuation of the attempts to increase productivity of brickwork, aiming at automating the process of bricklaying itself.

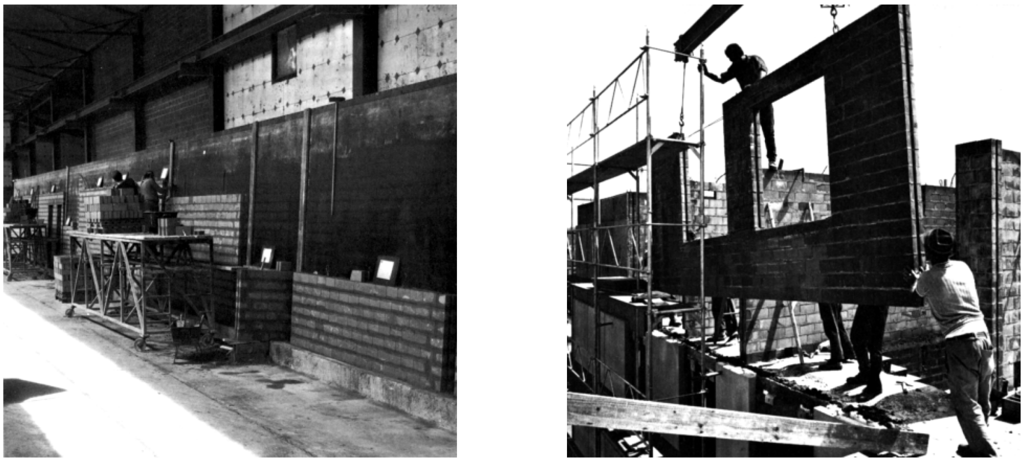

Figure 19. Prefabricating brickwork panels following the "Preton" process developed in the 1960s: (left) manual prefabrication process; (right) fitting of prefabricated brickwork panels on site.

3.2 Predecessors in robotic brickwork

With the introduction of robotics in construction (see Section 2.2), automating brickwork by the means of applying robots was subject of intensive research in the latter half of the 1980s and the first half of the 1990s.[133] In general, the process of bricklaying was considered to lend itself well to automating, since it mainly consists of a repetitive task, assembling identical discrete elements. Furthermore, from an economic viewpoint, rationalising brickwork was of high interest. In many countries, although to different degrees, brickwork makes up a significant proportion of overall construction work, especially for residential buildings.[134] Thereby, most of the costs for brickwork

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[133] Apart from earlier attempts applying robots, which are presented in this section, there have also been further efforts to mechanise parts of the bricklaying process, mainly in the field of prefabrication. The latter are deliberately excluded from the discussion in the scope of this thesis, since automation relies on non-robotic machines. One such example for semi-automated prefabrication of masonry was introduced by Anliker and later implemented in a production line for masonry wall elements for prefabricated houses. The machine sets down a complete layer of bricks in each cycle. Placing non-standard bricks, the scraping of the surplus mortar, as well as the insertion of necessary reinforcement is performed manually. Due to the concept of always putting down a complete layer of bricks only straight walls can be produced. However, this process is solely used for non-facing brickwork. F. J. Anliker, "Needs for robots and advanced machines at construction sites. Social aspects of robotics" In *5th International Symposium on Automation and Robotics in Construction* (Tokyo, Japan, 1988).

[134] In Germany the share of brickwork in relation to overall construction has been more or less constant at around 80% for residential buildings and 20% for non-residential buildings for the last 30 years. See Statistisches Bundesamt, "Bauen und Wohnen – Baugenehmigungen von Wohn- und Nichtwohngebäuden nach überwiegend verwendetem Baustoff Lange Reihen ab 1980," (Wiesbaden: Statistisches Bundesamt, 2013).

accumulate for labour.[135] Fundamental feasibility studies and implementation concepts were developed in the USA, Japan, Finland, Russia, England, Israel, and Germany.[136]

Congruent to the general endeavours to apply robotics and automation in construction, the predominant motivation behind all these research efforts was to improve the "productivity and cost effectiveness"[137] of brickwork. As a common denominator, the building industry was identified as technologically backward at that time, exhibiting a poor efficiency of labour, and mainly relying on traditional craftwork. On a social level, as short-sightedly argued by protagonists like Juergen Laukemper, robotic brickwork would liberate masons from strenuous physical work, which results in a high risk for back injuries and skin diseases due to contact with the aggressive mortar. He writes, "the objective of developing a masonry robot must be to free the human worker from cumbersome labour."[138]

As a result, the focus of these developments was geared towards mechanising the existing and well-established manual brickwork process. Instead of utilising available industrial robots with typical revolute axes, all the above-mentioned projects developed task-specific robots. While this allowed optimising the robotic machine for the specific task to pick up and lay down bricks – particularly, in regards to overall weight, payload, stiffness, and reach – the flexibility to use the machine in other ways was at the same time considerably minimised.[139] This implies that the possibility to adapt such specialised machines to other building processes, using different end-effectors and other materials than brick, or even use different brick sizes or execute other bond patterns is fairly limited (Figure 20).

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[135] The factor for labour costs of course varies from country to country. Further, it is dependent on the brick size and the bond being applied. As an example, in Germany generally, an average of 60% of the costs can be assigned to direct labour. See http://www.baupreislexikon.de/Bauleistungen/012-Mauerarbeiten/526 (accessed April 15, 2015)

[136] See A. H. Slocum and B. Schena, "Blockbot: A robot to automate construction of cement block walls," *Robotics and Autonomous Systems* 4, no. 2 (1988); F. Altobelli, H. F. Taylor, and L. E. Bernold, "Prototype Robotic Masonry System," *Journal of Aerospace Engineering* 6, no. 1 (1993); Y. Kodama etal., "A robotized wall erection system with solid components," in *5th International Symposium on Robotics in Construction* (Tokyo, Japan: Japan Industrial Robot Association (Jira), 1988); H. Lehtinen, E. Salo, and H. Aalto, "Outlines of two masonry robot system," in *Proceedings of the 6th International Symposium on Automation and Robotics in Construction* (San Francisco, 1989); E. Malinovsky et al., "A robotic complex for brick-laying applications," in *7th International Symposium on Automation and Robotics in Construction* (Bristol, 1990); D. Chamberlain, P. Speare, and S. Ala, "Progress in a masonry tasking robot," in *8th International Symposium on Automation and Robotics in Construction* (Stuttgart, 1991); Y. Rosenfeld, A. Warszawski, and U. Zajicek, "Full-scale building with interior finishing robot," *Automation in Construction* 2, no. 3 (1993); G. Drees et al., "Steuerungssystem für einen mobilen Roboter für Mauerwerk," *BMT. Baumaschine + Bautechnik*, no. 3 (1993); J. Andres, T. Bock, and F. Gebhart, "First results of the development of the masonry robot system ROCCO: a Fault Tolerant Assembly Tool."

[137] G. Drees et al., "Steuerungssystem für einen mobilen Roboter für Mauerwerk," 157.

[138] J. Laukemper, *Automation im Mauerwerksbau*, 33, 17.

[139] A reason why task specific robots were developed is also that commercially available articulated arm robots were not a commodity as they are today. Meaning, the investment for a task specific designed machine was similar to buying a robot of the rack, while a proprietary design could be optimised for the specific process. Further, with most of the developments the focus lay on mobile robots, fabricating brickwork in situ.

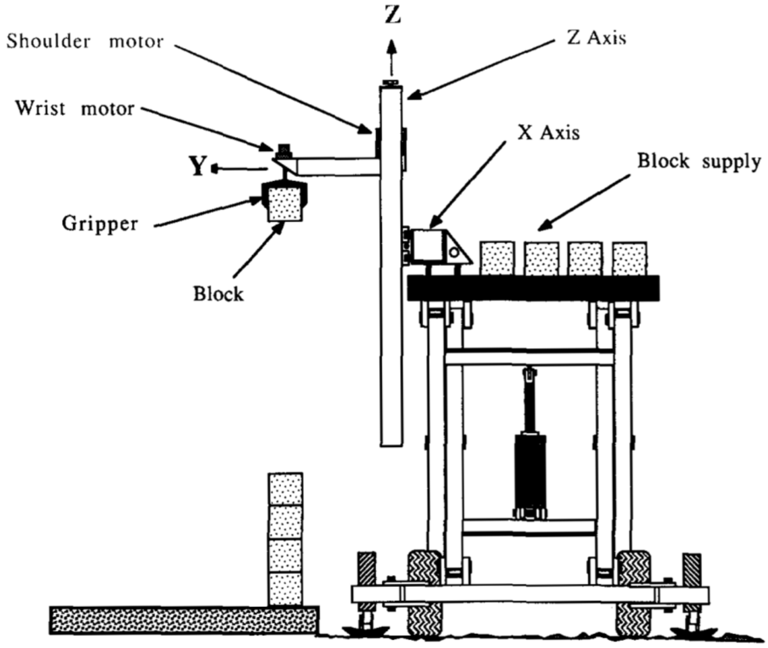

Figure 20. Schematic view of Blockbot, which exemplifies a task-specific robot developed for automated bricklaying.

All projects foresaw a high demand to build standardised straight walls, erected in a conventional stretcher bond, meaning that the kinematic of the robots was designed accordingly and limiting the ability to create other layout geometries (e.g. curves). Already in 1993, Frank Altobelli, Henry Taylor and Leonhard Bernold – although not having solved every mechanical aspect of the bricklaying process – discuss in their outlook the need to develop a flexible control system combined with CAD input. They argue that not all different variations of brick layouts can be foreseen.[140]

Within the above mentioned projects, the most advanced robotic brickwork systems, which were prototypically tested on site, were the so-called *ROCCO* and the *BRONCO* projects.[141] Both projects followed the concept of a mobile robot working on-site and placing the bricks in their final position. A main reason for this decision was that prefabricated brickwork needs to be reinforced for transportation. This makes a flexible layout of the wall elements even more difficult. Integrating the placing of the reinforcement in the robotic process was considered as too complex and would negatively affect the cycle time. Also, both projects concentrated on non-facing brickwork. Here, it was assumed that an acceptable quality of facing brickwork, especially regarding the execution of the mortar joints, was not feasible.[142] With only

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[140] F. Altobelli, H. F. Taylor, and L. E. Bernold, “Prototype Robotic Masonry System,” 32.

[141] J. Andres, T. Bock, and F. Gebhart, “First results of the development of the masonry robot system ROCCO: a Fault Tolerant Assembly Tool.”; G. Pritschow et al., “A mobile robot for on-site construction of masonry.”

[142] Cf. J. Laukemper, *Automation im Mauerwerksbau*, 33, 21.

one exception, all of the above mentioned studies were constrained to the automation of non-facing brickwork. This again indicates that the driving forces of the investigation were primarily of economic reason, since non-facing brickwork constitutes the majority of brick construction work. The only exception is again the work of Frank Altobelli, Henry Taylor and Leonhard Bernold, who followed the path to automate the fabrication of facing brickwork, criticising other attempts of lacking "the aesthetic appeal of traditional masonry."[143] In contrast to purely focusing on productivity, they touch upon the design and aesthetic aspects of brickwork. However, their research does not surpass a principle feasibility study.

While the *ROCCO* project uses concrete and sand-lime bricks bonded with a thin-bed mortar, *BRONCO* first aimed at utilizing common bricks laid in a classical 12-millimetre mortar bed. In the end, automating the mortar process proved to be extremely difficult and similar to *ROCCO* close tolerance bricks – in this case aerated concrete – combined with a thin-bed mortar were used (Figure 21).[144]

Figure 21. Robotic masonry systems: (left) ROCCO; (right) BRONCO.

The main difference of *ROCCO* and *BRONCO* is the payload they can handle, and with that the overall dimension of the robotic unit. While the *BRONCO* project oriented itself on automating conventional masonry work, the *ROCCO* approach foresaw to utilise the machines ability for handling an increased payload. *ROCCO* is capable of handling

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[143] F. Altobelli, H. F. Taylor, and L. E. Bernold, "Prototype Robotic Masonry System," 20. In order to reproduce the characteristics of a traditional brick walls with a robotic system, this approach reverts to the usage of standard bricks and mortar. In a first stage, research focused mainly on achieving a bond strength comparable to manual bricklaying. For this purpose tests were performed bonding two bricks with a single bed joint, making use of a computer controlled mortar supply to spread a uniform amount of mortar onto the first brick and a robot arm with a sensor equipped gripper to place the second bricks with a controlled force. The results proved that a similar bonding strength could be achieved to manually placing the bricks without load. Though, how such a system could be scaled up in order to achieve full-scale brickwork wall elements, as well as the possibility of laying bricks in different configurations, making use of computer aided design programmes, and thus realising non-standard brickwork, is only discussed theoretically. In addition, solutions on how to apply mortar to the head joints and how to introduce necessary reinforcement for prefabricated brick wall panels would still need to be found.

[144] G. Pritschow et al., "Technological aspects in the development of a mobile bricklaying robot," *Automation in Construction* 5, no. 1 (1996).

bricks of a dimension of 100 x 50 x 50 cm with a maximum weight of 350 kg.[145] Although, this capacity is impressive, working with conventional bricks of maximum 25 kg of weight that can also be handled by a human worker as was proposed in the *BRONCO* project exhibits several advantages.

Juergen Laukemper, who drew up a theoretical framework on requirements, methods and economics for automating masonry work, which served as the basis for the *BRONCO* project, argues that using large-sized, but lightweight bricks for robotic assembly of non-load-bearing interior partition walls brings no productivity advantage, since they can be manually erected in a comparable time.[146] Using large-sized modules for load-bearing walls, results in a heavy weight of the single bricks. This, in turn, has a considerable effect on the robotic device. In order to handle the increased payload, the joints and arms of the robot have to be designed accordingly, making the overall unit larger in its dimensions, heavier, and therefore not suitable for the deployment on site. Indeed, the prototype of the *ROCCO* robot weighed 3 t and the external footprint of the unit totalised to 2.5 x 1.7 m. Given these parameters, it was nearly impossible to work on a ceiling slab or pass through doors. In addition, using larger bricks the robot would need to be moved more often, thus costing time, in which the robot is not productive. Finally, using standard bricks that can also be placed manually allows a human operator to more easily intervene, for example, if the robot breaks down or complex details have to be executed that the robot cannot handle.

Both *ROCCO* and *BRONCO* reached a prototypical stage, demonstrating their abilities in a real world scale. However, with completion of the research projects by the end of the 1990s neither of them succeeded commercially. As outlined above, one barrier proved to be the complex handling of dimension tolerances and repositioning of the robot on the construction site. Further, small and medium-sized companies, which make up 80% the industry, were restrained from investing an estimated amount of 200.000-250.000 EUR for a specialised machine designed to perform only one specific task – the layering of bricks.[147] The indicated cycle-time of approximately one minute per brick for the *BRONCO* system did not support the case either.[148] Further development of *ROCCO* intended to use a special brick-system optimised for robotic assembly. While this benefits the overall assembly process, a constraining dependency on the system and

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[145] Although, handling a payload of 350kg is already extraordinary, there was even a second version of ROCCO developed. Its area of operation was geared to the erection of external walls of industrial buildings. This unit had a reach of 8.5m and the ability to handle a payload of 500kg. E. Gambao, C. Balaguer, and F. Gebhart, “Robot assembly system for computer-integrated construction,” ibid. 9, no. 5-6 (2000): 481-82.

[146] J. Laukemper, *Automation im Mauerwerksbau*, 33, 22.

[147] D.-I. h. R. Steinmetzger, “Neue Baumaschinen-Generationen mit Einsatz modernster Kommunikationstechnik” (paper presented at the 2. Tag des Baubetriebs 2002, Bauhaus Universität Weimar, 2002).

[148] “Kein Ersatz für den Maurer,” *Baublatt* 117, no. 96 (2006).

a specific manufacturer is established. Thereby, another barrier for commercial implementation was generated.[149]

Lately, research on robotic systems for bricklaying was picked up again by the Department of Mechanical Engineering of the Hanyang University in South Korea.[150] Apart from aiming to automate individual steps of the bricklaying process, their focus lies on path planning, a problem that is not specific to robotic masonry. Again, as in the research projects of the 1990s, automating the mortar process is analysed being too complex and ruled out. The proposed solution describes human-machine cooperation. The robot transports the stack of bricks and delivers the single bricks to its target position. From there the human worker takes over: applying the mortar on the brick, final positioning of the brick in the mortar bed and scraping off surplus mortar. Here, the robot is nothing more than the mason's co-worker. Although the authors introduce special algorithms for brick-pattern creation and the robot would signal were to put down the brick, when the human worker performs final positioning, the capability of highly precise placement of the robot is lost. Additionally, it can be expected that a human worker that masters the mortar work is an experienced mason, capable of building various brick patterns. Thus, the robot is reduced to the functionality of a lifting aid, similar to positioning cranes, which are applied on site for setting large-scale brick modules.

Although, all of the attempts of applying robots to automate brickwork were initially judged to be economically feasible, none of them could be implemented in the building industry and only few made it to a prototypical stage.[151] So far, research is focused on mechanising the manual bricklaying process and solving problems of automation and its main driver is to increase the productivity of brickwork. Design aspects and novel potentials arising from a robotic assembly process are not considered. However, mimicking existing manual processes and making them more efficient is not alone sufficient to affect a revision of common practice. A stimulus for innovation cannot be cost-effectiveness alone, but must result in novel building components – regarding their performance as well as their aesthetic appearance.

At the same time it is important to note that the failure of these projects was not always necessarily due to technological shortcomings, but that the endeavours of robotics in construction are also bound to a certain cultural and economic context. As such, these developments do not always follow a linear progression. Namely at the time, the

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[149] Regarding the problematic issues concerning the introducing of closed systems in construction versus open systems see for example M. Sharp, ed. *The Transformation of the Industry – Open Building Manufacturing*, Proceedings of the 1st International Conference (Rotterdam: 2007).

[150] S.-N. Yu et al., "Feasibility verification of brick-laying robot using manipulation trajectory and the laying pattern optimization," *Automation in Construction* 18, no. 5 (2009).

[151] Instead, the dominant strategy followed is to move the manual process away from the building site to a controlled surrounding, resulting in the manual prefabrication of brickwork panels. See for example G. Zenobi and P. Reinshagen, *Vorfabrikation mit Backstein*.

discussion focused on unit labour costs and productivity in construction.[152] For the robotic brickwork examples, the decision to develop specialised, task specific machines resulted in a loss in flexibility, because the execution of designs other than straight walls was restricted. This was subsided by the decision to use large-scale bricks, which is understandable in consideration of the productivity aspects, but which negates the versatility of the traditional small-scale brick module.

3.2.1 Computational design strategies

Since research on robotically assembled brickwork focused primarily on engineering the fabrication process, specific software tools or design strategies were not necessary for the initial design stage, but only became important at the stage of generating the control code for the robotic system. This method still resembles the traditional planning process, where in sequential steps a given design is transformed into execution plans.[153] In order to obtain the necessary digital data to generate the robot control code, the general approach taken by the robotic brickwork examples above was a top down process, where a given wall defined by its boundaries is broken down into the position of each individual brick.[154] Besides not making use of the flexibility of the robot given by its programmability in the design phase – meaning the potential to place every brick differently, thus creating brickwork design in a bottom up process – retroactively converting a design into a reasonable and stable brick layout relies on the fact that the initial design already follows basic constructive principles specific to brickwork. In brickwork, for example, a modular coordination is desired, which requires the dimensions of a building or wall element to be based on the chosen brick module.

In a similar strategy of a top-down process proposed by Shuato Li, modular coordination is neglected all together.[155] Li suggests adopting aerated concrete blocks, where each individual block can be processed to a desired form. By cutting or milling the blocks prior to assembly, they can be made to match any given design. Because facing bricks are much harder to machine than aerated concrete blocks and the quality of the resulting joints is an important factor of the overall aesthetics, such an approach is only viable for

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[152] As numerous economists have pointed out, the focus on unit labour costs as sole indicator for competitiveness does not suffice, but further aspects, like e.g. innovation, can be equally decisive factors. For example see C. Syverson, "What Determines Productivity?," *Journal of Economic Literature* 49, no. 2 (2011); or F. Jesus and K. Utsav, "Unit Labor Costs in the Eurozone: The Competitiveness Debate Again," (Annandale-on-Hudson: Levy Economics Institute, 2011).

[153] Once the design is handed over to the builder, no more significant changes can occur. This distinction between building and design, with the impetus to produce an identical copy (i.e. the building) of a design is historically discussed in depth by M. Carpo, *The alphabet and the algorithm*, 20-26.

[154] An example for such an approach is described in F. Herkommer and B. Bley, "CAD/CAM for the prefabrication of brickwork," *Automation in Construction* 4, no. 4 (1996). Also the discussed ROCCO project relies on an expert system partitioning a design into the individual building blocks, see T. Bock et al., "Automatic generation of the controlling-system for a wall construction robot," ibid.5, no. 1.

[155] See S. Li, *Entwicklung eines Verfahrens zur Automatisierung der CAD/CAM-Kette in der Einzelfertigung am Beispiel von Mauerwerksteinen*, vol. 16, Schriftenreihe des instituts für Angewandte Informatik/Automatisierungstechnik Universität Karlsruhe (Karlsruhe2007).

non-facing brickwork. In addition, depending on the overall geometry, such an approach of individually machining each brick can be very wasteful (Figure 22).

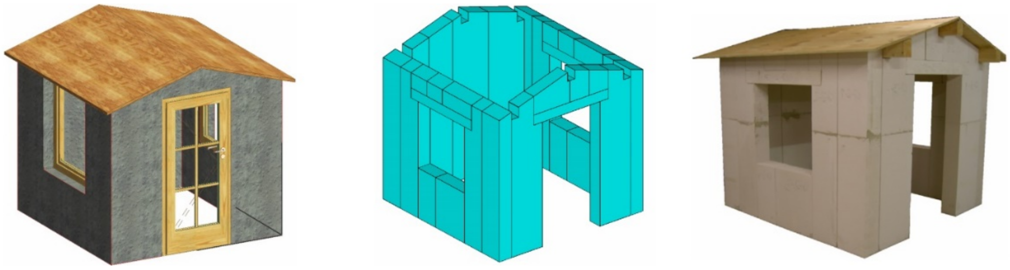

Figure 22. Segmentation of aerated concrete blocks proposed by Li: In a top-down process, a given design is segmented into individual blocks that are cut to fit.

In contrast, Rihani and Bernold propose a tool that respects modular coordination already in a CAD design environment.[156] A wall is represented by individual bricks, respecting both brick dimensions and bonding requirements. The individual bricks generated by the software are then used as the basic data to generate the robot control code. However, the individual bricks themselves cannot be manipulated and the tool is limited to straight walls and to a standard stretcher bond.[157]

More recently, Andres Cavieres, Russell Gentry and Tristan Al-Haddad have emphasised the importance of integrating knowledge-based parametric tools already at a conceptual design stage.[158] For a very similar problem of concrete masonry walls, they propose parametric templates that embed construction and structural design knowledge, while fabrication constraints are omitted. Although applicable at an early design stage, the initial brick distribution relies on an input surface similar to the top down process described above (Figure 23).

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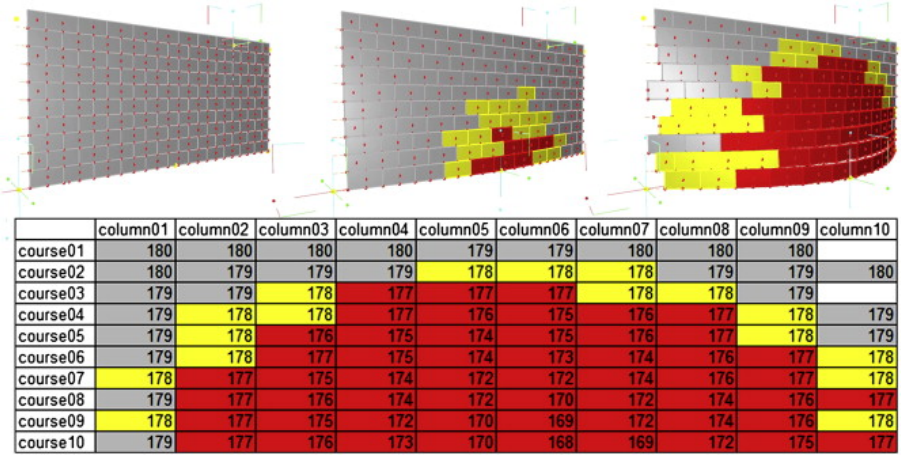
[156] See R. A. Rihani and L. E. Bernold, "Computer Integration for Robotic Masonry," *Computer-Aided Civil and Infrastructure Engineering* 9, no. 1 (1994).
[157] Ibid., 63-64.
[158] See A. Cavieres, R. Gentry, and T. Al-Haddad, "Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis," *Automation in Construction* 20, no. 6 (2011).



	column01	column02	column03	column04	column05	column06	column07	column08	column09	column10
course01	180	180	180	180	179	179	180	180	180	
course02	180	179	179	179	178	178	178	179	179	180
course03	179	179	178	177	177	177	178	178	179	
course04	179	178	178	177	176	175	176	177	178	179
course05	179	178	176	175	174	175	176	177	178	179
course06	179	178	177	175	174	173	174	176	177	178
course07	178	177	175	174	172	172	174	176	177	178
course08	179	177	176	174	172	170	172	174	176	177
course09	178	177	175	172	170	169	172	174	176	178
course10	179	177	176	173	170	168	169	172	175	177

Figure 23. Knowledge-based parametric tool for concrete masonry walls: The layout of the individual bricks is generated top-down taking a surface geometry as the initial input. A colour coding gives the designer direct feedback on the feasibility of a chosen curvature. In an additional step, reinforcement requirements based on a simplified structural analysis are calculated.

3.3 Synchronising brickwork design and robotic assembly

Having evolved over thousands of years, brickwork is a highly versatile construction type. The geometry of the single brick module is unchallenged in its simplicity and its potential to adapt to varying building styles.[159] However, due to mainly cultural and economic factors, as well as an erosion of bricklaying skills, the diversity in the application of brickwork has significantly decreased. At the same time, the construction process of brickwork, and the rules and tools applied are optimised to a high degree and can be considered coherent and custom-fit for the bricklaying process.[160] Leaving aside recurring attempts for rationalisation of brickwork, mainly by increasing productivity through the introduction of large scale brick modules and positioning cranes for a faster build-up process, one could characterise the assembly process of brickwork as "consolidated" – especially, in regard to facing brickwork.[161]

Further, the work discussed illustrates that brickwork, being a self-contained process in building construction, and composed out of the stacking of a small number of simple

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[159] See Section 3.

[160] This is of course also true for other materials and construction types that exhibit a long history of application in architecture, for example, timber constructions. Where the CNC-manufacturing of timber is already highly advanced. Interestingly, the introduction of digitally-controlled manufacturing machines led to a reintroduction of traditional wooden joints associated with manual craft work, which had been replaced by steel joints due to a decrease in skills and for economic reasons. See C. Schindler, "Ein architektonisches Periodisierungsmodell anhand fertigungstechnischer Kriterien, dargestellt am Beispiel des Holzbaus," 209-11.

[161] This is not to say that there has been no advancements. However, these can mainly be assigned to non-facing brickwork, for example, developments in mortar technology, like thin-bed mortar, or perforated brick modules that are optimised for thermal transmittance.

elements, lends itself especially well to be performed by an industrial robot. However, the development of robotic assembly processes for brickwork so far, exemplifies some of the main misunderstandings of robotics in construction. The attempts were guided by a common goal to increase productivity of brickwork and mainly detached from the architectural design process. The results are specialised machines performing standardised processes. The potential to create diverse brickwork assemblies, by combining the versatility of the brick module with the inherent flexibility of robotic assembly processes, was overlooked in all these cases. Especially, brickwork-specific computational design strategies that respect the generic modularity of the brick and integrate parameters of assembly were neglected. Therefore, a new approach is needed that essentially synchronises brickwork design with robotic assembly processes.

4 EXPERIMENTS ON ROBOTICALLY ASSEMBLED BRICKWORK

4.1 Objectives of experiments

The physical investigations form a centrepiece of this thesis. The experiments serve to develop and validate a robotic-based production method for non-standard brickwork. They combine both the design and engineering of a robotic assembly process and, consequently, its application on a design task. Thereby, the experiments identify specific design strategies that incorporate essential criteria and parameters of an automated bricklaying process. Ultimately, the aim of the experiments is to establish an in-depth synchronisation of digital design with a robotic assembly process, and thereby leveraging novel architectural potentials of brickwork in comparison to common manual construction.

The results of the experiments are evaluated in relation to the manual assembly process, as well as the predecessors of robotic brickwork. Each experiment is a progression in further investigating and implementing a robotic-based design and assembly process. On the one hand, based on the experience of the preceding experiments, the robotic assembly process is advanced and further extended. Thereby, also increasing the level of explicit control that can be introduced into the process. On the other hand, specific qualities of the brickwork emerging from the robotic process are identified and exploited in the design task for subsequent experiments. Throughout the experiments, both the design and the process of making are viewed as integral parts that equally inform one another. The physical artefacts resulting from each experiment should convey a concrete notion of this approach and reveal aspects of their design and manufacturing process.[162] Nevertheless, they have to be regarded as the unfolding of a specific design idea out of a much larger solution space.[163]

All three experiments apply a robotic assembly process of brickwork to the architectural element of a wall and respectively its function as façade. The wall represents one of architecture's fundamental building elements to create space. In the form of façade, walls are highly visible elements of an architectural composition. As such, the

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[162] The imprint of an object's production history relates to Semper's definition that the work of art is a product of an underlying basic idea as well as external factors, like material and the way they are processed. G. Semper, "Entwurf eines Systemes der vergleichenden Stillehre," in *Kleine Schriften* (Berlin & Stuttgart: Spemann, 1884), 267-71.

[163] The three prototype walls designed by student groups in experiment 1 indicate this openness of the process, while the set-up of the other two experiments only allowed for the realisation of a single solution.

architectural component wall seems well suited to extract exemplary constraints and findings of robotic assembly processes for brickwork.

Further, in order to obtain relevant results, the experiments were conducted in 1:1 building scale. Thus, real world demands in terms of materiality, construction, as well as specific functional requirements had to be met in the design. This is essential, since material properties, as well as characteristics of constructive systems in their entirety are not scalable. For the work, to potentially have a serious impact on common building practice, applying real world parameters is an important requisite. Finally, in order to enable a direct comparison between the robotic assembly process and the manual process, standard facing bricks are adopted for all experiments.[164]

4.2 Method of experiments

As a basic method, the experiments are built up by 1) analysing the manual assembly process of brickwork and 2) transferring it to a robotic process. In doing so, aspects in the robotic process that differ from the manual work, as well as the design-relevant points of intervention in the digital process control are identified. This involves, for instance, certain mechanical and kinematic constraints of the robotic set-up, but also the question of how design information is transferred into the actual building process. Since the objective of the experiments is not automation per se, but to investigate architectural potentials arising from a robotic based assembly process of brickwork, the implementation of the robotic process is focused on those parts were the digital process control turns design relevant, rather than a mere mechanisation and optimisation of the complete process; and 3), ultimately, design strategies suitable for the robotic assembly process are explored by prototypically applying the fabrication process on a design task.[165] The aim of the design task is to analyse the possibilities and constraints arising from the materials, the constructive systems, and the fabrication process applied.

Although the result of all three experiments is to a large extent a completely automated assembly process for brickwork, the experiments' emphasis was mainly on design research. Here, the development of a robotically-controlled assembly process was seen as part of the overall architectural design task.[166] Tools and processes of fabrication are

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[164] Research is seldom accomplished alone. This is particular true for the practical experiments that, apart from intellectual impetus and exchange, also demand a fair amount of physical hands-on work. Especially, the large-scale experiments would not have been possible without distributing subtasks. Successfully conducting these experiments was a team effort, which consists of members of Gramazio Kohler Research the research group chaired by Prof. Fabio Gramazio and Prof. Matthias Kohler, students participating in the experimental courses, as well as industry partners. A full list of the people involved in each experiment and their primary role is given in the Appendix.

[165] In order to broaden the scope of the results, several design explorations were carried out within the scope of experimental student courses. See Section 4.4.

[166] Although previously developed robotic brickwork processes are analysed and serve as reference (see Section 3.2), the aim of the thesis is not to advance the technological shortcomings of these solutions, but addressing their shortcomings

always accompanied by constraints. In order to explore the design potential of a robotic assembly process, the chosen approach was to keep the process as open as possible. The experiments are iterations of developing a robotic assembly process and congruent design strategies, which are informed in each cycle through the findings of the previous experiments. The findings of one experiment set the basis to further develop the robotic process, for example, characterising what other process steps could be automated without compromising the overall design space. Thereby, specific design intentions could influence the development of the robotic process and vice versa.

Supporting the applied design strategies a range of software tools were developed. These allow for manipulating the assembly process and range from simple scripts to software applications, which integrate parameters of the fabrication process (i.e. material and fabrication constraints). While the developed digital design tools were not a primary objective of the experiments and are thus not part of their validation, they considerably contribute to the design exploration.

4.3 Fundamental parameters of an integrated digital design and robotic assembly process for brickwork

In contrast to the research efforts of the past devoted to developing robotic brickwork processes, the approach chosen in the presented research is not driven by rationalisation, liberating human workers from strenuous work, or the goal of automation itself. Rather, brickwork is selected as subject matter to identify in an exemplary manner architectural potentials arising from a digitally driven and fully integrated design and assembly process. Consequently, in transferring manual bricklaying to a robotic process, the main focus of the experiments lay on adopting a six-axis articulated robot arm to place the bricks. Further, as already mentioned above (see Section 4.1), the focus is set on facing brickwork. In contrast, earlier endeavours were mainly concerned with non-facing brickwork, since automating brickwork was mainly viewed as a functional assignment; meaning that the erected walls were purely seen as structural building elements, where the detail and aesthetic appearance could be neglected, as the bricks would afterwards be concealed by plaster.[167]

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in amalgamating novel fabrication technology with a broader architectural scope, which encompasses design and construction.

[167] Note, however, that applying plaster, being another subdomain of construction, was not part of the automation process in any of the robotic brickwork predecessors discussed in Section 3.2.

In what follows, the basic framework of the experiments is outlined. This includes the fundamental characteristics of a robotic assembly process for brickwork and key aspects of the manual process that, transferred to automation, potentially have to be reassessed.

4.3.1 Robotic set-up

Although, the discussed examples of robotic masonry systems were all concerned with the development of specialised machines performing the single task of bricklaying, already Juergen Laukemper observes that a six-axis articulated robot could be advantageous and viable for this undertaking. In fact, such a composition of the kinematic chain is best suited and most versatile, especially working in a dense workspace and the advantage of rotary axes over translatory axes in terms of control and stiffness.[168] Indeed, to a large part, standard industrial robots follow this kinematic layout and mainly vary in size, reach, and the payload they can handle. Today, such industrial robots are a commodity and there is no need to build a specialised machine.

For the first two experiments, a multi-purpose robotic work cell was employed. It is based on a six-axis articulated arm robot with a reach of 3 m and a payload of 100 kg.[169] The robot is mounted on a linear axis of 8 me. Thereby, the robot can span a workspace of maximum 3 m in height and 6 x 8 m in outline.[170] An external eighth axis in the form of a rotary table completes the set-up. Overall, the cell's set-up is not targeting a predetermined process, and, in addition, the robotic arm itself can be equipped with different end-effectors. Thus, a multitude of robotic processes can be realised (Figure 24). The pursued experiments expand on this generic set-up to realise a robotic system for the assembly of brickwork. It is important to acknowledge that every alteration of the robotic set-up has a direct influence on the potential design space. The specific robot model, its reach and payload, the end-effector tool, peripheral devices and their spatial layout set the physical boundaries and constraints on where and how the robot can operate.

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[168] Cf. J. Laukemper, *Automation im Mauerwerksbau*, 33, 101-07.

[169] The exact model is a KUKA KR150 L110. See KUKA Roboter GmbH, "Technical Data: KR 150 - KR 150 L130 - KR 150 L110," (Germany: KUKA Roboter GmbH, 2000).

[170] Due to its specific kinematics, articulated arm robots feature a complex cusp-shaped working envelope (Figure 1). Therefore, an infinite number of rectangular workspaces can be inscribed in the robot's working envelope, with each corner of the rectangle located at a point of maximum reach of the robot arm.

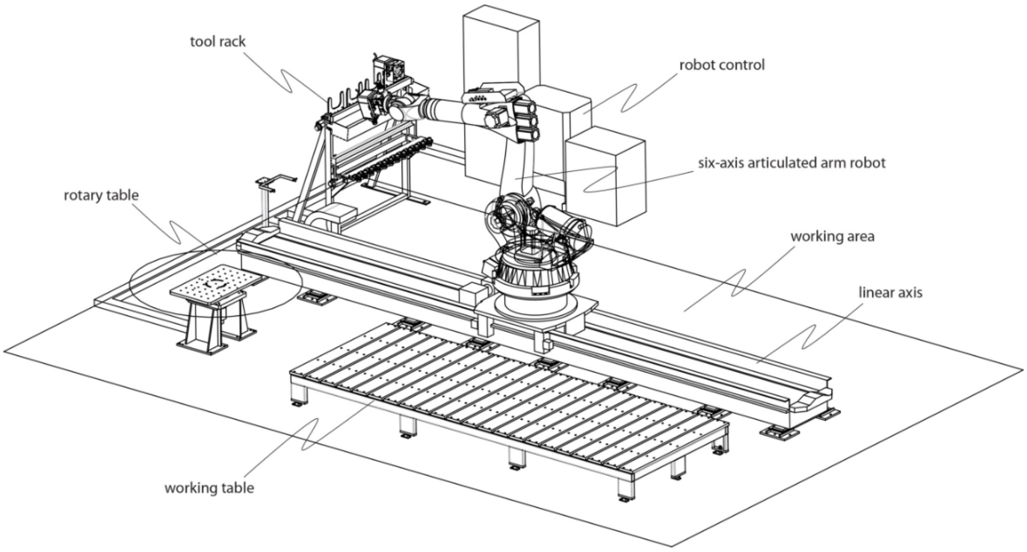

Figure 24. Layout of robotic set-up.

4.3.2 Material System

4.3.2.1 Brick

The experiments adopt standard facing bricks (as described in Section 4.4.2, 4.5.2, and 4.6.2). This preserves compatibility to standard assembly process, allowing manual intervention if necessary. Further, this enables a more direct comparison of the results between a robotic and a manual assembly process. In contrast, several of the previous robotic brickwork processes introduced new brickwork systems, specifically adapted to the robotic process. On the one hand, these included custom brick geometries, which allowed a self-interlocking of the bricks.[171] On the other hand, they strove to utilise the lifting capabilities of a robot by using larger and thereby heavier bricks.[172] Both these measures were meant to increase robustness and efficiency of the process, but at the same time, they fairly constrained the freedom in design. The positioning of self-interlocking bricks is already predefined through their geometry, while large sized bricks limit the degree of possible differentiation within a brickwork structure. Therefore, these measures result in an increase of standardisation of brickwork. However, it is exactly the ability to transfer a high degree of information into a brickwork assembly, which a digitally controlled robotic process can introduce. This

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[171] See W. Leyh, “Optimale Zustandsregelung von Montagerobotern im Hochbau” (PhD, Technical University Munich, 2000), 1.3-26-1.3-27.

[172] Specifically the *ROCCO* project aimed for a load capacity of the robot of 300 kg, cf. See ibid., 1.2-8. Also, for the *BRONCO* bricklaying robot a high payload was seen as an essential requirement to ensure an economic process, see G. Pritschow et al., “A mobile robot for on-site construction of masonry,” in *IEEE/RSJ/GI International Conference on Intelligent Robots and Systems (IROS)* (Munich1994).

ability is dependent on a free positioning of the bricks, as well as a relative high resolution, in order to create non-standard brickwork or to integrate openings and cavities.[173] At the same time, the precision offered by industrial robots today is sufficient so that improving the precision of assembly through self-interlocking of the bricks is not necessary. In addition, the argument of a greater efficiency through larger bricks cannot be hold up. With a certain brick size, erecting the wall manually, with the aid of a lifting device, will be just as fast as using a robot, which additionally has to be repositioned more frequently due to its limited reach.[174]

Finally, using standard facing bricks keeps the process open to apply any other commercially available brick system, as well as adapting to local material. The robotically assembled brickwork can easily be combined with manual assembled brickwork and eases the ability for human intervention in the process if necessary.[175] It is the approach of this thesis to enhance established processes through the introduction of robotic assembly, in contrast to creating new building systems adapted to robotics. The latter is coined with the phrase "robot-oriented design", and generally applies standardisation, thus limiting freedom in the assembly process and design.[176]

4.3.2.2 Joining

Usually, brickwork is a combination of bricks and mortar. While controlling a robotic arm to place a brick at a defined position in space can be regarded as a simple and straightforward task, applying mortar in an automated process is far more complex. Even more, as the intention was set on facing brickwork, where a thorough and high quality execution of the mortar joints is of great importance. The challenge to implement an automated mortar-based process becomes obvious, when recalling the description of the handcraft bricklaying process (see Section 3.1). Among the various operational process steps the mortar bed has to be laid out, surplus mortar scraped off and the brick levelled and set at the correct height. Additionally, when erecting facing brickwork, in order to realise a specific joint profile the joint has to be traced with a special tool to compress the mortar. In other words, erecting mortar joined brickwork requires considerable dexterous motoric skills combined with advanced sensory perception. A task enabled by a complex interaction that the human bricklayer is mostly unaware of,

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[173] For an investigation on the relationship between different module sizes, efficiency in fabrication, and information depth, see the *Resolution Wall* project in F. Gramazio and M. Kohler, *Digital Materiality in Architecture* (Baden: Lars Müller Publishers, 2008), 64-65.

[174] In the case of the *ROCCO* project, a bricklaying robot specifically designed for on-site work, this led to the obscure situation, that the robot's weight exceeded the average permitted ceiling loads and was not able to pass through standard door openings, see M. Dalacker, *Entwurf und Erprobung eines mobilen Roboters zur automatisierten Erstellung von Mauerwerk auf der Baustelle*, ed. T. Bock, vol. 1, Schriftenreihe: Planung, Technologie, Management und Automatisierung im Bauwesen (Stuttgart: Fraunhofer IRB Verlag, 1997).

[175] Considering the aspect of marketability, an open system is preferred. Thereby, the industry is not bound to one or only a limited amount of suppliers. Additionally, it is very difficult for new building systems to find acceptance and prevail in the industry.

[176] On "robot-oriented design" see T. Bock, "Robot-oriented design."

but holds as embodied knowledge. A transfer of the process of applying mortar to an automatic robotic process involves the deployment of multiple sensors, as well as intricate process control structures, which can become quite costly to realise, especially if one strives for a robust solution.

Therefore, a bonding method was chosen that is more appropriate for an automated robotic process. Instead of mortar, a structural adhesive is used, since applying controlled gluing paths is a process very well suited for a robot and commonly used in other industries.[177] In addition, using adhesive or thin bed mortar are familiar techniques for non-facing brickwork.[178]

However, the focus of the experiments is set on facing brickwork and here brickwork systems applying adhesive have not existed before. Practically, all facing brickwork is executed with thick bed mortar.[179] A reason being that as a restriction, bonding with an adhesive or thin bed mortar generally requires the use of planar bricks, meaning the top and bottom surface have to be grinded to achieve a perfect levelling of the bricks. This is necessary, since the adhesive, compared to a thick bed mortar, cannot compensate for dimensional tolerances of the bricks. The perpends are normally closed through an interlocking geometry of the brick sides (i.e. tongue and groove). As a consequence, such brickwork systems can only be laid in a planar stretcher bond.

Standard facing bricks feature dimensional tolerances of up to 10 millimetres. Combining these with adhesive in a facing brickwork system will thus require special measures (see Section 4.5.6.2). Additionally, due to the dimensional tolerances, wind and water tightness of the brickwork cannot be guaranteed. Moreover, since only the bed joints are glued, such a brickwork system will inevitably feature open perpend joints. However, these functionalities are less important for façade facing, which normally feature a water-bearing layer behind the brickwork. Furthermore, studies suggest that open vertical joints have no significantly harmful influences on water penetration. On the contrary, they can have a positive effect supporting bricks to dry faster, since they provide a greater surface area for the water to evaporate.[180]

Although, it cannot compensate for dimensional tolerances, the use of adhesive features several advantages over mortar.[181] Adhesive can be applied more precise, it is easier to

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[177] For example, the automobile industry applies automated gluing process for bonding windshields.

[178] Since all predecessors of robotic brickwork focused on non-facing brickwork, they reverted to thin bed mortar or adhesive respectively, since the application of mortar was ruled out as being too complicated to be implemented within an automated process (see Section 3.2).

[179] Of course, there are exceptions, but none of these could so far establish themselves as a significant alternative to a traditional thick mortar bed. An example for a completely dry stacked brickwork facing façade system has been used in the Netherlands, see H. Vekemans and R. v. d. Pluijm, “Daas-ClickBrick: Dry stack clay bricks for façades” (paper presented at the 13th International Brick and Block Masonry Conference, Amsterdam, The Netherlands, 4-7 July 2004).

[180] On the issue of water penetration of brickwork with open horizontal joints see H. Janssen et al., “Rain penetration through thin layer mortar brick façades with open vertical joints” (ibid.).

[181] A further advantage not mentioned here is that glued brickwork exhibits less thermal loss through the joints. Naturally, this only applies for closed brickwork.

process, and its preparation is less laborious than of mortar. Thereby, it can speed up the whole bricklaying process. Further, compression strength of glued brickwork is higher, since forces can directly be transferred between the bricks without passing through a layer of mortar, which only has limited structural capacities.[182] Finally, adhesive can potentially account for tensile forces, which is of particular interest in prefabrication, or for the realisation of non-standard geometries that do not act as compression-only structures. In these cases, the adhesive can make additional reinforcement, which, for example, is a requisite for prefabricated brickwork, mainly due to the dynamic forces acting on the elements during handling and transportation, obsolete (see Section 4.5.2).[183]

Nonetheless, when switching from a thick bed mortar to an adhesive – apart from technical and functional aspects – it also has to be acknowledged that mortar joints are inseparably connected to the image associated with traditional facing brickwork. The thickness and special detailing of the joints add to its distinctive aesthetic appearance. For a stretcher bond the joints account for up to 22% of the overall surface area, depending on the brick size used.[184] In addition, a variety of joint profiles can be used. Some reveal the edges of the bricks and accentuate their individual forms. Others obscure the edges and merge bricks and mortar to a homogeneous surface (Figure 25).

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[182] Presuming an even contact area between the bricks, allowing for a uniform force distribution.

[183] At present no standards exist that apply for glued brickwork under tensile forces, which of course is much dependent on the brick quality, as well as on the specific adhesive used. Nevertheless, the experiments demonstrate the enormous structural capacity of the applied adhesive.

[184] The maximum of 22% surface area is attained using DF format bricks (thin format according to DIN – length 240 mm, width 115 mm and height 52 mm) and standard bed joints of 12 mm and standard butt joints of 10 mm respectively. Using NF format bricks (normal format according to DIN – height 71 mm) the surface area of the joints still account for 18%.

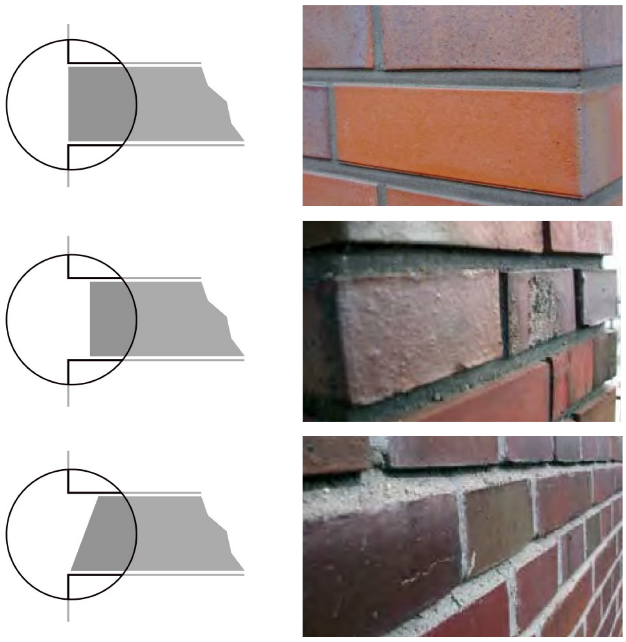

Figure 25. Three standard finishes for mortar joints of facing brickwork: (top) a flush joint underlines the overall wall surface; (middle) a raked joint accentuates the individual bricks through intensifying the light and shadow effect; (bottom) a weather joint emphasises the horizontal layering of the brickwork.

To conclude, the transfer of brickwork towards a robotic assembly entails rethinking the individual process steps under the premises of their suitability for robotic implementation. Overall, the use of mortar compared to adhesive not only affects technical aspects of its integration in an automated process, but also has consequences on a functional, structural, and also aesthetic level of the resulting brickwork. All these different facets have to be revised in a robotic assembly process and, ultimately, influence the results of the pursued experiments.

4.3.3 Mechanical tooling and periphery

A fully operational system is only achieved by integrating the robot with tools and peripheral devices geared towards a specific process (see Section 2.1). Especially, the end-effector, which is the actual tool attached at the end of the robotic arm, defines the actual material manipulation performed. In order to perform the process of bricklaying, the grasping capability of the human hand is transferred to a gripping tool. In comparison to the human hand, however, a mechanical gripper is a primitive device. For example, a gripper per se has no sensing capabilities. Therefore, the robotic system does not know if a brick is even gripped or has any notion on how much pressure is applied in putting down a brick. This information can only be gathered through integrating additional sensors. Although, as a means of simplification of the robotic set-up no force sensors are integrated for the experiments, meaning, for example, the height of the laydown position of the bricks relies solely on the robotic control. As a further distinction to manual bricklaying, a mechanical gripper imposes constraints on placing the brick. Depending on the gripping position and the extent of the gripping tool, certain positions of placement will not be achievable due to collision problems. While in the manual bricklaying process the hand's grip on the brick can easily be changed and the brick passed from one hand to the other. For the experiments, these constraints had to be incorporated into the designs. If specific design intents had to be met, the gripping tool needed to be re-engineered. Overall, a modular parallel gripper serves as the basis for the experiments. The actual fingers of the gripper can be built upon two base jaws, which are actuated pneumatically in a translational movement. The gripper has only two main states, open and closed, which are controlled by a solenoid valve. With this set-up, different gripping strategies could be realised in the experiments.

Since the used robotic system does not include any tools providing sensory feedback, it is mandatory that the bricks are fed to the robot at a precise and predefined position. Without information on how the brick is positioned in the gripper, the robot control cannot compensate for any displacement of the brick. This is different for a human bricklayer, who achieves precision while placing the brick (i.e. in aligning the brick to visual guidelines and already placed bricks). In contrast, the developed robotic system achieves precision through picking the brick. In order to attain a precise picking position a brick feed is integrated in the system, which is restocked manually and undergoes several iterations throughout the experiments (see Sections 4.4.1, 4.5.1, and 4.6.1).[185]

Besides picking and placing a brick, there are several tools that aid the manual bricklaying process. Recalling the general toolset for bricklaying, over half of the tools are directed to measuring or ruling tasks.[186] In a robotic process, these tools become obsolete. Their function is completely taken over by the robot control.[187] Through the possibility to precisely position the robotic arm in space, additional measuring and ruling tools are not necessary. Finally, a dispenser for the utilised structural adhesive replaces the trowel tool, which otherwise is used to handle the mortar. The dispenser allows precisely controlling the position and amount of adhesive applied to the bricks. Therefore, an additional tool for spreading the adhesive is not necessary.[188]

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[185] Further automating the feeding process, either by automating the restocking process, or through integrating feedback systems like a vision system to allow the robot to grip the bricks from an arbitrary position (e.g. directly from a pallet) can easily be envisioned. Since automating in itself is not an objective of this thesis and this process step has no fundamental impact on the resulting brickwork, development in this direction is not further pursued.

[186] See Section 3.1, Figure 16.

[187] Additionally, the plate depicts several tools intended for shaping a brick to a specific form. In the experiments, only full and half-sized bricks are used. Any special detailing, which in a manual process might have been performed through shaping the bricks, is realised solely through positioning.

[188] See Section 4.5.3, Figure 48.

4.3.4 Robotic control

Key to activate the flexibility inherent to a robotic system is its programmability. In order to exploit this flexibility in the design, the most direct way is to intervene and manipulate the robot control code. This approach puts the robotic assembly process at the heart of the design exploration. Design data thus directly controls the robotic system and thereby the assembly process. In other words, the designer can explicitly control the building process.[189]

Designing through programming the automated assembly process substantially differs from the top down approaches chosen by the earlier robotic bricklaying investigations. This can be explained with the different focus of this thesis, where the development of the robotic assembly process is recognised as part of the architectural design exploration. In general, the previous robotic bricklaying projects assumed brickwork to be constructed in a simple planar stretcher bond resulting in straight walls connecting rectangular. The development of the robotic systems was geared towards this premise and were thus limited in realising different geometries or bonding patterns. Flexibility was capped, because the starting point was already a standardised wall layout. Therefore, exploiting the digital control of the process to realise non-standard brickwork was prohibited. In contrast, the chosen approach to develop the robotic assembly and design process in parallel, while specifically considering the digital process control as a design parameter, i.e. the possibility to explicitly control every single brick of an assembly, fosters the engineering of an open, non-standard robotic process. Designing the assembly process bottom up allows defining new assembly rules and potentially new constructive systems.

The sequential process steps necessary to assemble a brick wall need to be made explicit in the form of control code for the robot to execute. This is similar to the example of pattern books that describe brickwork techniques and specific bond types through drawings. Traditional brick bonds generally follow very simple rules. These rules can easily be formalised in form of written text or in a more abstract way in form of an algorithm. By adding conditional statements like a loop, which defines the length and height of a brick wall, a simple script can be written that describes the assembly process in a finite sequence of steps (Figure 26).

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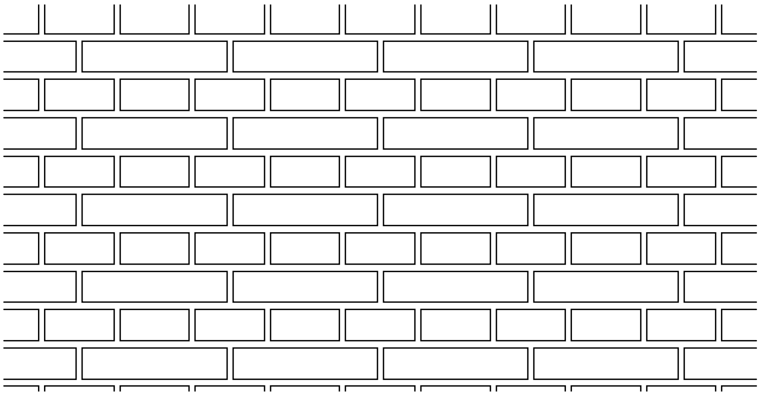
[189] This is different from a traditional design approach that defines the geometry of a final form. Instead, in this case all the sequential steps necessary to reach a final form are defined. This bottom up approach, where the process of making ultimately guides the design is of course not specific to robotic assembly processes, but could also be applied to any other manual or mechanised process. The difference is that here the process of making is made explicit and digital control of the robot brings about an immediate connection between design and making. In the first case the giving of form is put into the hands of a craftsman, or machinist, while the robotic assembly process can directly be controlled by the architect.



```
//English bond
for layer=0 to Total_Layers:
   for i=0 to Bricks_per_Layer:
      if layer=even:
         if i=0:
            set Stretcher at left Edge of Wall
         else:
            set Stretcher adjacent to the right of previous Brick
      else if layer=odd:
         if i=0:
            set Header centred over midpoint of stretcher in row below
         else:
            set Header adjacent to the right of previous Brick
      i=i+1
   layer=layer+1
```

Figure 26. Illustration of an English bond (top) and a corresponding pseudo code describing the bond as well as the assembly sequence. For simplification the width of the joints and quoins at the endings are neglected (top) and illustration of resulting brickwork (bottom).

On the one hand, this script describes the complete sequential assembly process and can be used to control the robotic system. On the other hand, the script describes the overall brick wall design. While the example illustrates a very simple assembly of a traditional English bond, the description of the assembly process can become more complex, introducing variation in the positioning of the bricks or adding additional rules arising from further design requirements. In the control code of the robotic system, design and assembly are integrated, which allows exploring the design space defined by a robotic process. As such, these scripts can be seen as the basis to develop simple fabrication and design tools for robotically assembled brickwork.

4.3.4.1 Process programming in KRL

Programming the assembly process puts the focus on programming the robot control itself. Most industrial robots offer two different programming systems, referred to as *online* and *offline* programming.[190] The first requires the robot system to be running, while the latter can be performed without the robot and the finished programs are copied on the robot control for execution. *Online* programming systems can basically be described as a *record and playback* system. In most cases a teach pendent, a hand-held control panel, is used to lead the robot through a sequence of motions. These are recorded and used to generate a robot programme in the background.[191] This is a very common way to program a robot, but it is limited to program repetitive tasks. Therefore, a programme obtained through *record and playback* only unfolds its power once it can be repeated multiple times. Applied to brickwork this would mean that the robot is taught once how and where to position each brick. Such obtained robot control programmes can then be used to rebuild the same wall over and over again. In order to apply the robot as a flexible assembly machine – able to realise non-standard brickwork – it is necessary to write custom robot programmes.

Robot programing languages are a mixture of imperative low-level programming languages and domain specific instructions and commands. In general, each robot manufacturer has its own proprietary language. In case of the robot adopted for the thesis' investigations this is the KUKA Robot Language (KRL). KRL is derived from PASCAL.[192] It provides typical programming statements such as variable assignments, conditionals and loops. Additionally, KRL features a set of robot-specific commands to control the motion and to interact with tools and peripheral devices.[193]

As a low-level programming language, KRL is simple, but has the disadvantage that it features only a limited level of abstraction. This makes writing the programme for the robot to perform a specific task complex, requiring time and expertise. For once, because code cannot as easily be reused, like for instances in object-oriented programming languages. Further, KRL only offers a narrow set of datatypes and, operators and functions for data manipulation are limited. This, for instance, makes it cumbersome to handle large data sets or perform complex geometrical calculations, which have to be broken down to available simple data types.[194] Actually, the use of low-level programming language is one of the reasons why the flexibility of industrial robots is rarely utilised, but instead robots are only programmed once to perform a repetitive task, often by the means of *online* programming.[195]

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[190] See for example M. Hägele, K. Nilsson, and J. N. Pires, "Industrial Robotics," 976-80.

[191] For an overview of robot programming systems see G. Biggs and B. Macdonald, "A survey of robot programming systems" (paper presented at the Australasian Conference on Robotics and Automation, Brisbane, Australia, December 1-3 2003).

[192] PASCAL was developed by Niklaus Wirth from 1968-1972, see N. Wirth, "The programming language pascal," *Acta Informatica* 1, no. 1 (1971).

[193] For a general reference of KRL see *KUKA System Software 5.5 - Operating and Programming Instructions for System Integrators*, (Augsburg, Germany: KUKA Roboter GmbH, 2010).

[194] KRL does offer the possibility to create composite data types in the form of so-called *STRUTURES* that can group any number of identical or different data types. However, these can be regarded as simple containers that do not support specific operators.

[195] See A. Hoffmann et al., "Hiding real-time: A new approach for the software development of industrial robots" (paper presented at the IROS 2009. IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, 10-15

Because of the limits of KRL, the design programming was performed using high-level scripting languages. This had the additional advantage to access predefined modules of existing software frameworks, such as, for instance, geometry libraries (see Section 4.5.4.1). Further, the scripts could be more easily tied to a CAD programme, which provided an available set of geometrical functionalities and a simple implementation of visual feedback. Nevertheless, the scripts still resembled the logic of the assembly process.

Still, a transfer to KRL is necessary to operate the robotic system. The difficulty here lies in accounting for the constraints of the robotic system. The control code must be so robust that it can handle all design variations, especially considering that a control error can not only yield an abort of the fabrication process, but can cause severe hardware damage. The robotic arm moves through physical space and an erroneous or unsynchronised movement, for example, in cooperation with other peripheral devices, can result in a collision of the robotic arm with itself, its environment, or destroying the workpiece.

The experiments apply two different programming approaches: A first straightforward approach is to generate a static control code on the basis of the design data. This can be compared to early G-code, where each line of code is a direct command to the machine with no encoding of logic. The viability of assembling a design on a specific robotic set-up can then only be evaluated through online testing or certain experience, that allow to judge the feasibility beforehand. A second approach is to implement a parametric control code, where the parameters are set by the data of an individual design. This requires that the available parameters are known in advance. This approach eases the transfer of a design to the robotic system, but it sets constraints on the design, because the parametric control code already defines the design space.

4.3.5 The robotic assembly process

Several differences between the general robotic assembly process and a manual bricklaying process can be identified. Considering the overall bricklaying process, the mason and his tools are replaced by the robotic arm and its end-effector, while the interface defining the outcome of the process is transferred from a drawing describing the design to information in the form of digital data. This brings about qualitative changes to the process. In the manual bricklaying process the human worker is critical

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October 2009). There are, of course, reasons why manufacturers stick to these proprietary, low-level programming languages. Primarily, because the robot control has to satisfy hard real-time constraints. Especially, regarding synchronisation of certain tasks. On the one hand, movement of the robot joints has to be synchronised, in order to ensure repeatability. On the other hand, certain processes require controlling tools synchronised to the robots movement. This is for instance the case in the gluing process of the experiments, where the trigger for releasing the adhesive has to match exactly the robot's position while in movement.

to the outcome. Although, the design might be defined by a third person, it is the mason's interpretation of the drawing and the quality of his work that defines the outcome. In the robotic process, the critical interface switches to the data input. The data defines the design and additionally controls the robot. In contrast to a drawing, the digital data is explicit with no room for interpretation (Figure 27).

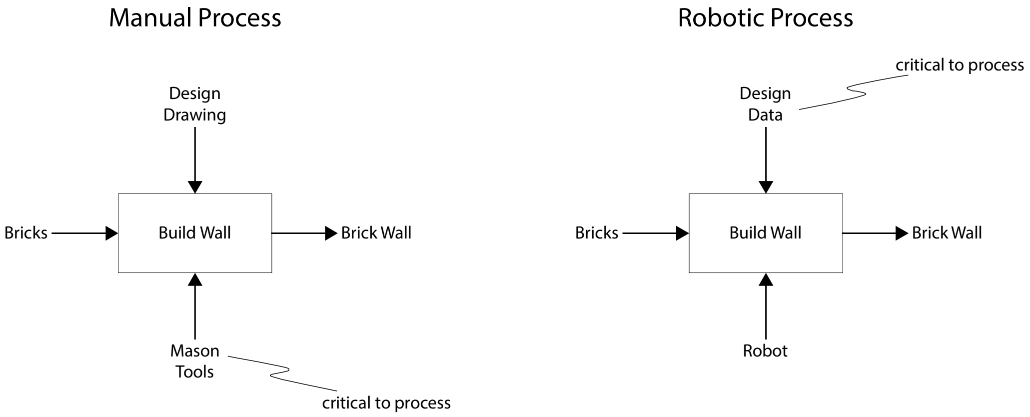

Figure 27. Conceptual diagram of bricklaying process: (left) manual process; (right) robotic process.

A further change is that the design input of the robotic process can basically have an infinite information depth, while the design input of the manual process is limited to the comprehension of the drawing. Even if the drawing would carry a similar information depth, converting this information into a physical output would at some point exceed the performance potential of the mason. In contrast, it is the inherent strength of the robot to precisely execute any number of commands, thus being able to follow a myriad of different instructions and transform them into a physical output.

The design input is the position of the individual bricks. In the bricklaying process, this information is transferred into the actual physical positioning of a brick. A mason needs to set up a system of guides to position a brick. The correct positioning is then achieved through visual alignment to the guide system. Whereas, the robot can work without any additional guide system. This ability to freely place a brick without the need for reference – except its own coordinate system – becomes even more apparent, if one considers brickwork, where none of the bricks are aligned to one another. While for a traditional bond the guiding system can be set up for several courses and bricks can be parallel aligned to one another, in the afore mentioned case the mason would need to set up a special guiding system for each individual brick. It is this freedom in placing individual bricks, increasing the information depth of brickwork, which accounts for the design potential of a robotically assembled brickwork (Figure 28).

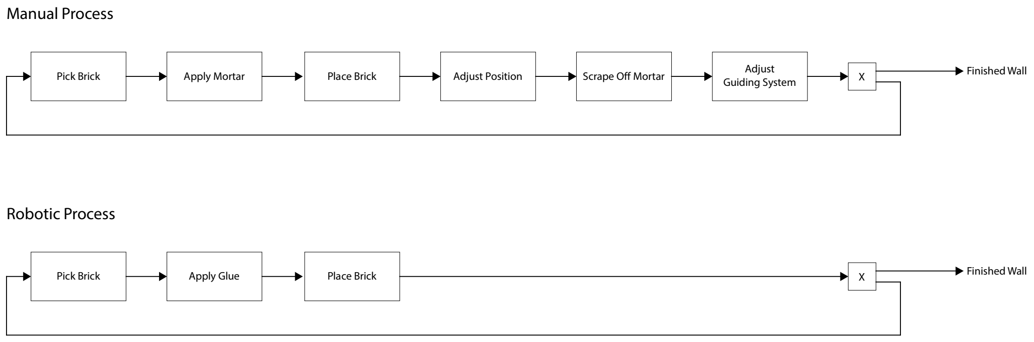

Figure 28. Process diagram of bricklaying: (top) manual process; (bottom) robotic process.

Foremost, the digital control of the assembly process is central parameter of the experiments. In addition, the above mentioned aspects of the robotic set-up, the materials, and the tools used and how these influence the resulting robotically assembled brickwork are essential. If combined, they decisively affect the resulting artefacts of the robotic process. Evaluation criteria of the experiments are on the one hand aspects of the advanced design process applied, i.e. how the brickwork is conceived, and, on the other hand, the resulting architectural brickwork artefacts and their tectonic and structural qualities. The goal is thereby to identify the potential impact of an integrated design and robotic assembly process on brickwork.

Figure 29. Experiment 1: Student physically testing brick assembly strategies (see Section 4.4).

Figure 30. Experiment 1: Robotic assembly process (see Section 4.4.1).

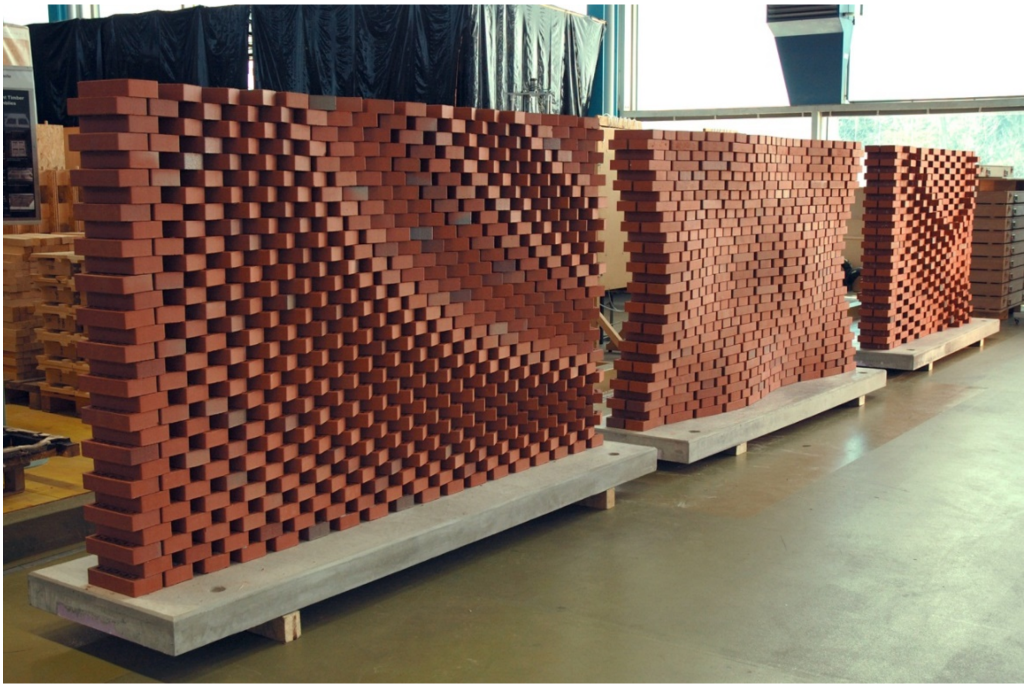

Figure 31. Experiment 1: Three wall prototypes (see Section 4.4.6).

4.4 Experiment 1: The Programmed Wall

The first experiment investigates the basic design implications of a robotic assembly process for brickwork that allows digitally controlling the spatial positioning of the individual bricks.[196] For this purpose, a simple dry assembly process was implemented on the robotic system described above (see Section 4.4.1). Further, scripts that generate brick walls in several standard bond formats and visualise these in a CAD environment were prepared (see Section 4.4.4). These scripts set the basis for the design exploration. An additional script post-processed the CAD data into the control data for the robot (see Section 4.4.5).

On this basis three student groups were challenged to design a brick wall of three metres length and two metres height within a four weeks elective course. Because the walls were supposed to be free-standing, they were required to be at least one brick thick.[197] The students were asked to involve themselves with the robotic assembly process and to explore appropriate designs which could be fabricated at 1:1 scale. Specifically, the students were requested to exploit the capability of the robot to position every brick differently according to digital specifications without an additional effort. Each wall of the given dimension consists of about seven hundred bricks and the students where challenged to develop strategies on how to apply controlled design information on a large set of elements (i.e. the alignment of the bricks). In a first step, the students dealt with the logic of bonding, their criteria for assembly, and static properties. Manual stability tests were used to verify their concepts and rules for assembly (Figure 29). In a second step, the students formalised these rules based on the provided scripts in order to automatically generate their wall designs. The combination of both physical tests and the geometrical examinations on the computer furthered an intuitive understanding of the potentials as well as the limitations of the fabrication process.

4.4.1 Robotic set-up

The physical experiment was conducted on the robotic fabrication set-up described in Section 4.3.1. In order to meet the specific demands of a brick stacking process within the limits of the experiment's objective, the general robotic set-up was expanded by a custom feed for providing bricks and an end-effector to grip the bricks. The brick feed is manually supplied with bricks. It is a simple chute where the bricks slide through gravity. Its main purpose is to carry the bricks to a predefined gripping position for the robot. This position must be known since the robot is not equipped with any sensors that

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[196] For a list of all people involved in the experiment, see Appendix.

[197] This is different from contemporary facing brickwork, which for numerous reasons is applied for non-load-bearing structures in form of a curtain wall with the main functions of weatherproofing and marking an aesthetic finish to the building. Such brickwork features a maximum thickness of only one half brick.

would allow to find the exact gripping position autonomously. The bricks are assembled on a concrete base to achieve a planar starting ground and it allows the finished brick walls to be transported. Although the brick walls were designed for a dry stacked process, a two-component epoxy based adhesive was manually applied for each layer for final production. The adhesive was to assure safe transportation of the brick walls. In this case, the physical robotic positioning of the bricks informed the human worker on where to apply glue. The schematic layout of the robotic set-up, as well as the flow of material and information is illustrated in Figure 32.

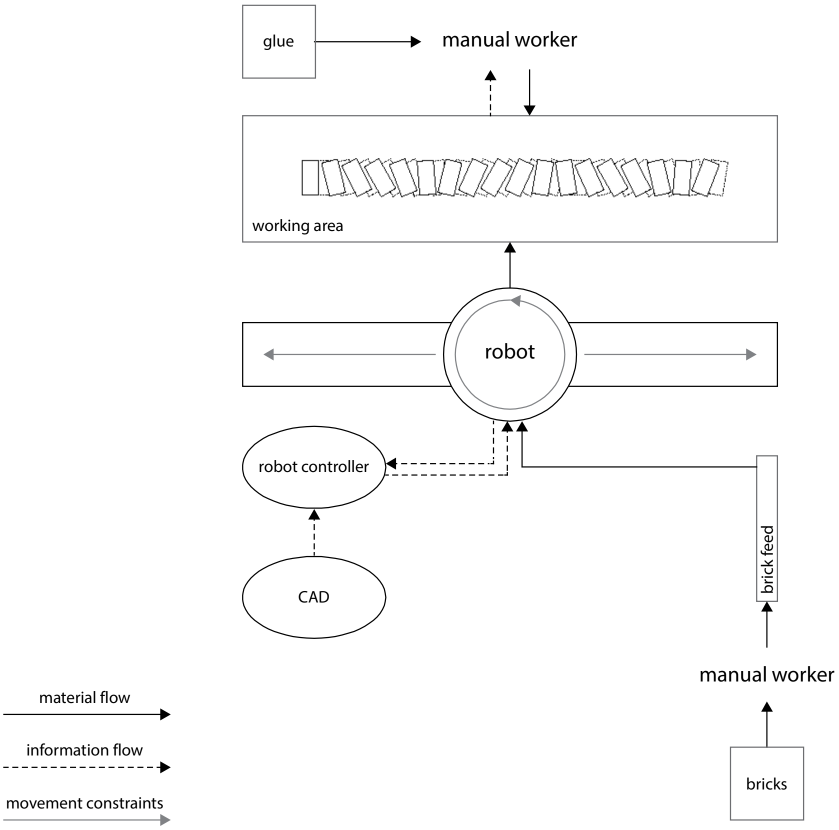

Figure 32. Experiment 1: Scheme of robotic set-up and assembly procedure.

4.4.2 Material System

For the experiment a standard perforated facing brick was employed, with the dimension of 240 x 115 x 52 mm.[198] A commercially available structural adhesive was applied for gluing. This two-part, epoxy-based adhesive is intended specifically for use in

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[198] Specifically, a Kelesto-Sichtstein was used. For product specifications according to EN 771-1:2011, see Keller Holding AG, "Produktedeklaration der Werke Frick und Paradies nach EN 771-1:2011," http://www.keller-systeme.ch/bdata/files/_file_itemFile_bdataFileExt/10132_CE_Deklaration_September_14.pdf, (accessed April 15, 2015).

construction in combination with various materials (e.g. concrete, bricks, mortar, steel, wood, glass, etc.) for anchoring or repair purpose.[199] The adhesive is solvent and styrene free. Its main characteristic is that it needs no pre-loading stress and for most instances, the resulting bond is stronger than the main material itself. In relation to the bricks used in the experiment, for example, the compressive strength of the adhesive is 70 N/mm^2 and thereby twice as high as compared to the brick itself, with only 35 N/mm^2. The adhesive can be applied to a maximum layer thickness of 30 millimetre. However, in the layered assembly process of brickwork, the adhesive will be compressed to a minimum thickness through the weight of the bricks in the upper layers. As a result, the brickwork will appear as if it had been dry stacked.

4.4.3 Mechanical tooling and periphery

The perforation of the brick allowed to apply an internal gripping strategy. The base jaws of the general gripping device of the robotic set-up are equipped with four pins, two for each side. The brick is grasped and released through the translational movement of the two pin pairs when opening and closing the gripper. Applying such gripper has the advantage that the end-effector imposes no geometric constraints in placing the brick – every brick can be placed in direct contact to already processed bricks on all four sides (Figure 33).

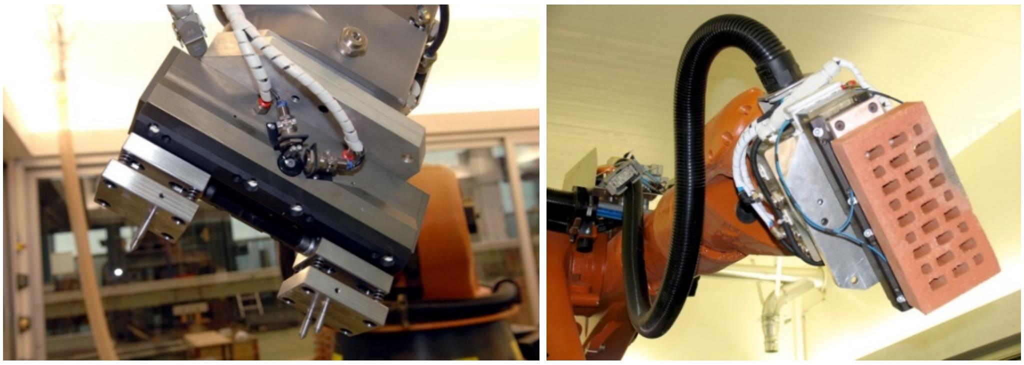

Figure 33. Gripping tool (left). Internal gripping allows connecting the brick on all four sides (right).

In this experiment, this advantage comes with the cost of imprecision in positioning a brick. The bricks' dimension and also the position and dimension of its perforations exhibit a certain degree of tolerances. This imprecision of the perforations is passed on to the robotic process when the brick is gripped and, ultimately, to the final position

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[199] The structural adhesive applied is a Sikadur-30, SIKA, "Product Data Sheet - Sikadur-30," http://gbr.sika.com/en/solutions_products/document_download1/construction-downloads/structural_strengtheningpds.html, (accessed April 15, 2015).

where it is placed. Tolerances of the bricks' dimension are located in a range of +/ - 3 mm. In order to avoid collisions between the bricks due to their imprecision, a sufficient gap between neighbouring bricks has to be considered in the design of the walls. For a standard brick bond, this is negligible, since the dimensions of the brick applied follows rules of standard modular coordination, meaning the proportion between width and length already imply a 10 mm perpend joint, which can account for the brick tolerances. However, it becomes critical, once the rigid grid of a standard bond is loosened or the bricks are rotated. Since the robot cannot adapt to tolerances occurring during process execution, like, for example, slightly correcting the laydown position of a brick to prevent collision, it is important that material tolerances, as well as tolerances introduced through the robotic assembly process, are already integrated in the design.[200]

4.4.4 Digital design

For this experiment the 3D animation software MAYA with its embedded scripting language MEL was applied as a design environment. This set-up allowed a close coupling of scripting a design and its virtual representation. Thereby, it enabled a constant visual validation of the consequences that changes and variations within the script brought about. Because the students were all novices in programming, several basic MEL-scripts were provided that enabled to generate a wall with different traditional brick bonds such as an English bond, Flemish bond, and a header bond (Figure 34, Figure 35, and Figure 36). Based on these scripts the students could implement their own design ideas, by manipulating and adding additional parameters to the script. The structure of each script follows the logic of the sequential fabrication steps. The bricks are generated in the order they are laid out in each course, layer by layer. Thus, the bricks are already generated in the correct sequence in which they have to be processed by the robot for fabrication. Additionally, this facilitated the transfer of the students' hands-on tests into abstract code, for example, in regards to the stacking logic.

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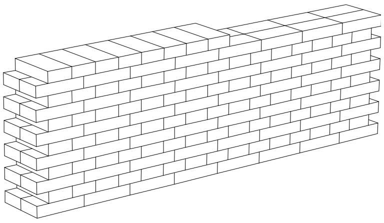
[200] This is of course again dependent on the robotic set-up. For example, it is imaginable that the robot adapts to material tolerances during process execution, if the system is equipped with sensors providing the necessary feedback.

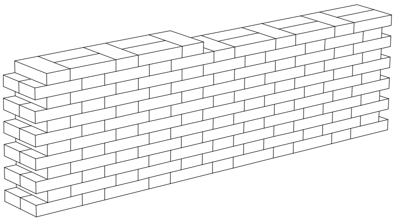


```
//English bond

bw,bl,bh=BrickWidth,BrickLength,BrickHeight

for layer=0 to Total_Layers:
  for i=0 to Bricks_per_Layer:
      if layer=even:
          set_Brick (X=i*bl,Y=0,Z=layer*bh,Rotate=Stretcher)
          set_Brick (X=i*bl,Y=bw,Z=layer*bh,Rotate=Stretcher)
      else if layer=odd:
          set_Header_at_Position(X=(i+1/4)*bl+,Y=0,Z=layer*bh,Rotate=Header)
          set_Header_at_Position(X=(i+1/4)*bl+bw,Y=0,Z=layer*bh,Rotate=Header)
      i=i+1
  layer=layer+1
```

Figure 34. English bond: Illustration of bond (top); pseudo code describing its assembly sequence (bottom). For simplification, joints are neglected.

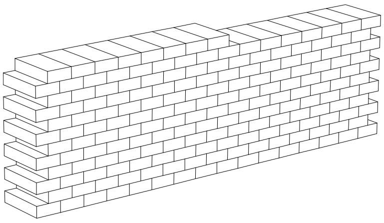


```
//Flemish bond

bw,bl,bh=BrickWidth,BrickLength,BrickHeight

for layer=0 to Total_Layers:
  for i=0 to Bricks_per_Layer:
      if layer=even:
          if brick_number=even:
              set_Brick(X=i*bl,Y=0,Z=layer*bh,Rotate=Stretcher)
                        set_Brick(X=i*bl,Y= bw,Z=layer*bh,Rotate=Stretcher)
          else:
              set_Brick(X=i*bl + bw,Y=0,Z=layer*bh,Rotate=Header)
      else if layer=odd:
          if brick_number=even:
              set_Brick (X=(i+1/4)*bl,Y=0,Z=layer*bh,Rotate=Header)
          else:
              set_brick(X=(i+1/4)*bl+bw,Y=0,Z=layer*bh,Rotate=Stretcher)
              set_Brick(X=(i+1/4)*bl+bw,Y=bw,Z=layer*bh,Rotate=Stretcher)
      i=i+1
  layer=layer+1
```

Figure 35. Flemish bond: Illustration of bond (top); pseudo code describing its assembly sequence (bottom). For simplification, joints are neglected.



```
//Header bond

bw,bl,bh=BrickWidth,BrickLength,BrickHeight

for layer=0 to Total_Layers:
  for i=0 to Bricks_per_Layer:
     if layer=even:
        set_Brick(X=i*bw,Y=0,Z=layer*bh,Rotate=Header)
     else if layer=odd:
        set_Brick(X=(i+1/2)*bw,Y=0,Z=layer*bh,Rotate=Header)
     i=i+1
  layer=layer+1
```

Figure 36. Header bond: Illustration of bond (top); pseudo code describing its assembly sequence (bottom). For simplification, joints are neglected.

4.4.5 Robotic assembly process

The robot control programme consists of the main control programme and a subroutine for picking the bricks. The subroutine for picking the brick at the predefined position of the brick feed was generated by teach programming. The robot arm was moved manually through the necessary sequence of motions for picking the brick. These motions, as well as the opening and closing of the gripper were recorded and stored as a global subprogram in the robot control (Figure 37). The main control programme is generated automatically from the design data. Within the MAYA design environment, a MEL-script reads the position and spatial orientation of each brick of the wall and translates these into the control commands for the robot to assemble the wall. Because the designs already generate the individual bricks in a logical fabrication sequence an additional sorting of the bricks for the robotic assembly is not necessary.

In order to avoid unforeseen movements of the robot arm due to unpredictability of the design input, a movement strategy was chosen where the robot's relative position towards the final brick placement always stays the same. This is achieved through moving the robot along its external linear axis synchronous to the course of the wall. Thus, the positions of the axes of the robot arm are nearly the same for each brick in one layer. Only their spatial orientation, such as a rotation or a shift of the brick, accounts for a minimal change in the axis value. Activating the linear axis compared to activating the complete working envelope of the robotic arm itself can generally be considered as having a negative effect on the process speed. However, as process efficiency is not the main objective of the experiment, this strategy guarantees reachability and avoids singularities[201], especially as the process should work for different wall designs that where not known in advance. Additionally, in order to avoid crashes the robot sets each brick from a safety position linear above its final placement position. The robot programme halts after each layer to enable the manual application of glue (Figure 37).

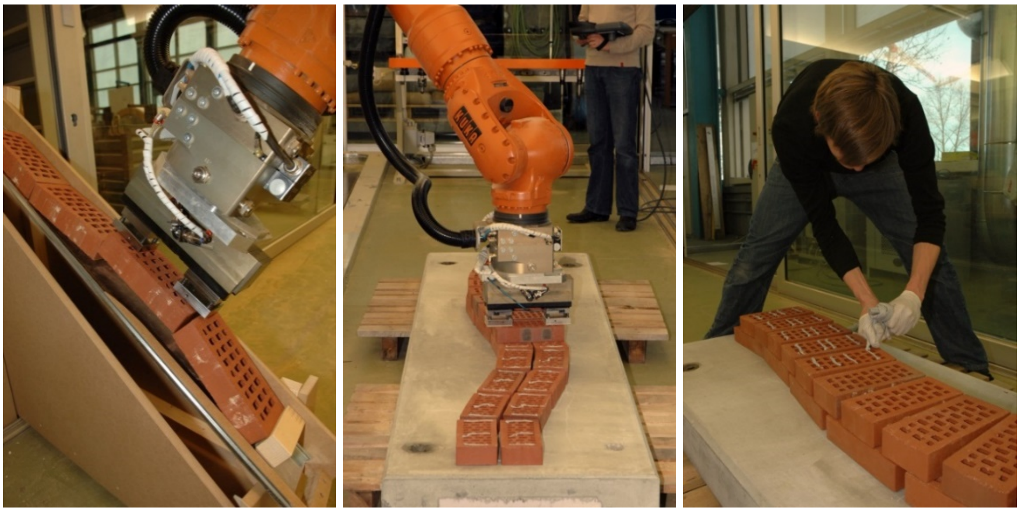


Figure 37. Experiment 1: Process steps of assembly. (left) Picking brick with end-effector from brick feed; (middle) placing brick; (right) manual application of adhesive.

A diagram depicting the design and fabrication process of the experiment can be seen in Figure 38. The creative process of developing the design is controlled by the design blueprint, i.e. design of a 3 by 2 m brick wall, and the design constraints. On the one hand, these are hard constraints such as gravity, the chosen brick module, and the impossibility for bricks to intersect with one another. On the other hand, constraints that accrue from the fabrication set-up have to be considered in the design. These are reachability issues due to the layout of the manufacturing cell and the kinematics of the robotic arm, as well as the design of the end-effector. In contrast to the constraints concerned with feasibility and stability of the wall, these are also soft constraints that can be influenced by the designer, for instance, by changing the design of the gripper tool. This ability to control both the digital and the physical aspects of the fabrication process sets it apart from mere industrial mechanisation.

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[201] In the case of the applied KUKA robot, *singularities* cause a robot programme to abort. They occur when two or more axes of the robot arm align collinear. In this situation, the robot control cannot clearly assign a rotation movement to one of the axes.

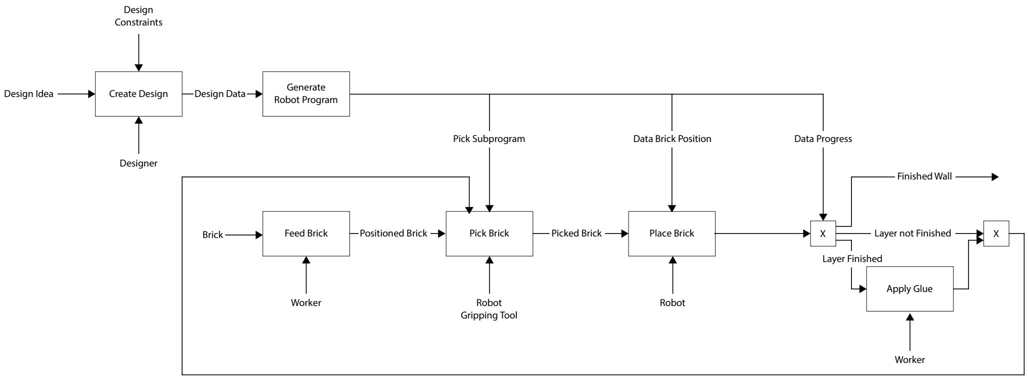

Figure 38. Experiment 1: Diagram of assembly process.

4.4.6 Results

Given the robotic set-up and a basic design script, each student group developed a distinct design proposal, based on one of the three initial bonds: 1) English bond, 2) Flemish bond, and 3) header bond. The built prototypes, although different in their aesthetic appearance, all reflect a notion of the underlying procedural design.

4.4.6.1 Design exploration 1: English bond

With its alternating stretcher and header courses that ties together the different layers over the depth of the wall, the English bond achieves a very stable construction. The basic design idea was to challenge the stability and to manipulate the wall profile. The wall oscillates around its centre axis. Parameters of the amplitude and the frequency of the oscillation are dependent on stability criteria, as well as the bond pattern and brick dimension applied. For reasons of stability, the amplitude should not exceed half the wall thickness. Further, each amplitude in one direction of the wall results in an equal amplitude in the opposite direction. Thus, the centroidal axis of the wall remains balanced. Bond pattern and brick dimensions define the maximum possible slope of the amplitude and thereby the frequency, depending on whether it is possible to follow the curvature without overlaps of the bricks or the butt joints becoming too large. Once these rules were formulated, they were integrated into the basic script for an English bond. In changing the parameters for amplitude and frequency, infinite variations of wall designs could be generated. However, they all follow the same defined ruleset and can be regarded as instances of the same design family. For the fabrication of the 1:1 scale prototype, a parameter set was chosen that best illustrates the basic design idea of the interrelated oscillation on the predefined wall dimension (Figure 39).

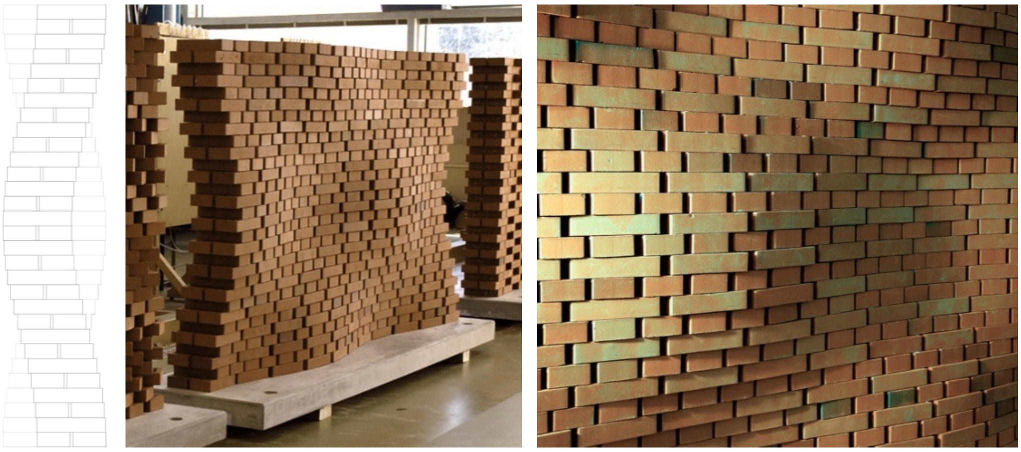

Figure 39. Prototype design 1: (left) section illustrating the countervailing bulge in both directions; (middle) overall view of wall; (right) detail of bulge.

4.4.6.2 Design exploration 2: Flemish bond

Design 2 is based on a Flemish bond, where the header bricks are shifted perpendicular to the wall surface and thus creating a three-dimensional patterning of the wall. In each course of a Flemish bond stretcher and header bricks alternate in one course, while the header bricks are centred over the stretcher bricks in the row below. This allows for an effective bonding between the stretcher bricks even if the headers are removed completely. The result would be an open bond with the stretcher bricks overlapping one quarter brick. The design plays on this characteristic of the Flemish bond, by shifting only the header bricks, while the stretcher bricks stay in their regular position. As a means to define the amount to which the header bricks are shifted, the basic wall script is coupled with a control surface representing the wall area. The surface is displayed in the design environment and can be deformed manually by the user. The distance of the surface towards the original wall plane informs the value by which the header bricks are shifted. If a header brick is shifted by more than a brick width, they are removed completely, leaving a gap in the wall. Within a Flemish bond, the header bricks fulfils the function of tying together the stretcher bricks in the depth of the wall. Therefore, the gaps in the wall may not exceed a certain threshold. Due to the nature of the Flemish bond, the manipulated header bricks all lie on a regular grid. The shifting of bricks can therefore be interpreted as pixels in a computer-generated image. However, because of the relative coarse resolution, the shifting of the bricks creates a very expressive pattern (Figure 40).

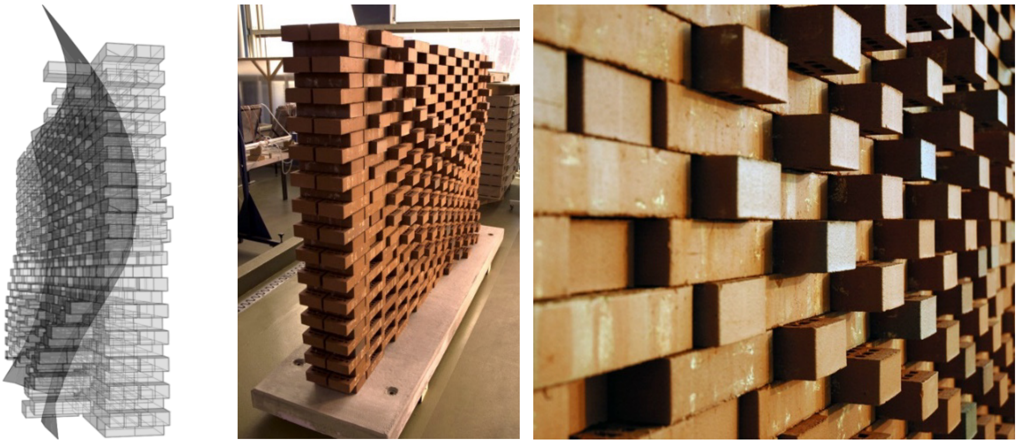

Figure 40. Prototype design 2: (left) screenshot of design concept, a surface informs the shift value of the header bricks; (middle) overall view of wall; (right) detail of wall with protruding header bricks.

4.4.6.3 Design exploration 3: Header bond

On the basis of a traditional header bond, design 3 creates a visual effect, using a seemingly simple approach. Here, only a single parameter is manipulated, the rotation of each brick around its centre axis. Instead of aligning the header bricks parallel to one another, they are now allowed to rotate at an arbitrary value. The maximum degree of rotation of each brick is dependent on the width of the gap between the bricks chosen for the header bond and the rotation of the neighbouring bricks. Pulling the header bond apart and creating an open bond allows for a greater degree of rotation. However a minimum overlap area between the bricks of each course must be guaranteed. The position of the bricks though stays within the flat plane of the wall and fixed on the rigorous grid of the given header bond. As a means to inform the degree of rotation for each brick, different mathematical functions are applied. Then, the rotation for a specific brick at the position x, y within the two-dimensional grid of the wall surface is the resulting value of $f(x, y)$. In order to ensure that the difference in the rotation value between neighboring bricks would not be too great and thus to avoid overlaps, only continuous functions, where a *small* change in the input results in a *small* change in the output, could be applied.

Through a simple rotation of the individual bricks a play of light and shadows is achieved, which gives the wall a textile appearance. Although the bricks do not protrude the two-dimensional plane of the wall the rotation creates the impression of a three-dimensional deformation. This perception is intensified, if the exposure to light changes or if seen from different viewpoints (Figure 41).

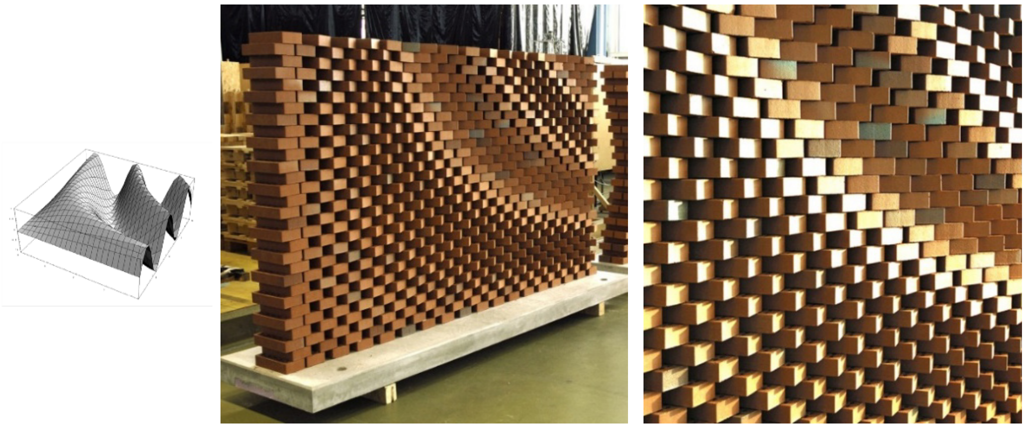

*Figure 41. Prototype design 3: (left) plot of a subset of an exemplary two-dimensional input function f(x, y) = sin(x * y); (middle) overall view of wall; (right) detail of wall surface with rotated bricks.*

4.4.6.4 Summary

The three design explorations are directly informed by the possibilities and constraints of the robotic set-up and, at the same time, by the constructive logic of traditional brickwork. Each prototype wall has its very own distinct expression. However, they share a common logic in revealing a notion of their underlying procedural design and robotic assembly process. While using identical units – the brick – and assembling them according to the constraints of traditional brick construction like bonding and overlaps, variable unforeseen patterns are created. Obviously, the pattern of the brickwork and the position of the individual bricks follow a distinct set of rules, though these might not be as easily deciphered as for traditional brickwork, where the exact position of a brick to be placed can easily be deduced from the pattern of the already laid bricks. As such, the experiment can be regarded as important proof of concept that directly integrating digital design and robotic assembly processes is viable and may leverage further architectural potentials to instigate novel design solutions.

For the experiment, the degree of automation of the robotic assembly process was considerably low. The robot was applied where its digital control became relevant for the execution of a design, which is the positioning of the individual bricks. This can also be identified as the main difference between a robotically controlled assembly process and its manual counterpart: A robot fed with digital control data can position every brick differently without an additional effort. All three prototype walls exploit this difference in the robotic assembly process. In contrast to traditional drafting as a means to convey a design idea, the design was formalised in form of a computer script. On the one hand, the robot needs an explicit set of instructions in order to perform the assembly process. This explicit code can be utilised as a means to explore numerous design instances, which can be parametrically generated. In turn, the design configurations follow a specific ruleset, but vary in their geometrical manifestation and thus facilitate non-standard assembly processes. On the other hand, already the 3 x 2 m brick walls of the experiment consists of over 700 bricks for each prototype. Creating a design by individually positioning every single brick manually in a conventional CAD environment would be unjustifiably time consuming and resembles the impracticality to manually construct such a brick wall. Therefore, in order to exploit the capabilities of the robot to precisely position every brick, formalising design rules in form of scripts or high-level digital design tools (such as, for example, the input surface that informs the dislocation of the header bricks) is indispensable.

While the experiment was a first physical demonstration of a robotically controlled assembly process of non-standard brickwork, appropriate digital design strategies, as well as the defining characteristics of the robotic process were addressed on a fundamental exploratory level. Especially, considering the practical application to real-world building projects, further work must include the automated and controlled application of the adhesive, in respect to the amount and precise area of application, in order to ensure structural soundness of the complete brickwork system. Additionally, since in its existing form the robotic set-up is geared towards prefabrication, issues of layout of elements, transportation, and installation become crucial. Insofar, exploring these aspects and advancing on the current findings were the focus of the following experiment.

Figure 42. Experiment 2: Robotic assembly of elements for the non-standard brickwork façade of the Gantenbein winery (see Section 4.5.5).

Figure 43. Experiment 2: View of installed façade of the Gantenbein winery (see Section 4.5.6).

4.5 Experiment 2: Gantenbein Winery, Robotically assembled non-standard brick façade

While experiment 1 served as a general proof of concept, demonstrating that applying robotic assembly processes is not only technical feasible, but can lead to novel expressions in architectural design, experiment 2 investigates the potentials and limits of the process in a real-world building context. For that reason, the process developed in experiment 1 was applied to the design and fabrication of 420 sq. m of façade for the extension building of a winery.[202] The scaling of the design task from a single wall element to a complete façade is accompanied by a re-engineering of the robotic process. On the basis of the experience and knowledge gained in experiment 1 the process was developed further, with particular attention turned towards ensuring a consistent fabrication quality and a reasonable process time. In addition, the substitution of mortar through an adhesive was further developed, validated and optimised. Thereby, the focus lay on the performance of the adhesive in regards to stress and shear loads.

While the wall designs of experiment 1 did not have to meet any specific demands, the facing brick façade of the winery building had to fulfil certain functional requirements. Together with the framing parameters for the façade, these where already predetermined by the architects and could not be altered anymore.[203] The façade acts as a filter. Its primary function is to prevent the wine mash's exposure to direct sunlight[204], while allowing enough light to pass through to illuminate the interior room during daytime without need for artificial lighting. Wind and weather proofing is performed by a second inward layer of polycarbonate double-webbed slabs. Apart from an entrance gate and one door providing access to the roof terrace the façade was to be completely closed. A reinforced concrete skeleton builds the primary structure of the annex. The facing brick façade was to be inserted in the fields between the concrete columns (Figure 44).

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[202] The extension of the winery is a project of Bearth & Deplazes Architects, the façade was designed in collaboration with Gramazio Kohler Architects. On the overall project see V. Bearth, A. Deplazes, and D. Ladner, *Amurs 18 ausgewählte Arbeiten von Bearth & Deplazes Architekten* (Zurich: gta, 2013), 74-89. Please refer to the Appendix for a list of people involved in the project.

[203] The execution of the structural skeleton of the annex building was already close to finished. Initially, the façade was supposed to be executed in sand-lime bricks positioned upright, such that the vertical perforation would allow sunlight to enter the building. There was little more than three months to further develop and execute the design and fabrication process.

[204] The winery extension holds the grapes for fermentation just after harvest. Exposing the mash to direct sunlight would influence the colouring of the wine.

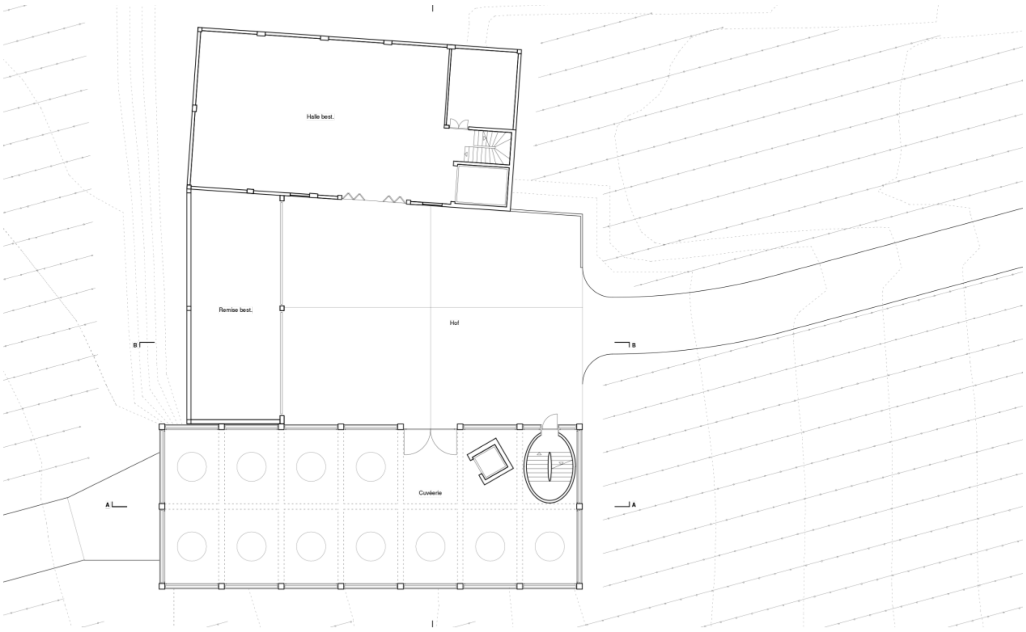

Figure 44. Ground floor plan of the winery complex with the new extension building at the bottom.

Besides the functional aspect of serving as sunlight filter the facing brick façade was particularly supposed to give the new extension of the winery an iconic character and act as a trademark for the wine company.

4.5.1 Robotic set-up

The façade elements were fabricated on the same general robotic set-up already adopted for experiment 1. With the experience gained in the previous experiment the robotic set-up was expanded and the existing tools and peripheral devices improved. The main enhancement was the integration of an automated gluing process (see Section 4.5.3). The process had to guarantee a consistent quality of the glue joints throughout the fabrication process, in order to ensure the structural safety of the completed façade elements.

Other elements of the previous set-up like the gripper and the brick feed were reengineered. The gripper had to be adapted to handle solid bricks (see Section 4.5.3). Additionally, the façade elements required that the picking and placing of half bricks had to be integrated into the process. Half bricks are needed at the beginning and end of a displaced course in order to come out even at the edge. This required a second brick feed. The feeds were also reworked for an easier and gentler transportation of the bricks towards their pick position, to prevent harming the brick surface through physical impact. Additionally, the feeds were equipped with a pressure sensor informing the robot control if a brick is present and ready to be picked. While the brick feeds are still loaded manually, considering the fabrication volume of 22’000 bricks this measure was taken to improve the safety and reliability of the process.[205] The schematic layout of the robotic set-up is illustrated in Figure 45.

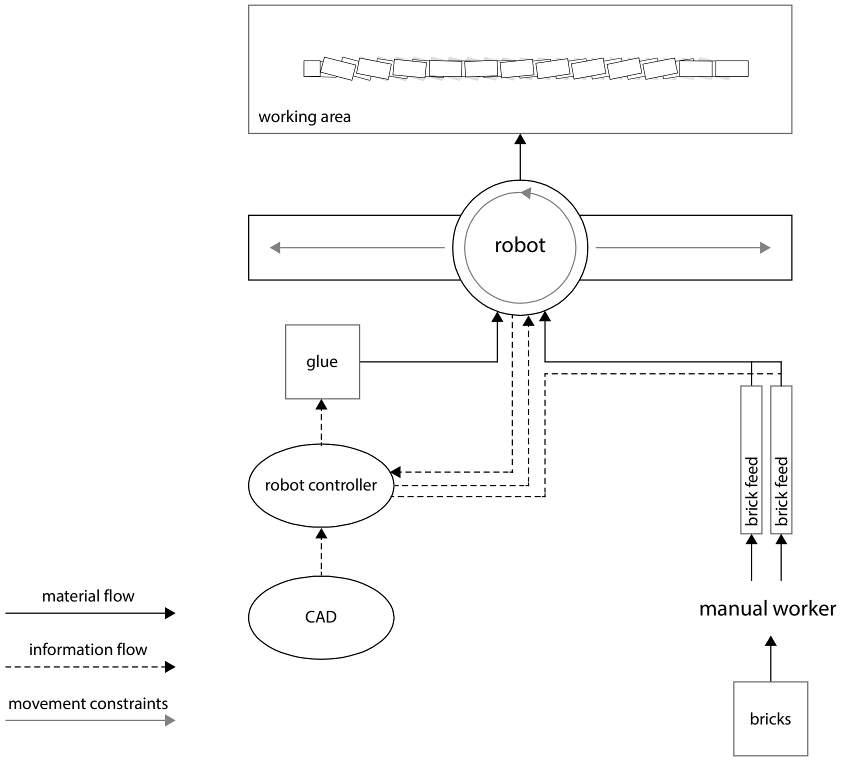

Figure 45. Experiment 2: Scheme of robotic set-up and assembly procedure.

4.5.2 Material System

For structural and aesthetic reasons a solid clinker brick was chosen for the façade, featuring standard dimension 240 x 115 x 61 mm.[206] Because utilising mortar in an automated robotic process was ruled out at the beginning of the experiments, again an adhesive served as a bond between the bricks. However, for the façade the adhesive had to meet structural requirements. Since the façade elements were prefabricated, the glued brickwork needed to withstand dynamic forces during transportation. Once in place, the façade elements are mainly subject to wind loads. Therefore, the adhesive in

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[205] The manual loading of the brick feeds can be considered as further quality insurance. Through visual examination the worker feeding the bricks would single out broken bricks or those featuring small cracks, which might compromise the structural stability of the completed façade element.

[206] The Kelesto clinker used, features an even higher compressive strength of 40N/mm^2 than the brick used in experiment 1. For Product specifications according to EN 771-1:2011, see Keller Holding AG, “Produktedeklaration der Werke Frick und Paradies nach EN 771-1:2011”, http://www.keller-systeme.ch/bdata/files/_file_itemFile_bdataFileExt/10132_CE_Deklaration_September_14.pdf, (accessed April 15, 2015).

combination with the bricks has to be able to transfer shear and tension forces. In traditional prefabricated brickwork using mortar, both horizontal and vertical steel reinforcement is integrated in the elements. Considering the non-standard brick patterns realised by the robotic assembly process, this is not an option. As the bricks are all potentially positioned and rotated differently, especially vertical reinforcement can hardly be inserted through the bricks in a straight line. In standard manual prefabrication, bricks with matching holes are used in the areas where the vertical reinforcement is placed. For non-standard brickwork, as realized with the robotic process presented here, each brick would need to have an individually drilled hole according to its position in the overall brickwork assembly. Such an approach would contradict the fundamental thesis of this research, where the aim is to introduce complexity and differentiation of a final product through a robotically controlled assembly process, rather than already in the individual component being assembled.

On account of the experience gained during the previous experiment, it was estimated that the glued brickwork would exhibit a sufficient performance. However, in order to realise an automatic application of the adhesive, a different product was used than in experiment 1. This features the same performance, but it possesses less filler material, which makes it easier to be applied through an automatic dispenser.[207] An obstacle proved to be the fact that the building regulations and norms do not provide for bricks to take tension forces, which they clearly need to do in a bond with the adhesive. As such, this combination of bricks and adhesive represents a novel constructive system for brickwork. In order to obtain a reliable evaluation of the actual load-bearing capacities several structural tests were performed. To determine the general quality of the bond between the adhesive and the specific bricks used, both an adhesion and a shear test were conducted. Additionally, the specific design of the façade elements was tested in regard to horizontal wind loads. The results of the tests proved the initial assessment, with the façade elements withstanding up to 8 kN/m^2 (Figure 46). Thus, using an adhesive for bonding the bricks instead of mortar has the advantage that no additional reinforcement is needed in the prefabrication of brickwork.[208]

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[207] The adhesive applied is a Sikadur-330. The adhesion tests of both Sikadur-30 and Sikadur-330 proved that the performance of both products is comparable. SIKA, "Product Data Sheet - Sikadur-330," http://gbr.sika.com/en/solutions_products/document_download1/construction-downloads/structural_strengtheningpds.html, (accessed April 15, 2015).

[208] Testing was conducted in cooperation with structural engineers, as well as both the brick company and the company supplying the structural adhesive. A detailed view of the results can be found in the Appendix 1.

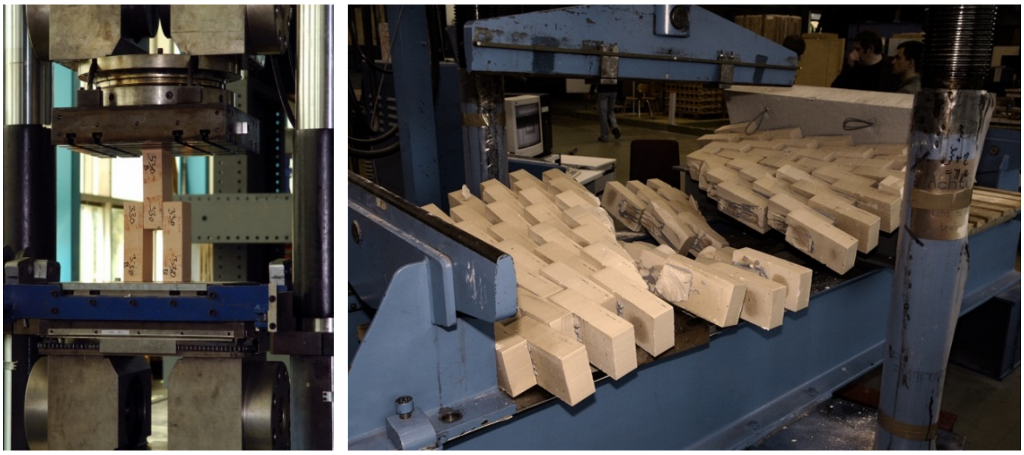

Figure 46. Structural load tests: (left) Shear test of glue connection between bricks; (right) horizontal load-bearing test on a section of a façade element after failure.

4.5.3 Mechanical tooling and periphery

In this experiment the robot needs to perform two distinct operations: handling of a brick (i.e. picking and placing), and applying the adhesive. The handling of the brick is realised through equipping the robot arm with a mechanical gripping tool, while applying the adhesive is automated in comparison to the manual application in experiment 1.

Because the design adopted a solid brick, the internal gripping strategy of the previous experiment could not be applied. Instead an external gripper was chosen. In order to achieve this, a two-finger parallel gripper was built upon the base jaws of the general gripping device of the robotic set-up. The bricks are clamped along their long flank between the two fingers. This gripping strategy limits the degree of freedom in placing the bricks, since the bounding geometry of the gripper prohibits to place bricks oriented with its long flank in close proximity towards already processed bricks. This is a direct constraint on the design space and must thus be considered already in the early design phase. For example, this gripper does not allow realising any of the wall designs of experiment 1 (Figure 47).

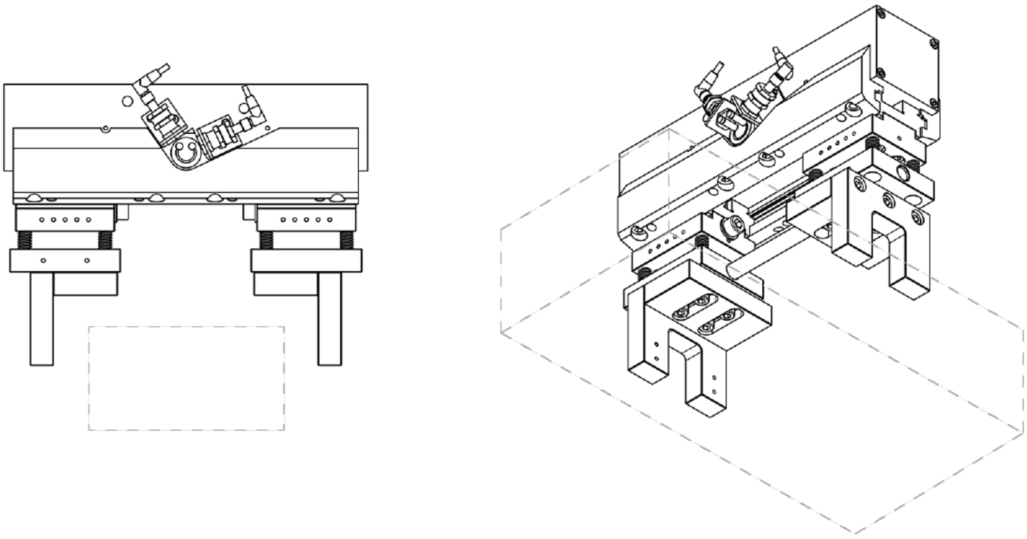

Figure 47. External gripper tool of experiment 2: (left) side view; (right) isometric view.

In the design and development phase an alternative vacuum gripper was considered. Such a gripper could limit the contact area of the gripper to the top surface of the brick, thus maintaining the freedom of placing the bricks identical to experiment 1. This alternative was ruled out because it could not be built upon the existing robotic set-up, but additional resources, i.e. a vacuum pump, would have needed to be installed. Additionally, because the constraint of the gripper did not affect the specific design of the façade a grasping mechanism was considered more secure as the dust from the bricks can cause a clogging of the vacuum cups, making them prone to malfunction.

Applying the adhesive on the bricks is realised through an external tool. This means the process of a robotic arm guiding a tool to operate on a workpiece is reversed. Instead the robotic arm moves the workpiece alongside a fixed tool position. The external tool is referenced and coordinated with the robot control. All necessary transformations for the robot arm to perform the required movements are automatically performed by the robot control system. External tools are an easy way to perform multi-tooling operations with a single robot arm – without the need to change end-effectors. The adhesive is applied using a customised pneumatic metering dispenser, normally used as a handheld device. The dispenser can be equipped with double chamber cartridges holding the two-component epoxy adhesive applied in the process. The air supply for triggering the pneumatic pressure is connected to the robot control. Thus the triggering of the dispenser can be synchronised with the movements of the robotic arm (Figure 48).

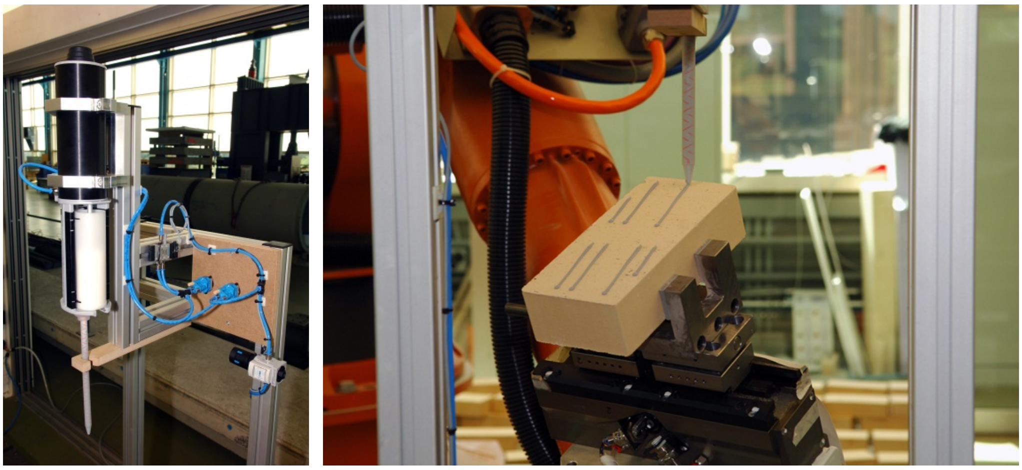

Figure 48. External gluing tool: (left) customised pneumatic metering dispenser; (right) robot moves workpiece for applying adhesive with external tool.

Within a non-standard robotic bricklaying process, digital control of the exact position of the glue paths, as well as the amount of glue applied is a necessity. The glue paths match the individual overlap area between the bricks and is therefore different for each brick. In a manual process this could again only be achieved through an additional guide system.

4.5.4 Digital design

In experiment 2, the same design environment was employed that already served as the basic set-up in the previous experiment, using MAYA for visualising the design in combination with its embedded scripting language MEL. The layout of the façade into individual panels and the constructive volume these could occupy were already predefined, featuring a maximum depth for the brick façade of 180 millimetres. This led to the decision of adopting the design strategy exercised for design 3 of the previous experiment, where the position of the bricks are fixed on a planar grid and patterns in the bond are created solely by rotating the bricks around their centre axis. Although instead of an open header bond an open stretcher bond was chosen for the initial distribution of the bricks.

Overall, the façade consists of over 22’000 bricks. A greyscale image acts as the design input to control the rotation of each individual brick. A MEL-script maps the information of the image file as a two-dimensional projection onto the façade. Thereby, the greyscale value of a pixel in the image file is interpreted as the rotation value for the corresponding brick. The rotation of the bricks interpolate between predefined maximum values in both directions – with the mean value being equal to a rotation value of zero (Figure 49). The chosen control strategy allowed for an intuitive design of the façade pattern. The designer does not need to be proficient in programming, but can apply standard image editing software, which he might be more acquainted with.

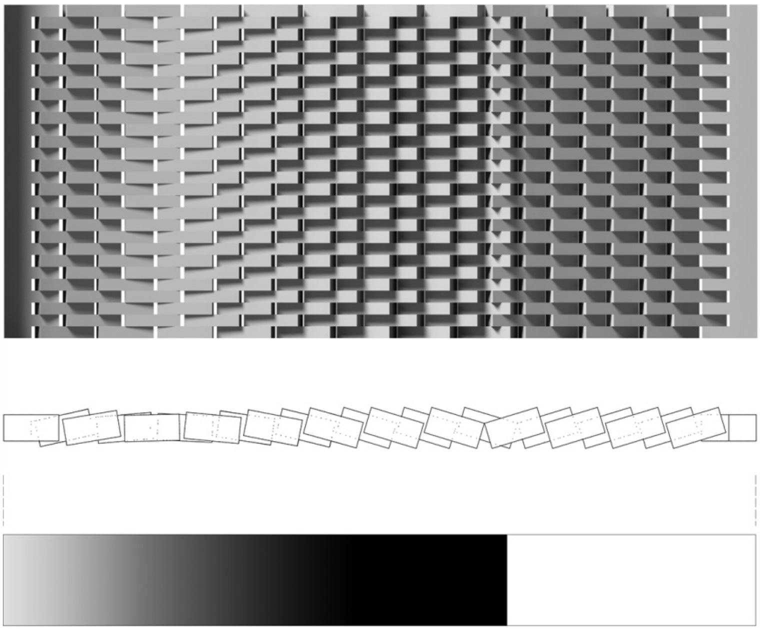

Figure 49. Example of image mapping: (bottom) input image; (middle) resulting stretcher course; (top) front view of resulting façade element. The bricks at the sides are not rotated in order to achieve a uniform straight connection to the concrete pillars at the edges.

4.5.4.1 Software tool: ROB Creator

Subsequently to realising the façade of the Gantenbein winery, the design principles applied were generalised in the custom software tool *ROB Creator*.[209] The software was implemented using the programming language Java. It enables the user to design straight walls in an open stretcher bond of one half brick thickness, choosing from a library of standard brick sizes, and mapping images to the façade, which get translated into rotational movements of the individual bricks. The aim is to enable a simple-to-use interface for designing non-standard brickwork, while encapsulating expert knowledge and thus ensuring that every can be executed with the robot. Therefore, the software is a first attempt to provide a design tool tailored to a robotic assembly process of brickwork.

The user interface is divided into a viewport displaying the wall design and a field displaying the editable parameters of the design. The user interacts with the model

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[209] The software was developed to accompany the mobile robotic fabrication cell *ROB Unit* (see Section 4.6).

through uploading image files to the software and changing the individual parameters. In extension to the closed façade of the Gantenbein winery, the software additionally allows for defining openings within the wall. The software follows the general concept that the brick module constitutes the basic unit of the design. While the overall length of a wall is always maintained – the difference due to the brick modules length can be compensated by varying the gap size – the height of the wall can only be a multiple of the chosen brick height. When changing one parameter, all other parameters are preserved, thus variations in gap size or different brick dimensions can easily be evaluated, for instance, without changing the overall dimension of the wall. Maintaining the concept of the brick as the basic design unit, openings in a wall can be realised by directly selecting the bricks defining the corners of the window. The software additionally provides some basic image editing tools, e.g., cropping and decimation filtering, and the effect of the patterning can be controlled through manipulating the maximum degree of rotation as well as the number of bricks per layer. The software calculates the limits for these parameters automatically, to ensure that a structurally sound bond is maintained and no intersections between the bricks occur. Moreover, the software checks if sufficient structural bonding can be achieved between the individual bricks. Such a case is not automatically prohibited. An insufficient structural bonding between individual bricks does not necessary cause the overall structural system to fail, but the distribution of such areas in respect to the complete wall have to be assessed. Therefore, this is considered a "soft factor" and the bricks in question are marked in the model to be externally evaluated by an expert. Finally, the software enables the user to export the design data, i.e. both the parameters of the brick position and the corresponding glue paths.[210] This information can then be post-processed for fabrication on a specific robotic set-up, as for example the *ROB Unit* (see Section 4.6.1).[211] An overview of the most basic software functionalities can be seen in Figure 50.

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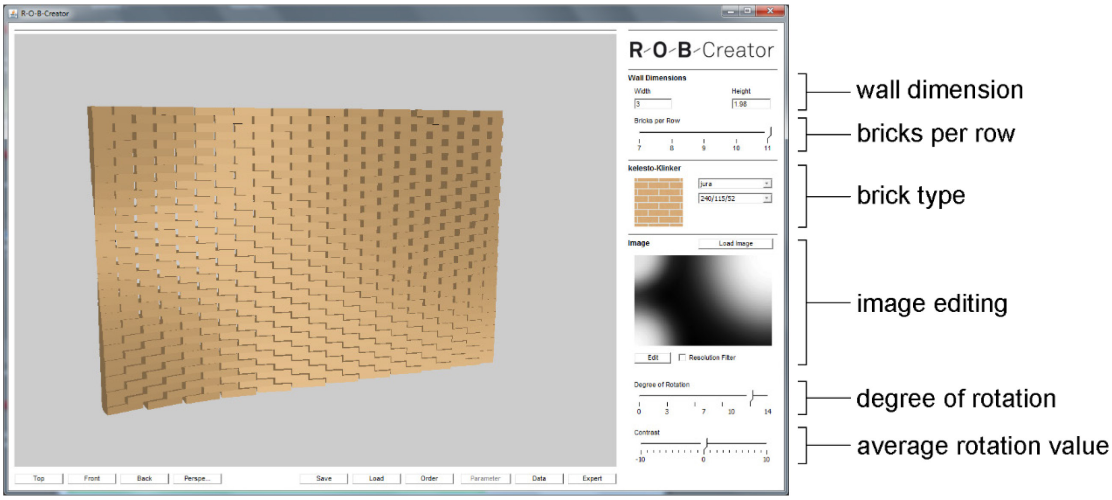
[210] The software makes use of the General Polygon Clipping library (GPC) to generate the polygon of the overlap area between two bricks as a basis for calculating the gluing paths. See General Polygon Clipper library Ver. 2.32, http://www.cs.man.ac.uk/~toby/alan/software/gpc.html, (accessed April 15, 2015).

[211] The software is accompanied by a post-processor specific for the *ROB Unit*, which was likewise implemented in JAVA. The post-processor allows combining the design data of maximum of 4 walls and combines these into a single control programme for the robotic set-up. Additionally, the software generates fabrication plans for the robot operator, depicting the production charge and providing information on the volume of bricks and adhesive needed for production, as well as an estimated production time.


R-O-B-Creator

Wall Dimensions

Width: 3

Height: 1.98

Bricks per Row: 11

kelesto-Klinker: jura, 240/115/52

Image

☐ Resolution Filter

Degree of Rotation

Contrast: 0

Figure 50. Screenshot of ROB Creator software.

4.5.5 Robotic assembly process

Contrary to the previous experiment the control programme for the robot is divided into the main programme and a data file. The main programme holds all necessary commands to move through one process cycle: 1) picking a brick, 2) applying adhesive, and 3) placing the brick. All movement commands are parameterised. The actual information on a specific façade element is stored in a data file. This holds the final position of each brick, as well as the glue paths applied to the brick. This has the advantage that the main programme file stays the same and can be reused for each façade element. The specific hardware set-up, the process logic, and the in- and output of sensors is all defined within the main programme file, while the information on the specific element to be processed is independent. Especially, when changes or tweaks have to be performed on the process, this can then be easily achieved through adapting the main programme file. Such changes only have to be performed once without the need to regenerate all the fabrication data. On the other hand, the data file is not hardware-specific and could be produced on a different robotic set-up and a different control file. The data file is generated directly from the design data by means of a MEL-script. This script sorts the bricks in the order they should be processed by the robot and calculates the overlap area of each brick from which the glue paths are generated. There is a data file for every façade element. Because up to four façade elements can be fabricated in parallel, splitting the control and the data file has the additional advantage that the operator can decide on which elements to produce directly on the shop floor.

The process diagram resembles that of experiment 1, however, featuring the exception that the gluing process is now integrated as an automated step in the robotic process and a sensor at the brick feed informs the robot control if a brick is present and ready to be picked (Figure 51). The robot picks a brick and guides it to the external glue dispenser tool. The glue paths are applied according to the control data and are different for every brick. Since the adhesive should not be visible on the final object, they are dependent on the effective overlap area between the currently processed brick and the bricks in the course below. The glue is applied as four paths parallel to the axis of the wall element, thus the effective lever for taking torsion forces of wind loads stays constant (Figure 48).[212]

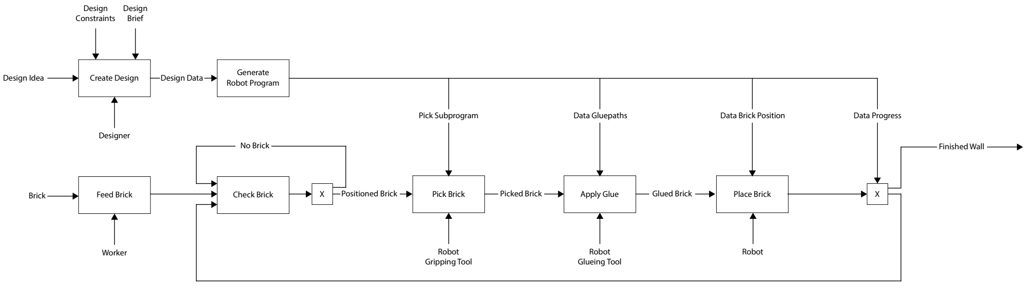


Figure 51. Experiment 2: Diagram of assembly process.

4.5.6 Result

The specific parameters for the façade were tightly framed from the outset, with the primary structure of the building already being under construction. In order to adapt to the given primary structure, the 420 sq. m façade is divided into 72 elements, each between 3.33 m and 4.57 m long and 1.48 m high. These elements are inserted between the reinforced concrete pillars of the primary structure. Each element is assembled on a concrete lintel, which connects back to the pillars and transfers the wind loads into the primary structure. Four elements are always stacked on top of one another. The vertical loads are transferred directly through the elements into the ground foundation (Figure 43).

4.5.6.1 Design strategy

The primary function of the façade is to act as a sunlight filter. Due to the maximum available constructive depth for the façade of 180 mm, an open stretcher bond was chosen as basic layout for the brickwork.[213] Through additionally manipulating the

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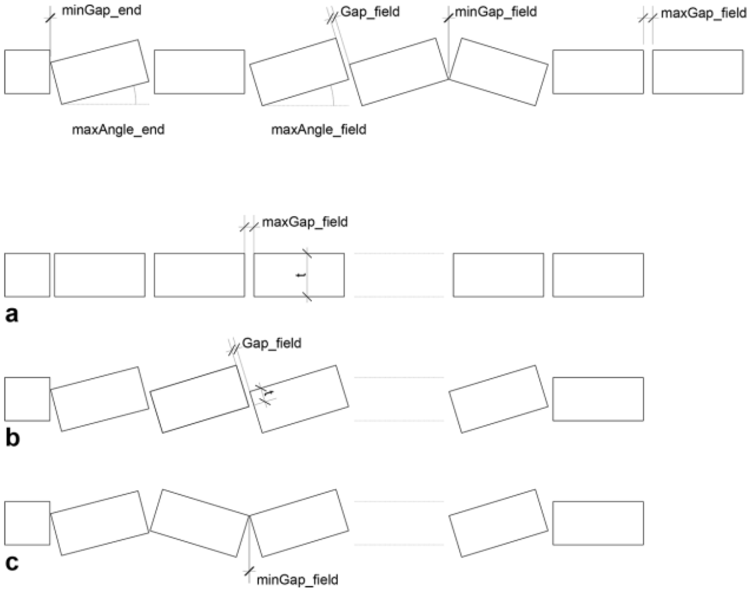
[212] Here, the design process is controlled by the design brief for the façade, structural constraints, and the specific demand to filter the sunlight. At the same time, the robotic set-up – especially the chosen gripping strategy and the geometry of the end-effector tool – constrain the freedom of how the bricks can be assembled. For more information, see Section 4.5.6.1.

[213] For a façade of half a brick thickness a stretcher bond features the greatest load-bearing capacity, because the overlap areas between the courses are maximised, see W. Belz, *Mauerwerk Atlas*, 184.

rotation of each brick, the degree of closure of the gaps within the open stretcher bond can be controlled. At the same time, the rotation of the bricks allows to apply a unique pattern to the brickwork. The spacing between the bricks was the result of a negotiation between a defined percentage of an overall perforation of the façade enabling enough light to pass through, the given width of the elements, and aesthetic aspects regarding the visual effect of the façade pattern. The spacing of the bricks has a direct effect on the maximum possible degree of rotation of each brick without causing intersections. While the degree of opening was calculated from the design data, 1:1 scale prototypes served as a means to determine the visual effect. The prototypes demonstrated that already small changes in the rotation of the bricks, i.e. less than 18 degrees, induce great visual plasticity. Further, the prototypes revealed a different perception of the non-standard brickwork depending on once viewpoint. While from the outside, the reflection of the sunlight emphasises the tectonic plasticity of the brickwork, the interior gives prominence to the contrast between the gaps, where the light can pass through, and the closed brick surface. However, this contrast between interior and exterior viewpoint collapses once the spacing of the bricks exceeds a certain threshold. Finally, an overall spacing of 2 cm was chosen, which allows for a maximum deviation angle of 17 degrees (Figure 52, Figure 53).



Element 3.33 / 12.5
brick/row: 12 1/2
element length: 3330.0mm

Attributes
maxAngle_end: 14.58°
maxAngle_field: 16.96°

minGap_end: 2.0mm
minGap_field: 2.1mm
maxGap_field: 25.2mm
Gap_field: 13.7mm

a
gap: 9.57%
depth t: 115mm
b
gap: 5.06%
depth t: 38mm
c
gap: 0.76%
depth t: 0mm
a/b/c
gap: 5.13%
depth t: 51mm

Figure 52. Study of relation between brick spacing, rotation, and the resulting effective gap between the bricks.

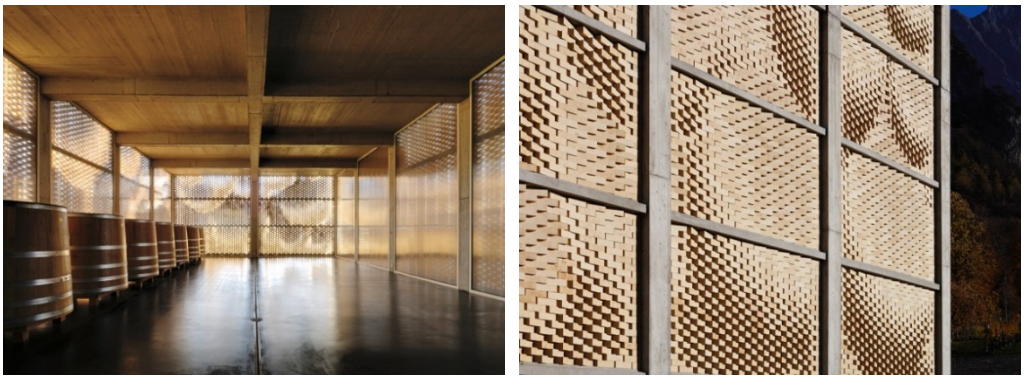


Figure 53. Resulting façade: (left) interior view illustrating the effect of diffuse light entering through the façade; (right) shadow play of brickwork on the outside of the façade.

The design script allowed testing various patterns on the façade, simply through selecting different digital image files. Thereby, the script ensured that the above mentioned parameters of brick spacing and maximum rotation were met. The client's desire to map his trademark signature on the façade proved to be unsatisfying. Due to discretisation and the necessary shift between each row in order to create a sufficient bond it is difficult to map sharp edges on brickwork. Tests visualising numerous input images revealed that gradient transitions are best suited to be reproduced on such a façade. Finally, it was decided to map a spatial pattern on the façade. This has the advantage that no seam is visible on the façade, as it would be the case where the beginning and end of a two-dimensional image meet. The pattern gives the impression of different sized spheres packed inside the building (Figure 54).[214] Images aligned to the four façades of the building are taken from a digital model of this situation. The rotation induced by the mapping of the images fades out at the edges of each element, in order to guarantee an alignment to the connecting concrete pillars.

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[214] For more information on how the design was generated see F. Gramazio and M. Kohler, *Digital Materiality in Architecture*, 95.

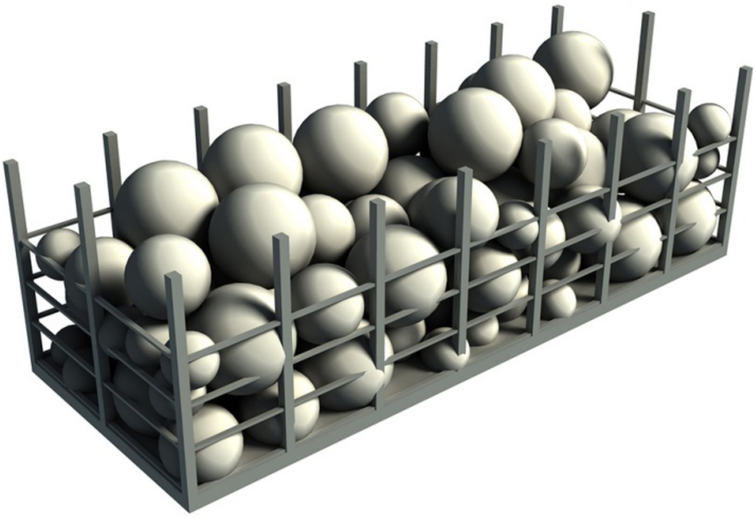

Figure 54. 3D-computer simulation of spheres packed within building.

4.5.6.2 Tolerances

While the structural adhesive expands the scope of application of brickwork, dimensional tolerances of the bricks have to be considered. Bricks are composed out of natural materials, whose composition in combination with the burning process result in dimensional inaccuracy. Even within the same batch bricks can show dimensional tolerances of up to 1 centimetre.[215] In traditional brickwork these tolerances are evened out through the mortar layer and are of no relevance. The structural adhesive, though, is not able to compensate any tolerances, which add up with each layer.

More specifically, the tolerances of the bricks originate in their production process. On the one hand, the brick's dimension differs due to different material compositions and changing parameters during the burning and curing process. On the other hand, a recurring geometrical imprecision is caused by the extrusion process. Standard bricks are extruded lying on the side and then cut to the desired height. At this point the clay composition is still ductile, causing the clay to slump and deforming the rectangular shape of the brick in side view towards a trapezoid. The bottom of the extruded brick, which normally is the backside of a facing brick, is thus slightly higher than the front side. In the case of bricks used in this experiment, assembling all bricks with their front side showing in the same direction already causes a brick wall of less than 1 m height to tip over.

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[215] Acceptable dimensional tolerances of bricks are defined in DIN German Institute for Standardization, "Clay masonry units – Part 100: Clay masonry units with specific properties," (DIN German Institute for Standardization, 2012).

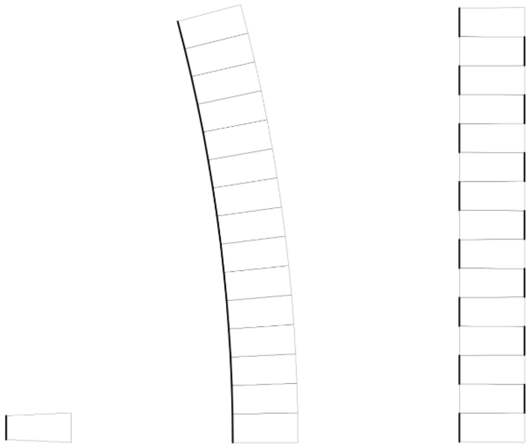

Figure 55. Geometrical characteristics of bricks: (left) graphical exaggeration of the trapezoid shape of a brick in side view; (middle) side view of a wall with all bricks facing in the same direction; (right) side view of wall with every other brick rotated in the opposite direction.

For the façade two measures were taken to compensate for these tolerances. In order to counteract the tilting of the wall, every other brick is rotated with its backside facing to the front (Figure 55).[216] As a second measure to compensate for the different height of the elements, the elements' height was limited to 1.48 m. Empirical tests showed that this would keep the height difference to a maximum of 2 cm. This difference could then be accounted for by the horizontal joints between the elements during installation.

Tolerances or imprecision in the module when using ready available building products like bricks becomes an issue when these building products are coupled with a highly precise digital controlled robotic assembly process. This is even more the case when for the ease of automation operational steps of the process, which would traditionally compensate for these tolerances like bonding the bricks with the means of mortar, are replaced by a process that does not show the same properties. Within the scope of the experiment, through the measures described above, as well as selecting bricks which already exhibit a high degree of precision, these tolerance issues could be dealt with.[217] Nevertheless, this becomes an important issue, especially concerning the question if robotic assembly processes will establish themselves in the building industry. Here, the

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[216] The back side of the bricks usually show marks from the production process, which is why in standard brickwork the bricks are assembled all in the same direction. Rotating the bricks in every other layer would have resulted in clearly visible horizontal lines in the brickwork. For aesthetic reasons it was chosen to rotate every other brick in one course creating a checker effect, causing the different qualities of the two brick sides to blend into one another.

[217] Actually, it is possible to produce more precise bricks already with the production facilities at hand and recent experiments conducted by the brick company *Keller AG Ziegeleien* support this approach. Up to now with traditional brickwork, there was just no necessity for a greater control of the dimensional tolerances in the production process.

process would certainly benefit, if it can handle any available brick module and does not rely on proprietary building product, which would restrict application.[218]

4.5.6.3 Summary

Experiment 2 picks up on the successful results of the initial experiment and advances methods and techniques for robotic assembly processes of brickwork, as well as corresponding design strategies. Applying these on the design and fabrication of a complete facing brick façade, demonstrates the applicability and robustness of the process in a real-world scale. Moreover, the process was able to deal with demands and constraints set by the specific design task.

As a result, a unique visual effect of the façade is achieved. Its appearance constantly alters in dependency to the viewer's distance, the point of view, as well as the weather and lighting conditions. For example, the façade presents itself soft and continuous from afar, while accentuating the tectonics and sharp edges of the bricks from near. This façade could hardly be assembled manually. The logic of the placement of the bricks during the assembly process of the individual layers is no longer manually accessible, due to an abstractness that only dissolves in the finalised whole.

Further, the experiment demonstrated that applying structural adhesive to brickwork instead of mortar, avoids the need for reinforcement and allows assembly of non-standard bond patterns, which otherwise could only hardly be realised. Moreover, adopting structural adhesive for bonding adds a new quality to brickwork: to be activated to take tension forces. Applying a robotic assembly process to brickwork therefore does not only bring about a change in the information depth in regard of positioning each single brick, but also a new performance quality of brickwork emerges. While in this experiment the bricks within one element of the façade are basically arranged in a straight wall, with their centre of gravity aligned, the structural adhesive will allow to realise more complex, three-dimensional geometries, which would not be possible in a mortar-bonded brickwork system. Further investigating and exploiting these characteristics of a robotically assembled glued brickwork system is therefore one of the main focus of the following experiment.

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[218] The question of tolerances and how to deal with them is beyond the scope of this thesis. But these findings did trigger further research on the subject matter within the group of Gramazio Kohler Research, see V. Helm, "In-situ-Fabrikation: Neue Potenziale roboterbasierter Bauprozesse auf der Baustelle" (PhD, Academy of Media Arts Cologne, 2015).

Figure 56. Experiment 3: ROB Unit assembling a segment of the Structural Oscillation installation (see Section 4.6.5).

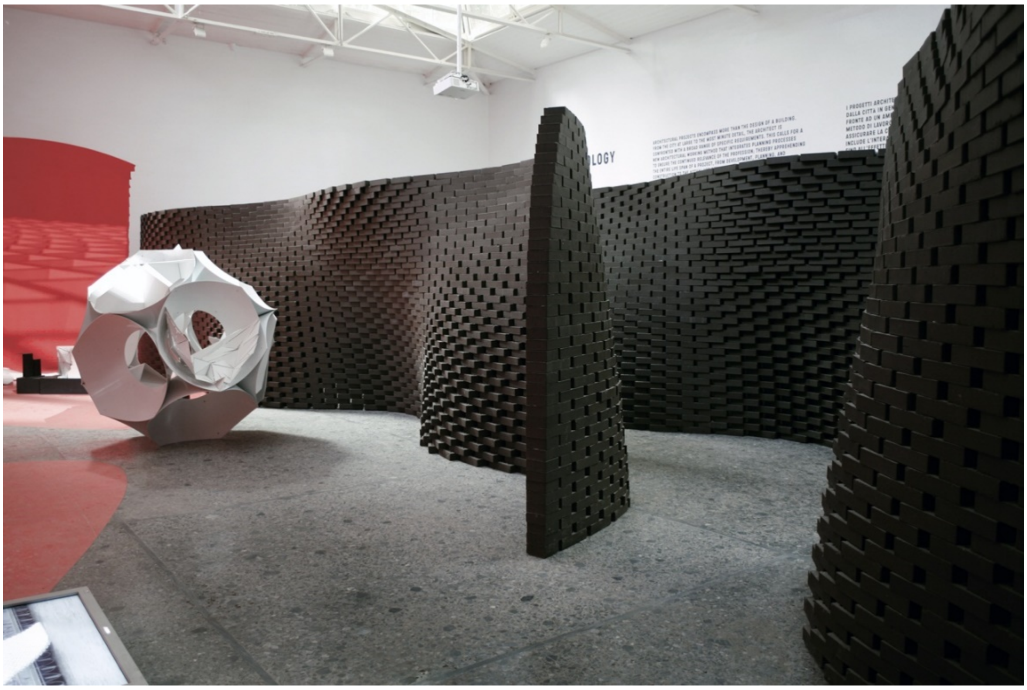

Figure 57. Experiment 3: Structural Oscillation installation in the Swiss pavilion at the 11th International Architecture Exhibition in Venice, 2008 (see Section 4.6.6).

4.6 Experiment 3: ROB Unit – Structural Oscillations

The final experiment discussed in depth within the scope of this thesis translates the findings of experiment 1 and 2 into the development and implementation of a fully automated fabrication unit for the robotic assembly of brickwork, the so called *ROB Unit*. The *ROB Unit* is conceived as a mobile field factory.[219] As such, it can leave the protected environment of a factory and enables an automated prefabrication of building elements directly on the construction site. Thereby, the *ROB Unit* expands prefabrication by facilitating short transportation routes and a just-in-time coordination with the construction site, and, moreover, combining these with the advantages of robotic fabrication, like the realisation of non-standard assembly processes. The *ROB Unit* is a complete robotic workshop based on the general layout of the robotic research facility applied for the previous experiments. Housed in a modified freight container it can easily be deployed all over the world. The robotic set-up is generally open to carry out various different fabrication processes, but the preinstalled tools and peripheral devices are laid out for a robotic assembly of brickwork.[220] In addition to the robotic set-up, a design software capitalising on the possibilities of the robotic assembly process for brickwork is developed, as well as a postprocessor software which generates the robot control code for the specific set-up of the *ROB Unit*.[221]

The exhibition project for the *11th International Architecture Exhibition* in Venice,[222] served as a first field test for the *ROB Unit*, demonstrating the flexibility of a robotic field factory. The mobile unit was installed on site in Venice and the robotic brickwork assembly process was applied to fabricate a 100 m long wall, which runs as a continuous ribbon through the Swiss Pavilion. The wall installation was part of a greater exhibition addressing the question of design research in Swiss architecture schools.[223] The brick wall structures the exhibition space and defines several areas for the individual contributions. The task to design the wall was utilised to further explore the design potential arising from the structural adhesive applied for bonding. Specifically, the conceived design utilises the capability of the glued brickwork to handle tension forces. The built wall features a double-curved geometry with areas of both tension and

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[219] For field factories used in construction during the years of economic boom in Germany, see S. Langenberg, "Geplante Gestaltung – Gebauter Prozess. Architektur der 1960er und 1970er Jahre," *Wolkenkuckucksheim* 13, no. 1 (2009), accessed April 15, 2015, http://www.cloud-cuckoo.net/journal1996-2013/inhalt/de/heft/ausgaben/108/Langenberg/langenberg.php

[220] The *ROB Unit* was developed for and is partly owned by an industry partner, which is seeking to commercialise the robotic brickwork process. For further information, please refer to the Appendix.

[221] The postprocessor can be used in combination with the design software, but if the individual brick parameters are given in the right format it is also possible to generate control data from any other inputs.

[222] The *Mostra di Architettura di Venezia* is an independent part of the Venice Biennale established in 1980. It takes place every two years alternating with the *Esposizione Internazionale d'Arte*. It is one of the most prestigious and extensive exhibition on contemporary architecture worldwide combining academic and practice.

[223] For more information on the exhibition, see R. Geiser, ed., *Explorations in Architecture, Teaching, Design, Research* (Basel: Birkhäuser, 2008).

pressure, which would not have been possible to realise with traditional brickwork using mortar, or other fabrication machinery for automated production.

4.6.1 Robotic set-up

The complete robotic set-up of the *ROB Unit* is housed in a specially adapted freight container of standard size, which allows it to be easily transported and shipped. The 20 ft. container accommodates an industrial robot mounted on a 5 m long linear axis, as well as the necessary control cabinet and all peripheral devices. An identical robot model was adopted as used in the robotic research facility of experiment 1 and 2. The front and top of the container can be swung open, so that the robot can reach the build area in front of the container (Figure 58). The reach of the robotic arm in combination with the linear axis covers a large enough to produce elements at an architectural scale.[224]

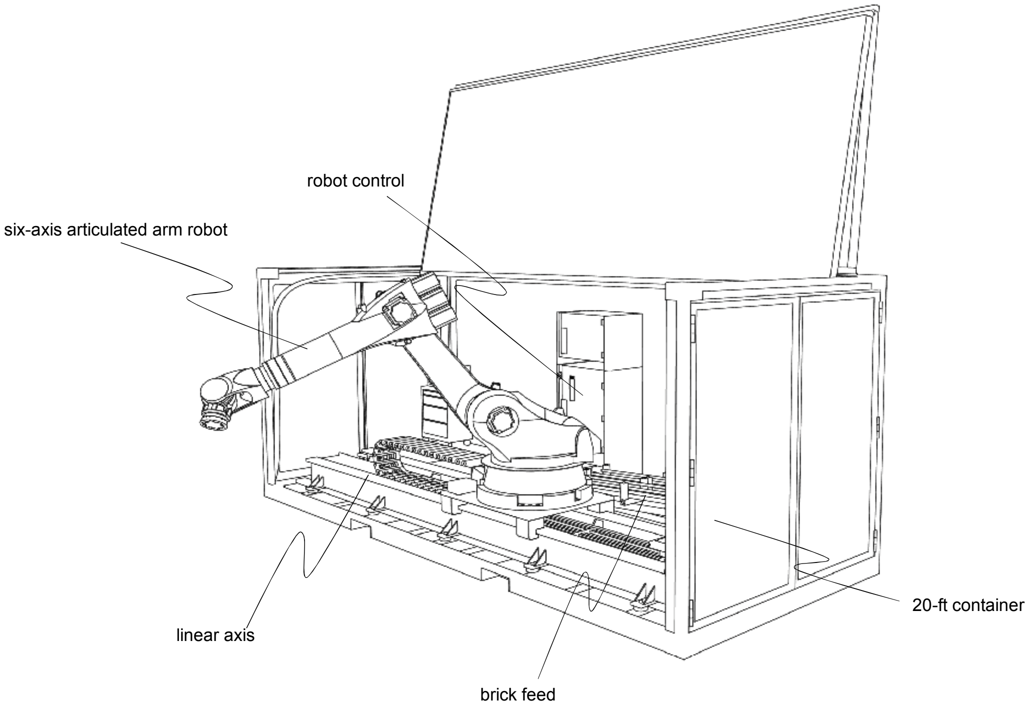

Figure 58. Conceptual design ROB Unit: The final design realised the opening of the front side and the roof differently, such that the roof would still provide weather protection.

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[224] The *ROB Unit* is able to produce facing brick façade elements of 4.0 x 3.5 m and is thus able to cover the height between two floors.

The tools and peripheral devices installed in the container are laid out for the fabrication of robotically assembled brickwork. There are three brick feeds, providing the process with a maximum of three different brick types, for example, dimension or colour. Each brick feed is equipped with a separation mechanism, so that the bricks can be picked without grinding against each other, which causes surface damage. A laser sensor checks if a brick is in position to be picked, adding robustness to the process. Further, a gluing station to apply the structural adhesive is part of the robotic set-up. Considering the possibility to also perform other tasks than the assembly of brickwork, the robotic arm is equipped with a tool changing system. This enables the robot to change its end-effector during a running process.

The peripheral devices are controlled via a Programmable Logic Controller (PLC). PLCs are standard to control machines in an industrial environment. They feature a high robustness and a real time processing of in- and outputs.[225] The PLC is used to control the separation mechanism of the brick feeds, the control of the parameters of the gluing station, as well as the safety system of the container. The robot control sends requests to the PLC and receives status reports on the peripheral devices, for example, that a brick is ready to be picked or that the gluing station is operational (Figure 59). In general, the set-up of the *ROB Unit* condenses the knowledge gained in the previous experiments, while adding additional security and safety features in order to guarantee a stable and reliable process in an industrial environment.

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[225] On a general overview on PLC see J. Stenerson, *Fundamentals of programmable logic controllers, sensors, and communications* (Englewood Cliffs, New Jersey: Regents/Prentice Hall, 1993).

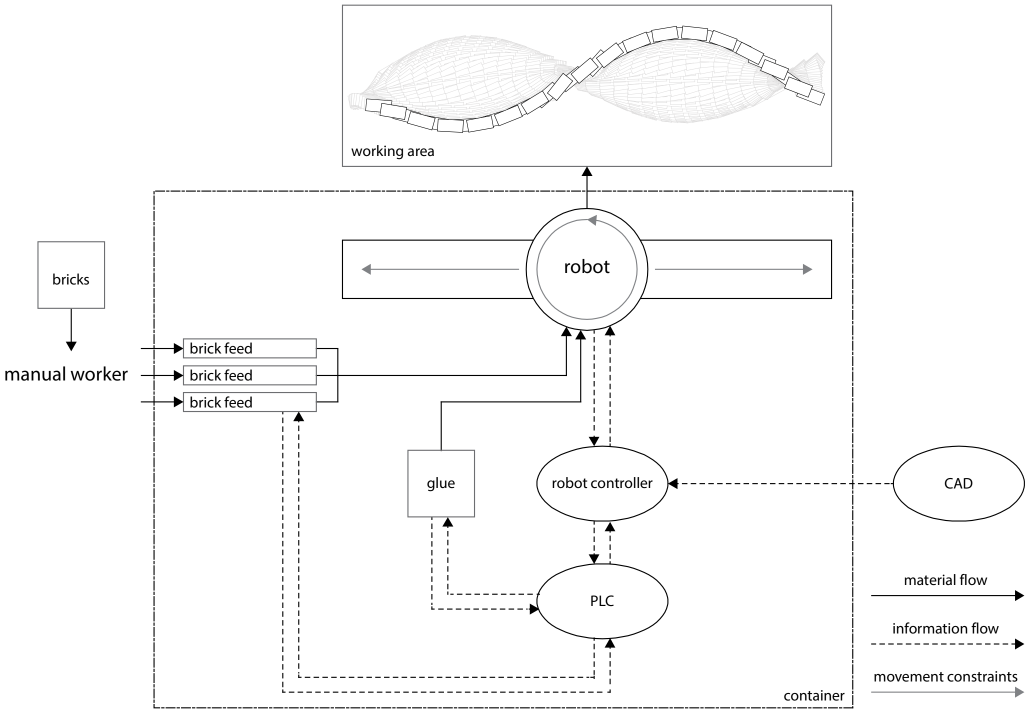

Figure 59. Experiment 3: Scheme of robotic set-up and assembly procedure.

4.6.2 Material System

The robotic set-up of the *ROB Unit* is laid out to process a large number of different brick sizes. Dimensions can range from 100-310 mm in length, 80-140 mm in width, and 50-140 millimetres in height. For the experiment a perforated clinker brick of the dimension 240 x 115 x 52 mm was used. The reason of choosing a perforated brick was twofold: First, the weight of a perforated brick is approximately 20% less compared to a solid brick. The dead load of the wall assembled from solid bricks would have exceeded the maximum permitted floor load of the pavilion where the wall was to be installed. Second, perforated bricks feature a lower dimensional tolerance than comparable solid bricks.[226] The 100 m long wall was produced in several segments, which later needed to be joined to form a continuous ribbon. Therefore, it was essential that the layer heights of each wall segment would coincide.

For bonding the same structural adhesive as for the façade of the Gantenbein winery was applied, which had been already thoroughly tested (see Section 4.5.2). While the adhesive features impressive tensile strength, its major drawback is its relative long curing time of up to 24 hours, dependent on temperature. This becomes an important factor for the effectiveness of a robotic field factory, since the brickwork can only be

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[226] This can be explained with a more homogeneous curing process of the perforated bricks, because they feature less material depth.

moved from its fabrication location and mounted in place once the adhesive has reached a minimal tensile strength to support the dead weight of the element. During curing time the brickwork element blocks production. In the case of the demonstrator project, this implicated that the robot could not work 24 hours, but produced one element per day, which was allowed to cure overnight.[227]

4.6.3 Mechanical tooling and periphery

A two finger parallel gripper was adopted as an end-effector, using the same external gripping strategy successfully applied in experiment 2 (Figure 60). In regards to the *ROB Unit* being able to process different types of bricks, an external gripping strategy seemed most universal. An internal gripper used in experiment 1 would rule out the processing of any solid brick. Additionally, the perforations can have numerous different patterns, while the outer dimensions of a brick are to a large part standardised. Perforated bricks on the other hand are the reason why a pneumatic gripper affecting the brick only on its top surface was ruled out in experiment 2. The disadvantage of limiting the freedom of positioning a brick caused by an external gripper was already discussed above. This disadvantage was judged non-critical, because in its commercial application the *ROB Unit* would assemble curtain-type façade elements of one half brick thickness, similar to the façade realised in experiment 2. Moreover, if necessary, the gripping position can be rotated 90 degrees. Therefore, the brick has to be put down and re-gripped. This has a negative effect on the cycle time and it is preferable to find an assembly sequence where no or only minimal re-gripping is required.[228]

The application of the structural adhesive is identical to experiment 2 (Figure 60).[229]

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[227] Although, adhesion tests performed suggest that at a normal temperature of 23° Celsius and 50% relative humidity a minimum curing time of 24 hours is required, through practical experience during the experiment a curing time of 8 hours proved to be sufficient to safely handle the elements. Please refer to the Appendix for a detailed description of the performance of the adhesive.

[228] Note, this is the initial set-up of the *ROB Unit*, which was regarded most general. However the concept of the *ROB Unit* is to act as a highly flexible field factory. Therefore, it is also equipped with an automated tool changing system, allowing to easily change the end-effector tool in order to realise different gripping strategies and handle various materials.

[229] Because the cartridges to be loaded into the pneumatic gun are relatively small and the pneumatic dispenser mechanism is error-prone, it is intended to substitute the current device with a mechanical dispenser that can process larger volumes of the chemical adhesive. This would allow the process to run for a longer period without manual intervention.

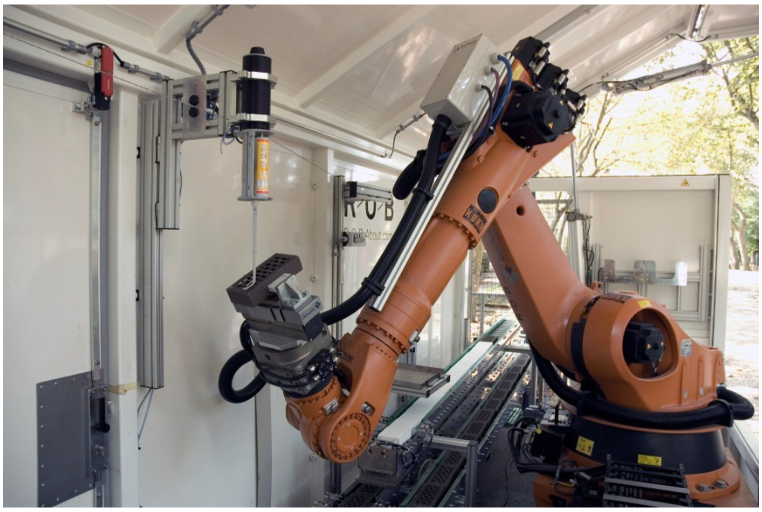

Figure 60. ROB Unit: showing parallel gripper and dispenser for structural adhesive.

4.6.4 Digital design

The basic design concept for the demonstrator envisaged a 100 metre long wall, which structures the exhibition space within the Swiss Pavilion. The demonstrator project allowed to pursue and expand on the design strategies for robotically assembled brickwork of the previous experiments. On the one hand, this concerns the step from off-site prefabrication towards an on-site field factory. While this does not necessarily require a different approach, one advantage of an on-site field factory is the reduction in lead time from production to instalment of a building element. Theoretically, this permits to react to site-specific and unforeseen situations, for example, adapting connection details to adjacent structures, which only become apparent once construction is already in progress. In this experiment this is not a critical issue, since the demonstrator is a freestanding wall within an already build structure. However, the approach already exercised in the previous experiments to describe the design as a set of parametrised rules, allows adapting the course of the wall in concert to the parallel fine tuning of the exhibition layout up to the moment of actual assembly. In the case of this experiment, freezing the design only to one month before the exhibition opening. To enable this, structural rules and fabrication parameters must be incorporated in the design process in order to bypass otherwise necessary iterations between different experts and to ensure that any change to the design is immediately buildable. On the other hand, the double-curved geometry of the wall required considering the individual brickwork elements not only in their final form, but also during the different stages of their assembly. Since the wall segments only become self-supporting once the adhesive has cured, support structures are necessary during assembly and have to be integrated in the robotic process. In other words, aspects of the assembly process become decisive parameters for the design exploration.

Again, the 3D animation software MAYA is employed as a main design environment, though this time scripting is performed using the Python scripting language instead of MEL. Because Python is not MAYA-specific, it constitutes a more powerful scripting environment. One of the advantages of applying Python is that, while having access to all MAYA-related MEL functionalities, it can capitalise on additional external libraries.[230] Further, apart from MAYA specific commands for display of the design, the developed code is platform-independent and can be reused adopting other CAD software.

The digital tools developed for this experiment allow the user to map a one half brick thick stretcher bond onto a manually modelled surface (Figure 61).[231]

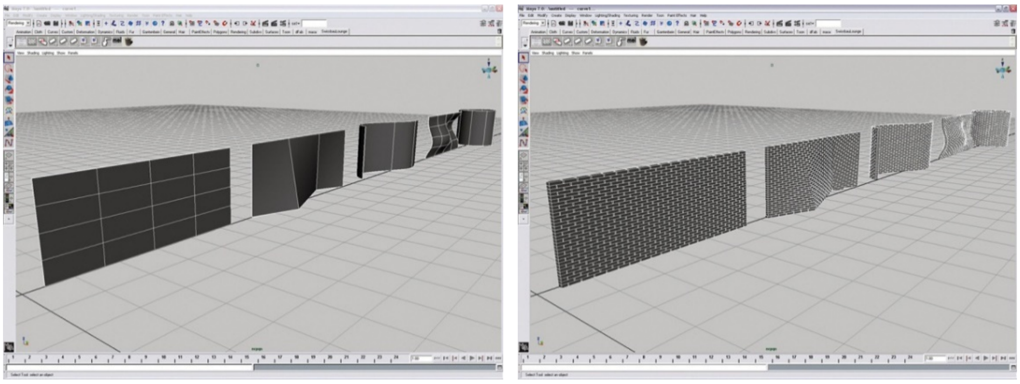

Figure 61. Screenshot of the surface mapping tool implemented in MAYA: (left) manually modelled surface; (right) resulting brick wall after mapping.

For the design of the demonstrator, instead of manually modelling the surface of the wall, several custom scripts were written implementing rules addressing structural stability to generate the surface from a two-dimensional curve. The curve represented the initial design input. It described the basic path of the wall through the exhibition pavilion, and therefore, how it would structure the space and provide for several individual exhibition areas. The curve could be manually manipulated and its final course was negotiated between all stakeholders of the exhibition. The double-curved surface generated from this curve follows the requirement that the wall would be produced in 4 m long segments and each segment would need to stand stable on its own. Therefore, depending on the degree of curvature of the two-dimensional curve at a specific location, the footprint of the corresponding wall segment is increased following

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[230] Specifically, the General Polygon Clipping library (GPC) was used to check for intersections between bricks and to generate the polygon of the overlap area between two bricks as a basis for calculating the gluing paths. See General Polygon Clipper library.

[231] The digital tool builds upon a surface mapping tool, originally implemented for a student workshop. In the workshop a student team developed an exhibition design for a trade show, cf. F. Gramazio and M. Kohler, *Digital Materiality in Architecture*, 62.

a continuous wave motion. In consequence, areas where the initial degree of curvature is low and that would otherwise result in an almost straight wall segment that could easily be tipped over, are transferred into segments with an increased stability. The added curvature of the footprint is balanced by a counter curvature in the top layer of the segment, with the wall surface interpolating between both curves (Figure 62). As a final stability check the centre of mass is calculated for each segment and related to the expected impact force of the visitors. In order to emphasise the expressive plasticity of the wall, the individual bricks are additionally rotated according to the degree of curvature, with a higher degree of curvature resulting in a higher degree of rotation of the brick.

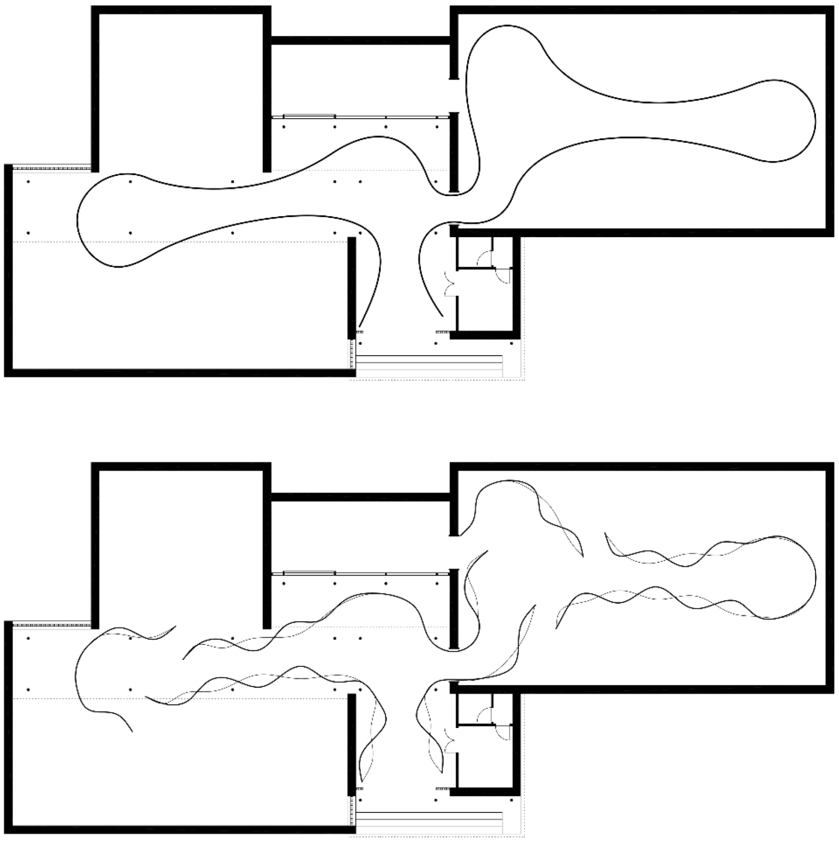
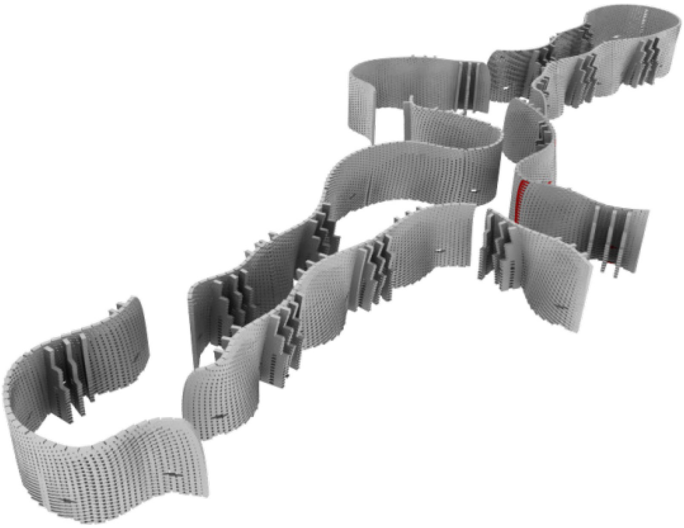


Figure 62. Floor plan of the exhibition pavilion: (top) Initial two-dimensional curve; (bottom) resulting double-curved surface generated according to overall stability.

Though, the adhesive needs a certain amount of time to cure, the double-curvature of the wall can only be realised through adopting a structural adhesive for the bonding. This means that during the build-up process the brickwork can be considered dry stacked. In order for the wall not to collapse during the robotic assembly process, support structures need to be introduced. Here the generic characteristic of the brick as a building module is instrumental (see Section 1.3.1). It allows to build-up the support structure from bricks without the need to introduce any additional scaffolding. As such, the assembly of the support can follow the same logic like any other brickwork structure. Since these bricks obviously do not need to be glued, building the support structure from bricks has the additional advantage that it can be reused. The location and necessary position of the support structure was determined empirically. With the experience of building several prototypes it was easier to manually define the position of a support structure by visually evaluating the model, than to formalise these rules in an automated process. Nevertheless, a small script aided the designer, so that the points where support was needed could be manually defined, while the necessary bricks and their position were generated automatically. The final design data combined with the support structure can then be exported and post-processed to generate the robot control code (Figure 63).



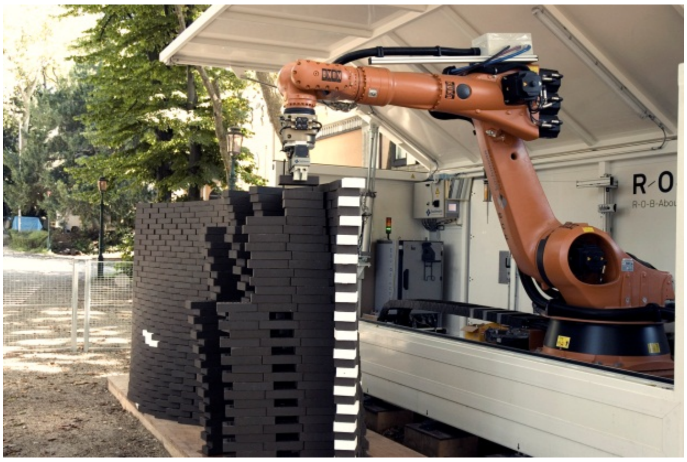


Figure 63. Fabrication data: (top) visualisation of the final export data, displaying all wall segments and support structures; (bottom) robotic assembly of support structure.

4.6.5 Robotic assembly process

Similar to experiment 2, the robot control programme and the data file describing a specific brickwork design are separated. The robot control programme is the formalised description of the brick assembly process. In addition, it incorporates the information on the specific hardware set-up, both in regards to the physical layout and the communication with peripheral devices. In case of the *ROB Unit* this is the definition of the in- and outputs to the PLC, which controls the brick feed and the gluing station, as well as their position in space. Further, it accounts for the specific physical constraints set by the container, which limits the envelope of potential movements of the robotic arm. The data file holds all information on the bricks position, their dimension, and is directly generated from the design data. While the control programme is specific to a robotic set-up, the data file is set up independently and could be used in different robotic scenarios.

The process diagram can be seen in Figure 64. An enhancement to the previous process is integrating the build-up of a support structure within the overall assembly process (Figure 63). Since, the support structure is also assembled from brickwork, it can easily be integrated into the overall robotic process. However, support bricks need to be identified in the data file of a design, because they have to be treated differently in the assembly process. Support bricks are dry stacked so that they do not bond to the final structure and can be reused. Furthermore, the movement path of the robotic arm for placing support bricks is different from placing normal bricks. Normal bricks in the course of a wall assembly are placed vertically from above. In order to account for the dimensional tolerances of the brick module a minimum gap of 2 millimetres is maintained between each brick. A brick in need of support might only overlap the course below by a few millimetres. Therefore, the supporting brick needs to directly connect to the brick below. To realise this without provoking a crash due to the dimensional tolerances of the brick, support bricks are positioned from the side until they touch the neighbouring brick. Finally, the sequence of laying the bricks in one course gains importance, due to the constraints yielding from the gripper geometry.

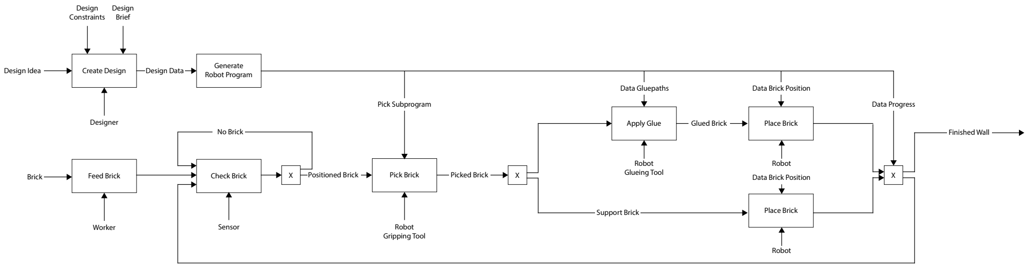


Figure 64. Experiment 3: Diagram of assembly process.

4.6.6 Result

Within the scope of this thesis experiment 3 finalises the physical investigations into an integrated design and robotic assembly process for brickwork. On part of the assembly process, the *ROB Unit* combines the findings of the previous experiments and presents a completely automated robotic assembly set-up for non-standard brickwork. Its mobility brings about both economic and ecological plus factors. Instead of complete building elements only the raw material has to be brought on site, hence drastically reducing transportation needs.[232] This is especially true for doubly curved elements, where the volume to weight ratio is unfavourable in comparison to straight elements that can be more tightly packed. Further, accommodating the regional bound nature of the building industry local materials may be applied. Also, assembly processes can be planned, implemented and tested off-site and then be distributed on compatible robot units worldwide that produce with the same accuracy and quality. The production of building parts happens just in time, synchronised to the progress of the building. Design and fabrication can therefore easily be adapted to unforeseen changes in the course of the construction process.[233]

The realised demonstrator project exploits the specific characteristics of the robotic assembly process, as well as the glue-based bonding system of the brickwork and integrates these into the digital design process. The design is based on a simple continuous curve, which runs through the Modernist pavilion of Bruno Giacometti on the grounds of the exhibition. The curve defines the path through the pavilion and creates individual exhibition areas. However, the actual course of the curve can be regarded secondary to the design. Its materialisation and architectural expression is a direct result of the curve's underlying rule set. These rules are derived from the structural requirements of the wall and how these can be met with the chosen material and the constructive logic of brickwork. Parameters of the robotic assembly process enhance the constructive logic and are incorporated in the generative rule set. On the one hand, it is the ability to transfer a quantity of information into physical reality, thus realising non-standard designs without additional effort. On the other hand, applying a structural adhesive for bonding the bricks, enables a structural behaviour of the brickwork that allows for its double-curved geometry. Thereby, the potential of glued brickwork is exploited further beyond substituting necessary reinforcement for transportation as in experiment 2. In order to ensure stability of the brickwork elements during assembly, the robotic process was extended by the integration of assembling support structure. Using the same unit, i.e. bricks, as the support material, unlike

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[232] Though, it must be noted that currently two factors work against this advantage. Firstly, transportation costs are unreasonable low and do not reflect the environmental footprint caused by shipping. Secondly, the necessary floor space to install the *ROB Unit* has to be made available on-site. For these reasons, most of the production work carried out by the *ROB Unit* so far has been produced off site.

[233] Besides the discussed project in Venice, meanwhile the *ROB Unit* was applied in diverse locations all over Europe, as well as in the USA. In each case local bricks with their own local dimensional standards were adopted. For more information see R. Baertschi et al., "Wiggled Brick Bond," in *Advances in Architectural Geometry*, ed. C. Ceccato, et al. (Wien: Springer, 2010).

traditional scaffolding, which most likely would be prepared out of wooden members, allowed a seamless integration into the automated process. Utilising the capabilities of the structural adhesive and integrating the build-up of support structures, allows creating structures that would not be possible to build in a traditional manual brickwork process applying bricks and mortar.[234] In the realised undulating wall of this experiment, these modified structural properties of the brickwork evocate a textile character, which contrasts to the firm materiality traditionally associated with brickwork (Figure 65).

Figure 65. Structural Oscillation: (top) Overview of the 26 individual wall segments; (bottom) image of final installation, the individual wall segments are combined to create a continuous wall.

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[234] Of course, there are possibilities to realise such double-curved brickwork structures without a robot. Probably the most famous examples are those of engineer Eliado Dieste, though these designs rely on reinforced masonry, see for instance R. Pedreschi, *Eladio Dieste*, ed. A. Macdonald and R. Pedreschi, The engineer's contribution to contemporary architecture (London: Telford, 2000). Examples on how to design expressive unreinforced masonry structures are given by J. Ochsendorf and P. Block, "Designing unreinforced masonry," in *Form and Forces: Designing Efficient, Expressive Structures*, ed. E. Allen and W. Zalewski (New York: John Wiley & Sons, 2009). However, to assemble these structures normally additional scaffolding is needed, either to support the structure during build-up, or to guide the bricklayer in positioning the bricks.

5 DISCUSSION OF RESULTS: AN INTEGRATED DESIGN AND ROBOTIC ASSEMBLY PROCESS FOR BRICKWORK

The experiments identify, develop and expose specific characteristics and implications of an integrated digital design and robotic assembly process for brickwork. Further, they present a corresponding material and construction system. The approach builds upon the *universal nature* of industrial robots as an assembly tool, which allows authoring both the control of the assembly process, and the mechanism of the physical material manipulation performed. Thereby, a bi-directional connection between brickwork design and its execution is established that allows the process of assembly to influence the design and vice versa. While the design is informed by the parameters of the robotic assembly process, the assembly process itself can be shaped according to a certain design intent. Design-relevant interventions therefore occur both at the level of control and the level of mechanism: On the one hand, by customising the sequential assembly steps performed by the robot. On the other hand, by adapting the physical tools with which the robot operates. The ability to shape and manipulate these two essential factors of the assembly process turn the robot into an epistemic tool for design exploration (Figure 66).

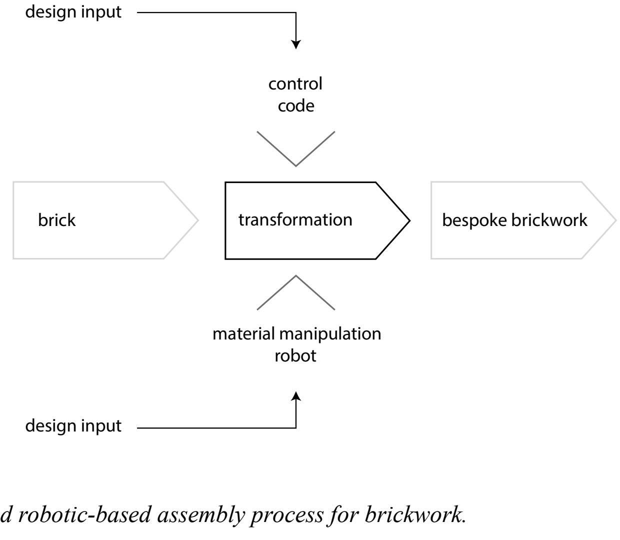

Figure 66. Integrated robotic-based assembly process for brickwork.

Engaging with control and mechanism of the assembly process already at the design stage distinguishes this approach from the previous purely engineering focused applications of robotics brickwork solutions (see Section 3.2). These developments were mainly motivated by rationalisation, adapting automation techniques to traditional building methods through mimicking the manual process. Though, as long as the final results are identical, seen from an architect's viewpoint applying robotic processes or manual labour is interchangeable. In contrast, applying robots as an epistemic tool for design exploration, brickwork design evolves into the interplay between conceptual ambitions and the engineering of an assembly process with its possibilities, as well as constraints. Thereby, the robot as tool overcomes mere automation and can have a substantial impact on architectural design and production.

The experiments mainly exploit the robot's ability to individually control a large amount of elements. The results of the experiments are bespoke brickwork assemblies that feature complex geometries, three-dimensional effects and patterns, while at the same time profiting from the benefits of automation, like repeatability, precision, and constant quality.

In the following, the characteristics and of implications of 1) an integrated robotic assembly processes, 2) a corresponding material and construction technology, and 3) design and planning strategies for robotically assembled brickwork are discussed.

5.1 Robot as a customisable tool for brickwork assemblies

In general, tools facilitate the achievement of specific goals in that they extend human abilities. Examining the possibility of craft in digital practice, Malcom McCullough divides tools into *prosthetic* tools that extend the body and *abstract* tools that extend the mind.[235] An industrial robot can be assigned to both of these categories. Like any mechanic machine the robotic arm is a tool to transmit power. Combined with a specific end-effector tool, this power can be extended towards the physical manipulation of matter, thus acting as a *prosthetic* tool. At the same time, the robot is an *abstract* tool that transforms information in the form of control code into actual movements and actions of the robotic arm. Both end-effector and digital control define the process the robot can perform and essentially the physical output it produces.

Moreover, both the robot's *prosthetic* and the *abstract* tool are customisable. On the one hand, through conceiving and choosing the end-effector tool the robot is equipped with

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[235] M. McCullough, *Abstracting craft the practiced digital hand* (Cambridge, Mass.: MIT Press, 1998), 62. Note that McCullough contribution is mainly focused on "crafting" virtual constructions.

and, on the other hand, by producing the control code that defines how the end-effector tool is moved through space. This characteristic increases the level of personal control that can be introduced into the robotic brickwork assembly considerably and is essential for the robot to become a critical parameter in the design process.[236]

5.1.1 Control: digital assembly information

5.1.1.1 Construction logic and material parameters

In the experiments, the brickwork assembly sequence is made specific through coded commands controlling the robot's movements and actions. Thus, alike objects digitally fabricated with CNC-machines, brickwork can be manufactured directly from its digital description. As a prerequisite, the brickwork has to be described, i.e. coded, following the logical sequence of the assembly process. And, ultimately, in the language of the control software for the robot to interpret and execute. In providing the code, the user gains explicit control over the assembly process. Based on the description of the constructive logic of a traditional brick bond for example, as it was the case in experiment 1 (see Section 4.4), slightly varying the assembly code allowed to create highly specific wall designs and robotically fabricate non-standard brickwork.

As the author of the control data, the designer becomes directly engaged with the process of making. Aptitude, technical skills and experience are introduced through the creation of the data describing the object, which at the same time controls the robot. This demands a design process, which besides formal considerations incorporates material properties at an early stage, as well as the manufacturing and construction process of the respective building elements. In other words, the knowledge of making has to be codified. This includes the elaboration of a specific placement and bonding logic to create ultimately a robust brickwork bonding logic, defining, for example, a minimal and maximum overlap area between bricks, in order to create a working brickwork system. For the design and fabrication of the façade in experiment 2 (see Section 4.5), this entailed that a minimum gap of two millimetres between the positions of two ideal bricks had to be guaranteed, in order to avoid collisions due to imprecisions of the bricks. Further, the control code had to account for the bricks being non-planar in reality, by placing every other brick in a 180 degrees rotated position. In the case of the double-curved wall elements of experiment 3 (see Section 4.6), first a description for an assembly process had to be found to incorporate the parallel assembly of a brick support structure – only thereby allowing for constructability. Without the support structure, the wall elements would collapse during assembly, since the centre of gravity of the wall

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[236] The aspect of control in relationship to craft is also emphasized by McCullough, "continuous control of process is at the heart of tool usage and craft practice." Ibid., 66.

shifts with every brick that is added to the construction. The elements only reach a stable state in their final form and once the adhesive has cured. Therefore, in a robotic assembly process for brickwork, it must be ensured that a stable equilibrium is achieved in each assembly step during the build-up process.

Overall, the experiments show that authoring and controlling the assembly process opens the opportunity for a design language to emerge that is rooted in material and constructive principles of brickwork.[237]

5.1.1.2 Precision and quantity

Further, the digital control governing the assembly process allows to achieve a precision in positioning the individual bricks that can hardly be realised in a manual bricklaying process. In the experiments, this point is identified as one of the main difference between a robotically-controlled assembly process and its manual counterpart. This becomes especially obvious, when the brick positions do not follow an easily comprehendible logic or can be visually aligned to the standard guiding systems used by the bricklayer.

A robot fed with custom digital control data can position every brick differently without additional effort. In comparison, a bricklayer can easily arrange bricks that have the same orientation or rotated by 90 degrees – either by straightening the brick according to the bricks already in place or against a guide line. However, as soon as an arbitrary shift of the bricks in any direction or a rotation other than 90 degrees is introduced, manual placement becomes very cumbersome. If the change in the brick position is continuous a skilled bricklayer might be able to place the bricks through visual feedback and approximating the position in relation to its neighbours. Indeed, the wall designs of experiment 1, as well as the undulating brick wall of experiment 3, can all be described as a continuous function. However, the bricklayer can hardly anticipate when a function has reached a turning point or point of inflexion. Further, a complex reference system cannot be avoided once the manipulation of the bricks position is discontinuous or at random. Such is the case for the façade of experiment 2, where a rotation of the bricks was derived from the pixel colour values of a digital image.

For a bricklayer to build the double-curved wall of experiment 1 or 3, for instance, a surface guide would be necessary to describe the wall. Meaning the surface geometry

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[237] The question of control within a production environment and how it can affect the resulting product was already raised by David F. Noble in 1978. In discussing automatically controlled machine tools, he questions, if a division of programming and machine operating within one shop was really necessary. Continuing to ask, “Could programming, like other tooling, be done closer to the floor or by people of the floor?” Noble argues that this development is mainly due to management seeking greater control over production. Although, Noble’s concern is a critique of capitalist society, read out of the perspective of the architect and designer, the question raised is of relevance for the relation between design and making discussed in the presented thesis. In that it poses the question on how design and making can benefit if viewed holistically. See D. F. Noble, “Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor,” *Politics & Society* 8, no. 3-4 (1978): 323.

of the wall would need to be build up as a falsework system in advance (normally built from of an easy-to-process material, such as, for instance, timber), which is discarded after construction. The façade of experiment 2 poses the challenge to place every brick at a different angle, which might only differ a fraction of a degree, while the centre points of all bricks has to be aligned – a task that would only be possible to execute manually applying a complex measuring strategy. Generally, as soon as the brickwork leaves a uniform and repeated rectangular bond pattern, or the wall is non-planar, manually referencing and verifying the position of each brick becomes challenging and costly. Here, the digital control of the robotic assembly process enables to easily realise highly differentiated and non-standard brickwork. The costs of the control code is the same, independent if the bricks are all positioned on a planar uniform grid or at an arbitrary position.

The potential to precisely place bricks at any specific position, without additional guiding or measurement aids, becomes increasingly evident once the number of bricks that are handled by the control code exceeds a critical threshold. This is the case, as soon as the brickwork is applied at an architectural scale, like, for instance, a façade. The wall based on a Flemish bond of experiment 1 might possibly still be assemble manually. Primarily, since only one-third of the bricks break out of the traditional Flemish bond. The translational movement of the header brick in its length direction can simply be measured in reference to the wall surface defined by the stretcher bricks. Nevertheless, the usage of additional measuring and alignment tools and the adjustment of each brick towards a different reference point – which must be known to the bricklayer – is time consuming and results in considerable extra effort. In the case of the façade of experiment 2, where the number of bricks that have to be specially referenced and aligned increase by factor hundred compared to the single wall designs of experiment 1, this extra effort can hardly be justified.[238]

The experiments expose a specific characteristic of robotically assembled brickwork, which is the ability to manage and process a large volume of data, whereby the control code can consist of a myriad of different assembly instructions. The physical manifestation of a design can therefore be precisely defined down to its smallest constituent element, the brick. This creates the opportunity for a new tectonic language of brickwork that features richness of detail, and which is not limited to merely economic considerations, but can extend over brickwork in its entirety.[239]

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[238] The threshold, where manual bricklaying "still makes sense" is of course not absolute and dependent on various factors, like skills of bricklayers, labour costs, etc.

[239] On the aspect of a new materiality emerging out of the application of digital tools in design and fabrication see F. Gramazio, M. Kohler, and J. Willmann, "Towards an Extended Performative Materiality – Interactive Complexity and the Control of Space," in *Theories of the Digital in Architecture*, ed. R. Oxman and R. Oxman (London: Routledge, 2014). and A. Picon, "Architecture and the virtual: Towards a new materiality?," *Praxis: Journal of Writing+Building*, no. 6 (2004).

5.1.2 Mechanism: end-effector

Alongside the digital control guiding the assembly, the physical tools enabling the robotic arm to perform the bricklaying process are customisable. The production of form and manipulation of material is dependent upon finding the right tool. Generally, a tool can always be seen as a specialised (cultural) artefact. While a specific task or process might only become possible through adopting or developing the right tool, in focussing on a specific task a tool at the same time introduces constraints. Often a tool is unique to a product and its manufacturing process.[240] Material, geometry, and mechanism of a tool might prevent it to be applied to a function other than its intended primary use. The tool applied thereby sets limits to the manufacturing process, so that choosing or even designing a custom tool is thereby an important part of the overall design process.[241]

The precision at which the industrial robot can operate makes most of the traditional bricklaying tools obsolete, primarily all of the measurement and alignment tools (see Sections 3.1 and 4.3.3). Foremost, the robot arm has to be equipped with a gripping tool as an end-effector, to be able to pick up and place bricks. Insofar, the end-effector does not replace a specific bricklaying tool, but adopts functions of the human hand. However, most gripping tools by far do not have the capabilities of the hand, most of all lacking any sensory feedback. The parallel gripper technology on which the end-effectors for the experiments are based, reduces the functionality of the hand to a two-finger grasping process. Moreover, it is limited to a single gripping strategy. Therefore, the chosen end-effector sets certain constraints on the assembly process that have to be accounted for in the design: On the one hand, the stroke of the gripper determines the maximum and minimum size of bricks that can be handled. On the other hand, the geometry of the gripper and the gripping strategy used sets constraints on how the bricks can be placed and/or on the assembly sequence (Figure 67).

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[240] See N. Callicott, *Computer-aided manufacture in architecture the pursuit of novelty* (Oxford: Architectural Press, 2001), 156.

[241] This resembles the approach of early craftsmen that often made their own tools. See for example D. M. Gann, *Building innovation complex constructions in a changing world*, 22.

Today, rapid prototyping technologies, like 3D-printers and laser cutters, ease and accelerate the option to design and manufacture custom tools. In traditional tooling for mechanisation, the fabrication of tools is very expensive. These costs only amortise if the tool can be applied accordingly, leading to mass production. Applying digital fabrication techniques for tooling allows fast cycles of development and production of tools. Tools can be designed for a specific process and can amortise over the course of a single project. Thereby, project specific tooling is possible. Tools are also cheaper, because they do not need to be as robust as in industrial production. Instead of operating on possibly millions of pieces, they might only operate on a diminutive fraction. Rapid prototyping technology can thus be a powerful means to realise process-specific tooling for robotic processes. See D. T. Pham and S. S. Dimov, “Rapid prototyping and rapid tooling – the key enablers for rapid manufacturing,” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 217, no. 1 (2003).

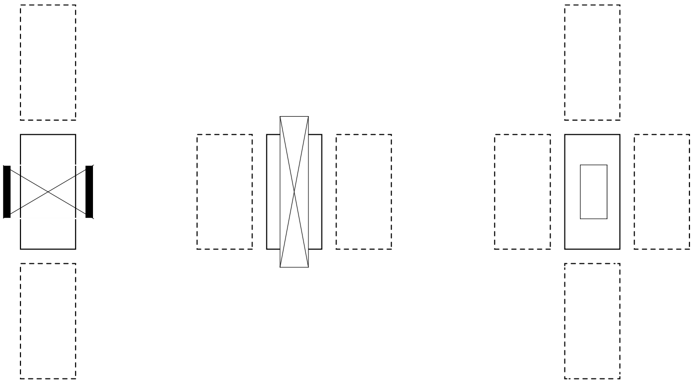

Figure 67. Three main gripping strategies and constraints in brick placement: External gripping by width of brick (left); external gripping by length of brick (middle); internal gripping of centre of brick (right).

Comparing the different gripping strategies of experiment 1 and 2, illustrates how different end-effector tools decisively change the potential design space of brickwork that can be covered by the robotic assembly process. More specifically, experiment 1 applies an end-effector tool with an internal gripping strategy. Thereby, allowing a great freedom in placement, since the brick can be positioned directly adjacent to any other brick on all four sides (Figure 67 right). With the change to an external gripping strategy in experiment 2, the two sides where the fingers of the gripper clamp the brick are blocked. Therefore, the bricks in one layer can only connect directly at the short end (Figure 67 left). As a result, none of the wall designs of experiment 1 could be robotically assembled with the end-effector tool of experiment 2.[242] There are different reasons for choosing a certain gripping strategy. For the experiments, a mechanical grasping of the bricks was favoured over for instance a pneumatic gripper, in order to ensure a reliable and precise gripping independent of the defilement or structure of the brick surface. Consequently, solid bricks can only be gripped externally.

The experiments substantiate that constraints arising from a specific end-effector tool already have to be integrated into the design. Since the end-effector tool is customisable, its design and function can be adapted to a specific design intent. This demands developing both design and the robotic assembly processes with its specific tools in parallel, allowing both to inform one another. The definition of the end-effector tool is then a trade-off between design intentions and its suitability for a robotic assembly process.

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[242] Of course, certain bonding patterns combined with a specific assembly sequence do allow for connecting the long edge of a brick with its neighbours also with the external gripping strategy. For instance, a course of alternating stretcher and header bricks can be realised by first placing all header bricks and only then inserting the stretchers in-between.

5.2 Material and construction technology

Besides the automated process of bricklaying, brickwork is likewise determined by the material and structural system employed. Within the experiments a novel material and construction technology was developed that corresponds to the robotic assembly process. Its main characteristic is the usage of adhesive instead of mortar for bonding, while any standard facing brick within a certain dimensional range can be processed (see Section 4.6.2).[243]

Applying adhesive in an automated process is common practice in industry, because viewed from perspective of automation, it is far more controllable than applying for example mortar. For this reason, already the predecessors in robotic brickwork substituted mortar with adhesive. Also, using a thin-bed mortar is known practice for manual brickwork. However, it is only applied for non-facing walls and the structural system is viewed similar to mortar-bonded brickwork, meaning that it is regarded as a compression-only structure.[244] In contrast, the construction technology developed within the experiments results in a unique brickwork system which employs adhesive for the bonding of facing brickwork and, moreover, it activates the flexural and tensile strength of glued brickwork.

In terms of brickwork's appearance, the main difference of glued brickwork is that, with the lack of mortar joints, the brick and its specific texture become dominant. While this might result in a tile like facing when the bricks are ordered in a planar surface, this impression immediately moves into the background, once the inherent potential of robotically assembled brickwork to arbitrary position each individual brick is activated. In this case, the tectonics of the bricks and the play of light and shadows predominates perception over brick joint ratio. The result of experiment 2, for instance, is a very expressive brickwork façade that alters its appearance constantly in dependency to the viewer's distance, the point of view, as well as the weather and lightning conditions. The façade presents itself soft and continuous from afar, while accentuating the tectonics and sharp edges of the bricks from near.

In terms of novel structural possibilities, utilising the tensile strength of the adhesive allows creating structures that would not be possible to build in a traditional manual brickwork process where bricks and mortar act as a compression-only structure. Especially, the half a brick thick double-curved complex wall geometries of experiment 3 are only possible in making use of the structural capabilities of the adhesive. As such,

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[243] Essentially, the basic building module can be of any material, like for instance concrete, as long as it exhibits similar structural properties like the clay brick.

[244] On calculating glued brickwork see for example, W. Jäger, *Mauerwerk-Kalender*.

the glued brickwork system correlates ideally with the robotic assembly process that facilitates spatial design thinking and the fabrication of non-standard brickwork.

Further, the glued brickwork as demonstrated in experiments 2 and 3 is well suited for prefabrication, being it in a factory environment or directly on site. The prefabricated panels can be easily transported and installed without any need for additional reinforcement, as is the case for traditional mortar-bonded brickwork. The lack of reinforcement additionally supports the assembly of non-standard bond patterns, which complicate the integration of steel rebar, because cut-outs in the bricks might not be on top of one another, or the rebar would need to be bend according to the wall profile. The high stiffness of the glued brickwork also reduces the need for structural support, for instance when attached to the primary building structure. Supporting the façade elements of experiment 2 with a lintel was a safety measure mainly due to the little experience with structurally-active glued brickwork, while experiment 3 proved that no additional support for transport or to install the elements is necessary (Figure 68).

Figure 68. Lifting of glued brickwork element. The brickwork resembles a stiff panel that does not need additional support for handling.

While prefabrication has the advantages of being independent of weather conditions and enables faster on-site construction, it also benefits the robotic process, especially when the task is to assemble a brickwork façade. In this respect, it is not so much the difference of working in a controlled environment versus an often unstructured building site, which obviously brings about an increase in complexity – an issue that posed a great challenge to earlier attempts of automating bricklaying, which all focused on in situ assembly. In fact, it is an issue of reachability. Normally, a brick façade is build up from the outside, meaning an on-site robot would need to be able to reach the complete height of building, or the robot and scaffolding would need to be designed such, that the robot can travel the complete extent of the building envelope. But also if a façade could potentially be assembled from the inside, as the specific situation of experiment 2 would have allowed, the robot arm would require a much larger reach in order to cover the complete floor height (in this case 4.5 m). A greater reach of the arm generally results in an increase in weight and dimension of the robot, which for instance rendered the *ROCCO* solution impractical for employment on the construction site (see Section 3.2).

A glued brickwork system also poses challenges. Foremost, the issue of dimensional tolerances of the bricks that, in contrast to a centimetre thick mortar joint, cannot be compensated for in a thin glue joint. A strategy chosen for experiment 2 and 3 was to rotate every other brick by 180 degrees and thereby balancing systemic imprecisions of the brick height. However, the experiments proved that this strategy only works up to a height of 2 metres, after which the addition of the dimensional difference of the bricks becomes too great. For the same reason, the elements cannot be built to a specific height. For the façade of experiment 2 this was compensated with a 2 cm horizontal joint between the elements. Since the brickwork elements are separated by a lintel this is not visually noticeable. However, for a continuous brick surface, which might additionally include openings for windows that have to coincide with predefined measurements, other solutions have to be found. A straight-forward solution would be to grind the bricks to a defined height before processing. Further, until now there is a lack of specific standards that cover glued brickwork under tension load. This can prove to be a barrier for implementing the technology in the building industry, since each project would need to be treated individually and evaluated anew.[245]

Nevertheless, in combination with a novel material and construction technology, the robotic assembly process for brickwork does not only bring about a change in the information depth in regard of positioning each single brick, but also a new performance quality of brickwork emerges. The structural adhesive increases the versatility of brickwork and massively expands the potential to design complex, three-dimensional geometries in brickwork.

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[245] The Swiss manufacturer of brick façade systems, Keller Systeme AG, holds a product certificate on glued brick façade panels. However, this is bound to specific materials, i.e. bricks and adhesive, as well as to a specific processing method. Therefore, it is far from a general standard and verification of individual cases are still necessary. See, Keller Systeme AG, "Prefabricated ceramic wall and facade elements." KOMO certificate no. K75618/02 (2014), Kiwa, Netherlands.

5.3 Design strategies for integrated robotic brickwork assemblies

The experiments suggest a design process for brickwork that is directly synchronised with the robotic assembly process. This is achieved through a close coupling of the design data and the control data for the robot. Both are authored by the designer and explicitly described through code.

On part of the control– regarding the robot as a customisable tool – the direct programming of the control code for assembly becomes a necessity. The robotic set-up itself and the process executed is subject to change. The robot can be equipped with completely different end-effector tools and peripheral devices, and the layout of the working cell can be modified for each process, which entails a further change in the physical constraints acting on the assembly process. This is a significant difference, for instance, in comparison to standard CNC-machines that are usually self-contained, tightly constrained to a single fabrication process and to a predefined working area. Here, Computer Aided Manufacturing (CAM) software can act as an interface to translate a geometrical representation of an object in the form of a CAD-drawing into control code for the machine.[246] For a robotic assembly process, however, this would only be possible once the set-up and process is unalterably defined. However, in a customisable robotic process, where the physical constraints are constantly changing, a CAM-like software cannot represent and control all potential set-ups and functionalities. Therefore, the robotic control code needs to be programmed for each specific process to account for its respective characteristics: On the one hand, these might only affect the internal course of the process. The layout and dimension of the container of the *ROB Unit*, for example, constrain the robots working envelope, which results in a different sequence of movements for the robot to pick and place a brick compared to the laboratory set-up of the preceding experiments.[247] On the other hand, changes in the gripping strategy or integrating a gluing process in the process instead of joining the bricks with mortar and thus opening up completely new structural possibilities for brickwork, are truly design relevant. As such, already the design data, besides formal considerations, must reflect the logic of the assembly process. This implies a design

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[246] Although, generating the control code for CNC-machines from CAD-drawings is the norm, there are numerous examples of architectural projects where the machine-code is directly scripted or generated within the workflow of a digital design process. However, in such cases the translation process of the CAM-software is skipped due to reason of automating, rather than the inability of the CAM-software, see for instance F. Scheurer, "Architectural CAD/CAM – Pushing the Boundaries of CNC-Fabrication in Building," in *Manufacturing Material Effects - Rethinking Design and Making in Architecture*, ed. B. Kolarevic and K. Klinger (New York: Routledge, 2008). It is revealing that the involvement of architects with CNC was mainly catalysed through the widespread introduction of CAD and CAM, as traced by Callicott. Only once architects could control the machines through drawing, they started to reassess manufacturing processes and the validity of predefined components to the benefit of their domain. See N. Callicott, *Computer-aided manufacture in architecture the pursuit of novelty*.

[247] Note, the layout of the robotic set-up also influence the dimensions of the elements that can be produced, which again can become relevant to the overall design.

method for brickwork that is closely connected to the tools and process of its physical execution.

5.3.1 Designing brickwork through code

In order to achieve a close coupling between the design data and the control data for the robot, the designs realised in the experiments are all developed from a step-by-step description of the assembly process. This approach is exemplarily illustrated by the design scripts depicting several traditional brick bonds that formed the basis for experiment 1. The script sequence of generating a brick object and defining its final position in a three-dimensional coordinate system is identical to the necessary sequence to follow when physically assembling the brick wall, i.e. picking a brick and positioning it in space (see Section 4.4.4). The step-by-step description is guided by parameters of the robotic set-up, the sequential steps of the assembly logic, and the constructive system. If combined, they bound a specific design space of potential brickwork.

This design space can only be fully explored by means of computational methods.[248] The robotic assembly process enables the controlled positioning of each individual brick within a façade. Therefore, design and fabrication of brickwork is not limited in its formal complexity. Conventional, manually erected brickwork is often restricted to a planar element and a monotonous, repetitive bond.[249] This allows designing and representing brickwork through its outer boundaries and assigning it a distinct brick bond, without describing the geometry of its constituent elements (i.e. the bricks). For conventional brickwork this information is sufficient. Given the bond type and the dimension of the brick unit, an experienced mason can easily erect such a wall. The predecessors in robotically assembled brickwork did not question the conventional design approach.[250] However, in order to exploit the potential of the robotic assembly process and to explore its full design space, a model explicitly depicting each single brick, as well as methods to individually manipulate their position in space, are requisite.

Taking into account that the number of bricks in the experiments – which ranges from 421 bricks for one of the wall designs in experiment 1 to 22,538 bricks for the façade of

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[248] Although not focusing on fabrication specifically, the general significance of computational models and writing problem-specific software, as a means of exploring multi-constrained design tasks has been highlighted by Axel Kilian. He argues that thereby constraints can lead to novel design solutions. See A. Kilian, "Design Exploration through Bidirectional Modeling of Constraints" (PhD, Massachusetts Institute of Technology, 2006). A similar point is made by Stan Allen, who states that a "[…] constraint is not an obstacle to creativity, but an opportunity for invention, provoking the discovery of new techniques." See S. Allen, *Practice architecture, technique + presentation*, Expanded second ed. (Abingdon: Routledge, 2009), XV.

[249] See J. W. P. Campbell and W. Pryce, *Brick: A World History*, 290.

[250] Therefore, specific software tools were not necessary for the initial design stage, but only became important at the stage of generating the control code for the robotic system. In a top down process a given wall defined by its boundaries is broken down into the position of each individual brick. See for instance, F. Herkommer and B. Bley, "CAD/CAM for the prefabrication of brickwork."

the Gantenbein winery – a conventional *manual* approach to explore a design, i.e. drawing the individual bricks, thereby defining their position and angle, is not viable. Especially, if one considers that a design process usually proceeds over several iterations, such an operation would be unjustifiably time consuming and resembles the impracticality to manually assemble these non-standard brickwork designs.

Besides the aspect of quantity (see also Section 5.1.1.2), the non-standard brickwork features complex dependencies of its composing elements that can only be handled through computational methods. Changing the spatial configuration of a single brick within an assembly can have a recursive impact on all other bricks. In order to achieve a coherent brickwork assembly with a proper bond, a minimum overlap area (i.e. minimum gluing surface)[251] between the bricks in the course above and below must be guaranteed, and obviously, intersections between bricks within one course must be avoided. These dependencies especially become apparent, once the bricks are not positioned within a regular grid anymore and the brickwork is non-planar, as exemplified by experiment 3. The double-curvature of the wall leads to a different length of each course of the wall. Since the unit size of the bricks are identical and the number of bricks per course has to be equal in order to guarantee a proper bond, the difference in length can only be compensated through varying the width of the vertical butt joints. Pulling the bricks within a course further apart automatically results in less overlap. Hence, the three-dimensional deformation is dependent on the dimension of the brick used and the minimum overlap area. But also, in the case of the façade of experiment 2, where the bricks are positioned in a rigorous planar grid, the rotation of the bricks can result in both an overlap below the limit value, as well as an intersection with the neighbouring bricks.

Moreover, these dependencies do not need to be limited to structural imperatives, but can just as well incorporate other functional or formal aspects. For the façade of experiment 2, for instance, the amount of sunlight penetrating the open vertical joints of the brickwork additionally governed the width of the gap between the bricks, as well as the degree of rotation. Ultimately, relationships and rulesets for assembly can come from various domains (e.g. architecture, engineering, fabrication, etc.) and the design code can be permeated with numerous information. Information, which thereby can be synthetically integrated into the brickwork, without breaking the programmatic coherence of the whole.

Finally, assembly of brickwork is a process in time, which in its entirety can hardly be captured in a static drawing – especially considering robotically assembled non-standard brickwork as realised in the experiments. A descriptive drawing can only carry a limited amount of information, which is insufficient for the robot to actually execute

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[251] The minimum gluing surface ultimately depends on the geometry and dimension of the brickwork and the forces it is exposed to. As a rule of thumb, an area of 50 sq. cm as general gluing surface was established throughout the experiments.

a design. Normally, expert knowledge – in the case of traditional brickwork that of the bricklayer – is needed to transform the execution drawing into reality. For example, the execution drawing gives no information on sequence of the necessary assembly steps. Basically, the assembly of brickwork implies building up a three-dimensional element out of a number of single pieces that are smaller than the final object. Obviously, the single bricks constituting the final object have to be placed and processed in a certain order to guarantee the feasibility of production. Foremost, the laws of gravity apply. Every brick placed must be supported either by already processed material, or through some kind of scaffolding, which becomes part of the assembly process, similar to the support structures applied in experiment 3. As such, not only the completed structure has to be structurally sound and stable as a whole, but it must be ensured that a stable equilibrium is achieved in each fabrication step during the build-up process.[252] Further, the reachability of the position of placement must be assured. Even in a layered process like brickwork, due to constraints of the gripping tool for instance the processing order of bricks within one layer can be essential.

Describing a brickwork design through code utilises the possibility to compose the process flow of a computer script to resemble the sequence of the assembly process. Thereby, describing a brickwork design through code can already incorporate the knowledge of making and eliminate what is otherwise referred to as the "fabrication gap".[253] The design is thus closely connected to the physical reality, which reduces transfer loss from conception to construction. Thereby, a design does not have to be made buildable retrospectively. Traditional intermediate steps, like construction design and execution drawings, which transfer a design into something buildable, are skipped.[254] This drastically shortens the time from design to execution.

5.3.2 Computational tools

As argued in the previous section, computational tools are indispensable, in order to control and creatively design robotically assembled brickwork. Moreover, parameters of construction and the assembly process have to be considered at an early design stage. Traditional CAD-systems mainly resemble manual drafting tools. Specifically, they are limited in designing with large number of elements. They offer no methods to efficiently compute and manipulate all constituent elements of a non-standard brickwork assembly. This limitation contrasts the possibilities opened up by a robotic assembly process.

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[252] Consider for instance stone arches or shell structures. Although some specific geometry allow for stable configurations during erection without the need for support, forces can only be transferred once the final geometry is achieved.

[253] See for instance, J. Rieffel, "Evolutionary Fabrication: The Co-Evolution of Form and Formation" (PhD, Brandeis University, 2006), 2-4.

[254] This does not necessarily imply that drawings or visualisations become unimportant per se, in developing the designs for the experiments, they still played an important role to verify and evaluate design variations.

Thus, traditional CAD-systems are not sufficient and digitally controlled assembly processes for brickwork clearly require new design tools.

All experiments rely on custom scripted tools. Since the scripts, in their process flow, resemble the assembly process, their development can be regarded as part of the design exploration. While some parts of scripts were reused for different design tasks, like the surface mapping tool applied in experiment 3, for the most part these scripts are highly project specific and cannot be readily generalised on a more abstract level, in order to address a broader scope of design exploration.

The software *ROB Creator* (see Section 4.5.4.1) was a first attempt to generalise and export certain design methods developed within the experiments. Specifically, the software encapsulates the design principle applied to the façade of experiment 2. It enables the user to map images on a brick wall element. The pixel values of an image are translated into a rotation value for the corresponding brick in the assembly. Nevertheless, the design possibilities are still very limited. Besides the possibility to map images, the basis for a brickwork design is restricted to a straight wall and a stretcher bond. Consequently, the software must be regarded as a first step in creating computational tools specifically geared towards a robotic assembly processes of brickwork. Without the need to explicitly write the assembly code, the software enables the user to design non-standard brickwork through informing every single brick. Additionally, basic assembly parameters, like minimal area of overlap, are integrated into the design software. While these impose constraints on the design, the software thereby guarantees that all created designs are feasible and buildable. By further providing the basic data for the control of the robotic assembly process, the software connects design, execution planning and assembly of brickwork in a unified computational planning tool.

But most of all, the software already incorporates concepts specific to working with discrete elements. The basic element of assembly, the brick, is at the same time considered as the basic design unit. This means that, for instance, openings and windows within a brick wall are primarily not defined through their dimension and measured position, but by selecting the bricks that define their embrasure. Further, the design, for example, adapts to changing the dimension of the basic brick unit. Hence, a design is developed from its constituent elements (the bricks) and the logic of their assembly, rather than through an overall geometry – thereby synchronizing the design with the robotic assembly process.[255]

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[255] Building upon this very concept, a step towards a general approach to designing non-standard brickwork was taken in a related project, implementing the possibilities of a robotic assembly for brickwork in a wider architectural planning process. See T. Bonwetsch, R. Baertschi, and M. Helmreich, "BrickDesign: A software for planning robotically controlled non-standard brick assemblies," in *first international conference on robotic fabrication in architecture, art, and design, Rob|Arch*, ed. S. Brell-Cokcan and J. Braumann (Vienna: Springer, 2012).

6 CONCLUSION

Through a succession of experiments, this thesis developed a fabrication model for robotically assembled non-standard brickwork and established corresponding design criteria and methods. The experiments successfully demonstrated the synchronisation of digital design and a robotic assembly process, and revealed the resulting architectural potentials. The experiments employed the manipulation of the robotic process (i.e. material and control) as integral part of a design strategy. Through deliberate manipulation, perceptual, spatial, and formal effects were achieved. In the matter of material, the most significant customisation of the brickwork process is substituting mortar by a two-component adhesive. While distinct qualities of the mortar joint are lost, applying a bonding method suited for robotic processing adds a new performance quality to brickwork, in that it can take tension forces. Thereby, brickwork structures with complex geometries can be realised, which otherwise would not be possible or only through introducing additional reinforcement. In the matter of control, the quality of the robot as a precise positioning tool was exploited. Facilitated by computation, the robotic process allowed for the explicit control over the position of every single brick within an automated assembly procedure, which significantly widens the design space, and enables the fabrication of highly articulated brickwork. Different design strategies to inform the brickwork and manipulate the control code were introduced. These included abstracted notation methods describing the sequential assembly steps, image mapping, as well as rule-based systems that act on an input surface.

The combined result of the experiments is a novel robotic-based production method for facing brickwork that directly integrates architectural design with the physical assembly process, enabling the automated production of bespoke brickwork.

6.1 Implications and contributions

Instead of introducing robotic systems to optimise productivity, this research presents robots as an epistemic tool for design exploration. The suggested approach is thereby thought to contribute to the ongoing discussion on the potential role of robotics in architecture and design. Given that the dissemination of robotics in the architectural domain has occurred only relatively recent and to large part is still on an experimental level, their nature and benefit related to architecture and design is not yet answered.

Rather, a similar effect like Kathryn Henderson formulated for the spreading of CAD software for professional engineering is witnessed. She argues that in their emerging phase new tools of high technology are often mystified beyond their capabilities and functions, but mainly appreciated for their status.[256] On a similar note Antoine Picon sees one of the main current functions of robots in “their supporting part in a narrative regarding the future of architectural discipline and the rising importance of automated fabrication.”[257] He continues, to rightly point out that the automation of building processes is not a new phenomenon, and that adapting architecture to the new conditions of industrialisation and the machine age has been a constant subject of interest throughout the 20th century.[258]

However, his thesis has made evident that engaging with robotic assembly processes has some novel implications. In identifying industrial robots as both a *prosthetic* and an *abstract* tool, robots can overcome mere automation and enter architecture. Both aspects of the robot are programmable and can thus be authored by the designer: On the one hand, through physical tooling, and on the other hand, through computation. This enables the bi-directional aligning of conceptual intentions of a design and the engineering of an assembly process. Ultimately, a design is developed in describing the necessary sequential steps for its realisation. This establishes a new craft-based design paradigm, where robotic assembly is an integrated part of architectural design thinking. Despite applying abstract notation in the form of control code and automated machinery for production, this approach differs from the former paradigm of industrialisation such that it allows for the automated fabrication of bespoke assemblies. In this respect craft is understood as a process, where the conception of a design and the transfer to a physical artefact are in combined control of one person.[259] However, personal knowledge and aptitude is not introduced in execution of the fabrication process, but at the level of designing a custom robotic assembly process and the code controlling the robot respectively. This opens the possibility to follow physical processes outside common standards, and it is exactly here, where the potential for an architectural “otherness”[260] lies.

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[256] See K. Henderson, *On line and on paper visual representations, visual culture, and computer graphics in design engineering*, 189.

[257] A. Picon, “Robots and Architecture: Experiments, Fiction, Epistemology,” 57.

[258] Ibid.

[259] See T. Bonwetsch, F. Gramazio, and M. Kohler, “Digitales Handwerk – Digital Craft.”

[260] The term “otherness” is introduced by Antoine Picon, describing the specific input of the robot, which to date might still be too early to clearly define, but what is distinctively different from traditional, human guided practice. See A. Picon, “Robots and Architecture: Experiments, Fiction, Epistemology.”

Here, on can also draw a comparison to what David Pye refers to the “workmanship of risk”, when discussing manual craft work. The term describes a process, where the outcome of is not predetermined, but dependent on the continuing control of the maker during execution. This is imposed by “workmanship of certainty”, where the result is unalterable defined once the process starts. The latter defines automated manufacturing processes. Individuality and diversity of the products that are connected with it is not a quality in itself. But for Pye a condition that possibly can create meaning. D. Pye, *The nature and art of workmanship* (Cambridge: Cambridge University Press, 1968).

6.1.1 Bespoke robotic brickwork assemblies

Describing brickwork as the process of its assembly has central implications on brickwork design. On the one hand, design is combined with fabrication thinking. The robot allows for the explicit control of each individual step within the assembly process. Synchronised with the design, this entails that brickwork is developed out of the logic of its material, construction principles, and the tools applied. Conceptual design and practical realisation are no longer sequential phases, as the data set that describes a formal shape is identical to the code off its making. Therefore, the design process is based on material and fabrication knowledge, where function and form are negotiated in an informed assembly process. In this case, form is primarily not geometry-centred, but derived from material and assembly logics.

Such a design process brings about a shift in the function of drawing within the process, since design development does not happen on the basis of the representation of a final form, but at the level of defining and manipulating an assembly process, respectively the control code of the robot. Moreover, the code can be permeated with information describing various dependencies, as well as it can describe the necessary sequential assembly steps, which, again, can hardly be captured in a static drawing.

Further, the non-standard brickwork designs realised in the experiments cannot be conceived in a two-dimensional planning process. Assembly is a process in space and the robotic arm can position a brick in six-degrees of freedom. Therefore, an assembly-based design process fosters truly spatial design thinking. Although in general the assembly of brickwork is a layered process and bound to gravity, the robotic process forces to think about each bricks position and rotation in space, as well as their dependencies.

Finally, the combination of the computational power at hand and a robot that can perform an arbitrary number of highly precise movements and material manipulations, empowers architects to intervene at the level of the smallest constituent element of an additive construction. Thereby, a high level of differentiation can be introduced. Instead of creating exceptions, varying functional and aesthetic aspects, such as, for example, structural stability, transparency, acoustics, and adaptation to site-specific parameters, can be synthetically integrated into a building element without neglecting overall coherence.

6.1.2 Robotically assembled brickwork technology

There have been several attempts to apply robots to the assembly of brickwork. These were focused on mechanising the manual bricklaying process and solving problems of automation. The main motivation behind these efforts was to increase productivity of standard brickwork, while the added design potential arising from a digitally controlled construction process were neglected. Further, relying on task specific robots, the flexibility inherent to robotic systems was lost, drastically narrowing the potential design space. Merely mimicking an existing process might be insufficient to affect a revision in common building practice, and so far none of these attempts could establish itself in the building industry.

This research presents an integrated design and robotic assembly process for brickwork that extends the spectrum of architectural planning and manufacturing methods and therefore creates a new level of robotic use in architecture. Thereby, it combines benefits of automation, like repeatability and consistent quality, with the characteristics of bespoke production, like variation and diversity. In an automated process it allows for realising unique brickwork featuring manifold geometries, three-dimensional effects, and patterns. The robotically assembled brickwork technology combines 1) a robotic fabrication process, 2) a material and construction technology, and 3) design and planning strategies.

The robotic fabrication process is based on an articulated arm robot equipped with a specific gripper tool and an external gluing station. Thereby it can perform the basic process of bricklaying, picking a brick, applying a binding material for joining and placing the brick in its final position. Within experiment 3, this set-up was extended towards a mobile fabrication cell, the *ROB Unit*. Apart from manufacturing in a controlled factory environment, the unit can be moved directly on to the construction site and perform on-site prefabrication tasks. Thus, taking advantage of working with local material, short transportation routes, and just-in-time production on the building site. The material and construction technology relies on a high performance glue connection between the bricks that substitutes traditional mortar joints. The connection is able to take tension forces, which accounts for several advantages: there is no need for structural support in the form of additional steel reinforcement, it entails the possibility to create more complex wall shapes, and it enables lifting and transportation with no need for lintels. Further, the robotic process and connection technology is compatible with standard bricks, allowing manual intervention if necessary.

In order to utilise the potential of the robotic process, its parameters have to be incorporated already at the stage of the architectural design. This crucial aspect has been neglected by previous robotic brickwork scenarios. But only thereby, can the design space spanned by the robotic assembly process be fully exploited. Instead of conventionally representing a brick wall through defining its outer boundaries, a model depicting each individual brick is needed. Since the amount of bricks soon exceeds a critical mass, computational methods are necessary to enable an intentional control and manipulation of the bricks. The experiments introduce several design strategies for robotically assembled brickwork, ranging from descriptive methods that explicitly list the sequential fabrication steps, to the mapping of images on a brickwork façade.

Further, the design software *ROB Creator* is introduced. Integrating design strategies developed throughout the experiments, the software is a first attempt towards an integral design tool for robotic assembly processes of brickwork (Figure 69).[261]

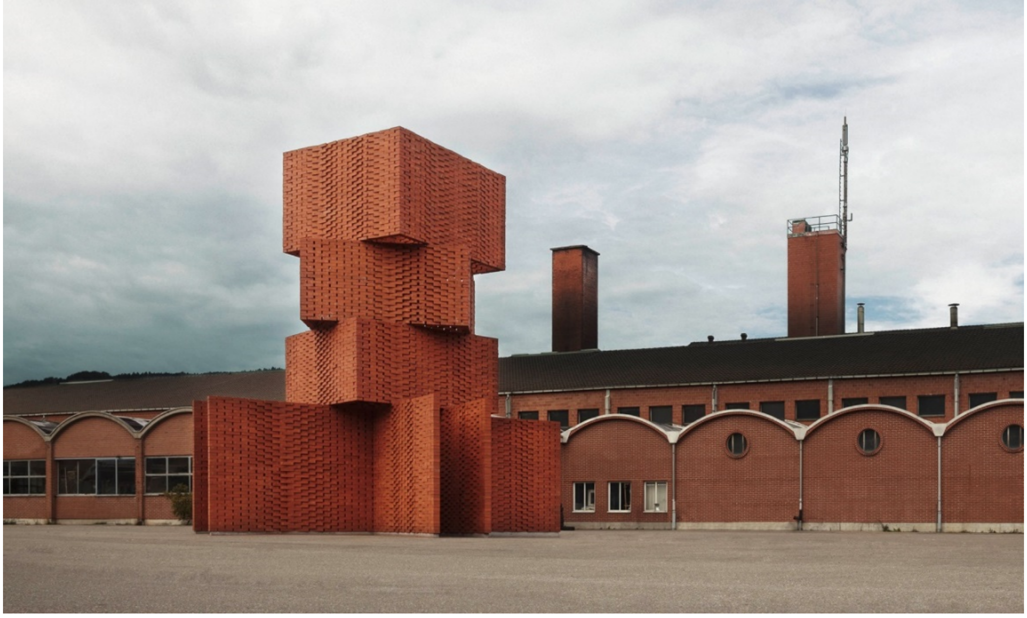

Figure 69.Gulliver, Kerim Seiler, 2009: The sculpture was designed applying the software ROB Creator and realised with the robotic assembly process presented in this thesis.

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[261] At the time of writing, the robotically assembled brickwork technology has been further developed and has evolved to a commercially available product, which is distributed by Keller AG Ziegeleien, see http://www.robmade.com/en/home/ (accessed April 15, 2015)
Several projects have already been realised that, combined with the results of the experiments within this research, indicate the versatility and architectural potential of the proposed process. Major further development steps occurred on part of the design software: *BrickDesign* is the result of addressing both limitations of common CAD-Software and the previous tool *ROB Creator*. The software tool allows for a creative control of a large number of units in order to foster a systemic, unifying planning process, thereby allowing exploring design solutions outside the commonly known standards. See T. Bonwetsch, R. Baertschi, and M. Helmreich, "BrickDesign: A software for planning robotically controlled non-standard brick assemblies."

6.2 Future challenges and research

6.2.1 Expanding robotically assembled brickwork

This thesis propagates a new use of robotics in the assembly of non-standard brickwork and reveals its characteristics and architectural implications. However, within its scope, these cannot be investigated exhaustively. The robotic assembly technology, the brickwork system, and corresponding design criteria were developed to such an extent that allowed the application within a real-world architectural context. Nevertheless, especially the design implications of robotically assembled brickwork and the yielding results cannot be extensively covered over the course of three experiments. Therefore, further research is required to deepen and extend the findings. It has been made clear, that these investigations can only be conducted in combination with physical applications. Already the presented experiments, have revealed the unique versatility of the seemingly simple brick unit. It is expected that with the described robotic assembly process further surprising and unforeseen brickwork solutions will emerge (Figure 70).

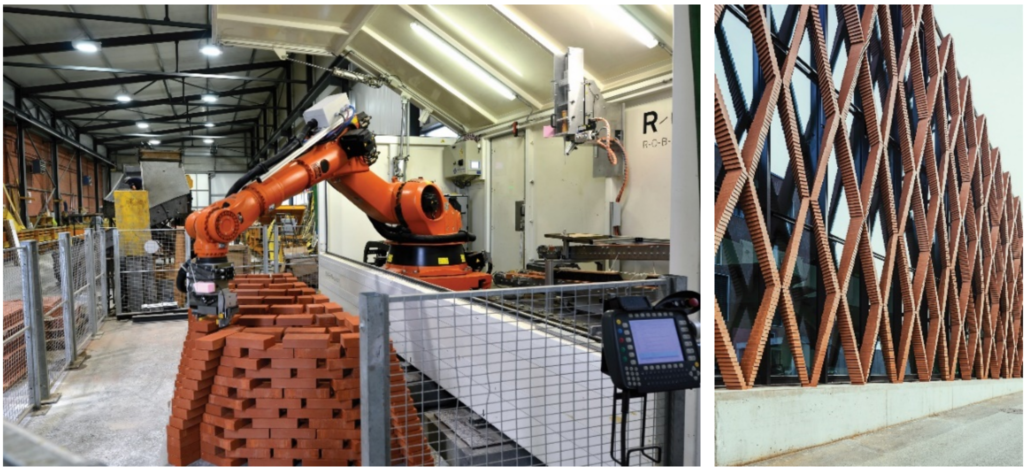

Figure 70. Gramazio & Kohler Architects, Façade Ofenhalle, Pfungen, 2012: (left) robotic assembly process of façade members; (right) installed façade.

In terms of the applied design strategies, it has been laid out that the assembly code can be permeated with various information. Here, especially the structural behaviour of the glued brickwork is of interest. So far, this could only be integrated on a minimal level, based on empirical findings. For future work, it would be of specific interest to introduce a factual structural model of the brickwork to inform the design. This would allow to fully explore the limits of the brickwork's structural capacity in relation its spatial configuration. Further, it could inform the assembly process on the necessity of providing additional support structure, since a stable equilibrium of the brickwork structure has to be guaranteed also during build-up. Additionally, a deepened knowledge and understanding of the structural behaviour of glued brickwork is necessary, in order to expand the current codes and standards with the proposed glued brickwork system. At present these do not provide for accommodating tension forces by the means of adhesive, and therefore proves to be a barrier for wider application of robotic assembly technology in the building industry.

Further, a worthwhile future development step would be to integrate additional sensory information into the robotic assembly process, allowing the robot to assess the outcome of its actions. In the experiments, the final assembly sequence performed by the robot is deterministic. Therefore, the robot, for instance, cannot react on the dimensional tolerances of the bricks used, which might result in the loss of height information or the complete assembly to become unstable. Integrating feedback would allow reacting on such unpredictable stages of assembly during the fabrication process. This would also have a fundamental implication on brickwork design that, instead of designing a predetermined result, rulesets for an adaptive behaviours of the robot could be described.

In terms of the fabrication technology, research in alternative adhesive solutions would be of particular interest. While the structural performance of the applied adhesive is more than sufficient, it exhibits a relatively long curing time of up to twelve hours until the brickwork elements can be safely handled and up to seven days until it reaches its maximum tensile strength. A faster curing time would not only allow for a more economic overall production, shortening time between assembly and installation, but could in many cases eliminate the need for support structure during build-up. An adhesive that would reach its full structural capacity shortly after a brick is positioned, would foster completely new spatial brickwork designs. At the same time, considering the issue of tolerances, an adhesive featuring filler material could compensate the imprecisions of the bricks.

6.2.2 Enhanced software tools combining robotic set-up and design

The experiments conducted within this research imply that new robotic fabrication processes demand new design tools. In order to fully exploit the potentials inherent to a fabrication process, its parameters have to be made available at an early design stage. Thereby, parameters of fabrication can inform the process of design exploration.

The software tools developed for the demonstrators of the experiments are highly project-specific and cannot be readily generalised on a more abstract level, in order to address a broader scope of design exploration. The web-based software *ROB Creator* has been a first attempt for a design tool. However, its application is limited to brickwork and the design space is constrained.

Thus, there is a need for design tools that represent abstract and more general aspects of robotic assembly processes, like simulation concepts of a sequential build up process and the handling and manipulation of a large amount of members without relating to a specific construction process. Therefore, in order to facilitate this connection, the goal would be a design environment that, on the one hand, aids in setting up, controlling, and simulating robotic assembly processes and, on the other hand, makes the specific parameters of fabrication available in the design process. This gains even more importance once feedback and real-time decision-making processes are integrated into the assembly process.

Robot manufacturers, as well as third-parties provide offline programming environments that can simulate robotic processes.[262] However, these would need to be coupled with the design environment, in order for the robotic set-up and design to bi-directionally inform one another.[263]

6.2.3 Prefabrication versus in situ construction

This research defines industrial robots primarily as a tool for assembly, which as such is predestined to be applied to construction work, which to a large extend is composed out of assembly tasks. Also, it emphasises the systematic difference in designing assemblies versus designing components. However, the experiments as well as the developed robotic assembly process for brickwork are applied to the prefabrication of architectural elements, which need to be transported and assembled to a larger whole on site. In the scope of this thesis, this allowed concentrating on the basic correlation of a robotic assembly process and architectural design. While prefabrication holds some advantages, like a more consistent and higher quality due to a controlled fabrication environment, a better control of work and faster on-site construction (working in situ) reduces transportation costs and allows for greater flexibility and adaptability to site-specific and un-modelled situations. Moreover, not all structures can be prefabricated, due to size limitations of transportation. Additionally, the necessary measures in order to make such structures transportable can become unjustifiably costly.

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[262] Examples are ABB's offline programming environment *RobotStudio* (http://new.abb.com/products/robotics/robotstudio; accessed April 15, 2015), or KUKA's *KUKA.sim* software (www.kuka-robotics.com/en/products/software/kuka_sim; accessed April 15, 2015).

[263] One attempt in this direction is the software HAL, which integrates the control of ABB robots into CAD programme Rhinoceros. See T. Schwartz, "HAL: Extension of a visual programming language to support teaching and research on robotics applied to construction," in *first international conference on robotic fabrication in architecture, art, and design, Rob|Arch*, ed. S. Brell-Cokcan and J. Braumann (Vienna: Springer, 2012).

Therefore, a worthwhile next step would be to move to the construction site and apply robotic processes in-situ. Whereas in the experiments the size of the assembled artefacts where limited to the kinematic range of the robotic set-up, it would be interesting to investigate the impact of robotic assembly processes on a larger scale. This entails that the robotic system must be able to manoeuvre to different working positions and technical aspects of localisation and tolerance handling, as well as issues of material flow would have to be solved. Further, questions of man-machine cooperation gain importance, since many automation solutions can be simplified through integrating human sensory information. Here, a lot can be learned from the predecessors of robotics in construction of the 1990s, which were primarily concerned with automating on-site work. Though, these where very much constrained to the processes they could perform and still relied on a more or less structured working environment.

A more interesting approach, especially regarding a potential design impact, seems to be the investigation of adaptable systems that can handle continuous change and unpredictable events common to a construction site. Comparable to manual craft work on-site, one could envision a robotic process that reacts on a given situation and adapts its process during build-up. A step into this direction is taken with the *DimROB* project.[264]

Ultimately, the robot could generate a design in the process of assembly, deliberately embracing errors and tolerances and re-adapting its strategy after every fabrication step governed by a rule based system.[265]

6.2.4 Robotic assembly processes in architecture

The application of an integrated design and robotic assembly processes is limited to brickwork within the scope of this thesis. Compared to other construction processes, the implementation of a robotic brickwork process can be regarded more easily manageable, due to a limited amount of control parameters. Though, concentrating on brickwork has been a deliberate choice as it allows investigating the fundamental implications of an integrated design and robotic assembly process in a real-world scale – without having to solve over complex problems of automation. As such, it served as a proof-of-concept that robotic assembly processes can indeed reveal latent qualities in constructive systems.

Research on robotically assembled timber construction indicates that certain findings can be transferred, as for instance the potential to interweave different functional

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[264] V. Helm, “In-situ-Fabrikation: Neue Potenziale roboterbasierter Bauprozesse auf der Baustelle.”

[265] A framework for an *Evolutionary Fabrication* is formulated by J. Rieffel, “Evolutionary Fabrication: The Co-Evolution of Form and Formation.”

properties,[266] but further experiments should be carried out that explore the impact of robotic assembly processes on a variety of different constructive systems.

Therefore, it is also too early to predict if robotic assembly processes will prevail in the building industry. One has to be cautious with prophecies on the future of building of any kind, especially recapitulating cultural influences and the specific structure of the industry, as well as the experiences of previous efforts on introducing robotics to construction. Nevertheless, robotic systems have become much more accessible. Most likely, robotic solutions will not eliminate other modes of production, but complement them, by enabling adaptive building processes, which enrich the spectrum of constructive and architectural solutions. The example of brickwork in this research indicates that robotic solutions will be adopted, where the digital control of the process gains advantage over a manual executed process and where this advantage becomes design relevant.

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[266] J. Willmann et al., "Robotic timber construction — Expanding additive fabrication to new dimensions," *Automation in Construction* 61 (2016).

BIBLIOGRAPHY

S. Allen. *Practice architecture, technique + presentation*. Expanded 2nd ed. Abingdon: Routledge, 2009.

F. Altobelli, H. F. Taylor, and L. E. Bernold. “Prototype Robotic Masonry System.” *Journal of Aerospace Engineering* 6, no. 1 (1993): 19-33.

J. Andres, T. Bock, and F. Gebhart. “First results of the development of the masonry robot system ROCCO: a Fault Tolerant Assembly Tool.” In *11th ISARC International Symposium on Automation and Robotics in Construction*, 87-93. Brighton, England, 1994.

F. J. Anliker. “Needs for robots and advanced machines at construction sites. Social aspects of robotics.” In *5th International Symposium on Automation and Robotics in Construction*, 145–50. Tokyo, Japan, 1988.

H. Asada, and T. Kanade. “Design of Direct-Drive Mechanical Arms.” *Journal of Vibration, Acoustics Stress and Reliability in Design* 105, no. 3 (1983): 312-16.

I. Asimov. *I, Robot*. London: Panther Books, 1968.

R. Baertschi, M. Knauss, T. Bonwetsch, F. Gramazio, and M. Kohler. “Wiggled Brick Bond.” In *Advances in Architectural Geometry*, edited by C. Ceccato, L. Hesselgren, M. Pauly, H. Pottmann and J. Wallner, 137-48. Wien: Springer, 2010.

C. Balaguer. “Soft robotics concept in construction industry.” In *World Automation Congress*, 2004., 517-22. Seville, 2004.

C. Balaguer, and M. Abderrahim. “Trends in Robotics and Automation in Construction.” In *Robotics and Automation in Construction*, edited by C. Balaguer and M. Abderrahim, 1-20: In-Teh, 2008.

C. Balaguer, M. Abderrahim, J. M. Navarro, S. Boudjabeur, P. Aromaa, K. Kahkonen, S. Slavenburg, *et al.* “FutureHome: An integrated construction automation approach.” *Robotics & Automation Magazine, IEEE* 9, no. 1 (2002): 55-66.

J. Barlow, and R. Ozaki. “Achieving Customer Focus in Private Housebuilding: Current Practice and Lessons from Other Industries.” *Housing Studies* 18 (2003): 87-101.

V. Bearth, A. Deplazes, and D. Ladner. *Amurs 18 ausgewählte Arbeiten von Bearth & Deplazes Architekten*. Zurich: gta, 2013.

M. Bechthold. “The Return of the Future: A Second Go at Robotic Construction.” *Architectural Design* 80, no. 4 (2010): 116-21.

W. H. Behse. *Der Maurer eine umfassende Darstellung der sämtlichen Maurerarbeiten*. Klassische Lehr- und Vorlagenbücher für den Praktiker. Vol. 13, Hannover: Th. Schäfer, 1996. Reprint of original edition from 1902.

W. Belz. *Mauerwerk Atlas*. 3rd ed. München: Institut für internationale Architektur-Dokumentation, 1993.

W. Bender. “Popular errors in the history of brickmaking technology.” *zi Ziegelindustrie International - Brick and Tile Industry International* 59, no. 12 (2006): 14-21.

G. Biggs, and B. Macdonald. “A survey of robot programming systems.” Paper presented at the Australasian Conference on Robotics and Automation, Brisbane, Australia, December 1-3 2003.

P. Blundell Jones. “Sigurd Lewerentz: Church of St Peter, Klippan, 1963–66.” *arq: Architectural Research Quarterly* 6, no. 02 (2002): 159-73.

T. Bock. “Automatisierung und Robotik im Bauen.” In *Wendepunkt(e) im Bauen - Von der seriellen zur digitalen Architektur*, edited by W. Nerdinger, 46-55. München: Edition Detail, 2010.

T. Bock. “The Integrated Project ManuBuild of the EU.” Paper presented at the 23rd International Symposium on Robotics in Construction (ISARC), Tokyo, Japan, 2006.

T. Bock. “Robot-oriented design.” Paper presented at the 5th International Symposium on Robotics in Construction, Tokyo, Japan, June 6-8 1988.

T. Bock. “Robot Oriented Design.” *Architectural Product Engineering* (1988).

T. Bock, and S. Langenberg. “Changing Building Sites: Industrialisation and Automation of the Building Process.” *Architectural Design* 84, no. 3 (2014): 88-99.

T. Bock, D. Stricker, J. Fliedner, and T. Huynh. "Automatic generation of the controlling-system for a wall construction robot." *Automation in Construction* 5, no. 1 (1996): 15-21.

T. Bonwetsch, R. Baertschi, and M. Helmreich. "BrickDesign: A software for planning robotically controlled non-standard brick assemblies." In *first international conference on robotic fabrication in architecture, art, and design, Rob|Arch*, edited by S. Brell-Cokcan and J. Braumann, 102-09. Vienna: Springer, 2012.

T. Bonwetsch, F. Gramazio, and M. Kohler. "Digitales Handwerk - Digital Craft." *Graz Architecture Magazine* 6 (2010): 172-79.

S. Brell-Cokcan, and J. Braumann, eds. *Rob|Arch 2012: Robotic Fabrication in Architecture, Art and Design*. Vienna: Springer, 2013.

T. Brogårdh. "Present and future robot control development—An industrial perspective." *Annual Reviews in Control* 31, no. 1 (2007): 69-79.

M. Cabrinha, J. Johnson, and K. Steinfeld, eds. *ACADIA 12: Synthetic Digital Ecologies*, 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). San Francisco, 2012.

N. Callicott. *Computer-aided manufacture in architecture the pursuit of novelty*. Oxford: Architectuaral Press, 2001.

M. Campbell-Kelly, and W. Aspray. *Computer: a history of the information machine*. 2nd ed.: Westview Press, 2004.

J. W. P. Campbell, and W. Pryce. *Brick: A World History*. Thames & Hudson, 2003.

K. Čapek. *R.U.R. - Rossum's Universal Robots*. Adelaide: University of Adelaide, 2014. http://ebooks.adelaide.edu.au/c/capek/karel/rur/index.html, (accessed April 15, 2015).

M. Carpo. *The alphabet and the algorithm*. Writing architecture. Cambridge, Mass.: MIT Press, 2011.

M. Carpo. "Tempest in a Teapot." *Log*, no. 6 (2005): 99-106.

A. Cavieres, R. Gentry, and T. Al-Haddad. "Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis." *Automation in Construction* 20, no. 6 (2011): 716-28.

D. Chamberlain, P. Speare, and S. Ala. "Progress in a masonry tasking robot." In *8th Int. Symposium on Automation and Robotics in Construction*, 3–5 June 1991. Stuttgart, Germany, 1991.

R. Clarke. "Asimov's laws of robotics: implications for information technology-Part I." *Computer* 26, no. 12 (1993): 53-61.

R. Clarke. "Asimov's laws of robotics: Implications for information technology. 2." *Computer* 27, no. 1 (1994): 57-66.

L. Cousineau, and N. Miura. *Construction robots : the search for new building technology in Japan*. Reston, Va.: ACSE Press, 1998.

M. Dalacker. *Entwurf und Erprobung eines mobilen Roboters zur automatisierten Erstellung von Mauerwerk auf der Baustelle*. Schriftenreihe: Planung, Technologie, Management und Automatisierung im Bauwesen. edited by T. Bock. Vol. 1, Stuttgart: Fraunhofer IRB Verlag, 1997.

C. Davies. *The Prefabricated Home*. London: Reaktion Books, 2005.

A. Deplazes. *Constructing Architecture materials - processes - structures a handbook*. Basel: Birkhäuser, 2005.

G. C. Devol. "Programmed Article Transfer." edited by U. S. P. Office, 13. United States, 1954.

G. Drees, G. Pritschow, M. Dalacker, J. Kurz, and R. Töpfer. "Steuerungssystem für einen mobilen Roboter für Mauerwerk." *BMT. Baumaschine + Bautechnik*, no. 3 (1993): 157-61.

J. F. Engelberger. "Historical Perspective and Role in Automation." In *Handbook of Industrial Robotics (Second Edition)*, edited by Y. N. Shimon, 3-10. New York: Wiley, 1999.

R. Evans. "Translations from drawing to building." In *Translations from drawing to building and other essays*. AA Documents, 153-93. London: Architectural Association, 1997.

C. Fitzgerald. "Developing baxter." Paper presented at the IEEE Conference on Technologies for Practical Robot Applications (TePRA), 22-23 April 2013 2013.

M. Fleischmann, and A. Menges. "ICD/ITKE Research Pavilion: A case study of multi-disciplinary computational design." In *Computational Design Modeling*, edited by C. Gengnagel, A. Kilian, N. Palz and F. Scheurer, 239-48. Berlin: Springer-Verlag, Berlin/Heidelberg, 2011.

R. Foque. *Building Knowledge in Architecture Case Studies*. ASP Vub Press, 2010.

N. Fukuhara, A. Shiga, J. Hashimoto, H. Yasuda, M. Nakajima, and Y. Norinaga. "Development of a robot system for large assembly welding of steel columns." *Welding International* 6, no. 10 (1992): 827-30.

E. Gambao, C. Balaguer, and F. Gebhart. "Robot assembly system for computer-integrated construction." *Automation in Construction* 9, no. 5-6 (September 2000 2000): 479-87.

D. M. Gann. *Building innovation complex constructions in a changing world*. London: Telford, 2000.

E. Garcia, M. A. Jimenez, P. G. De Santos, and M. Armada. “The evolution of robotics research.” *Robotics & Automation Magazine, IEEE* 14, no. 1 (2007): 90-103.

F. v. Gassel, and G. Maas. “Mechanising, Robotising and Automating Constrcution Processes.” In *Robotics and Automation in Construction*, edited by C. Balaguer and M. Abderrahim, 43-52: In-Teh, 2008.

R. Geiser, ed. *Explorations in Architecture, Teaching, Design, Research*. Basel: Birkhäuser, 2008.

D. Gerber, A. Huang, and J. Sanchez, eds. *ACADIA 2014 Design Agency*, 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). Los Angeles, 2014.

J. H. Gleiter. “Das Digital-Erhabene.” Neue Zürcher Zeitung, June 1 2013, 64.

F. Gramazio, and M. Kohler. *Digital Materiality in Architecture*. Baden: Lars Müller Publishers, 2008.

F. Gramazio, M. Kohler, and S. Langenberg, eds. *Fabricate: negotiating design & making*. Zurich: gta-Verlag, 2014.

F. Gramazio, M. Kohler, and J. Willmann, eds. *THE ROBOTIC TOUCH - How Robots Change Architecture.* Zurich: Park Books, 2014.

F. Gramazio, M. Kohler, and J. Willmann. “Towards an Extended Performative Materiality – Interactive Complexity and the Control of Space.” In *Theories of the Digital in Architecture*, edited by R. Oxman and R. Oxman. London: Routledge, 2014.

S. Groák. *The idea of building: Thought and action in the design and production of buildings*. London: E & FN Spon, 1992.

N. Hack, W. V. Lauer, F. Gramazio, M. Kohler, and S. Langenberg. “Mesh-Mould: Robotically Fabricated Spatial Meshes as Concrete Formwork and Reinforcement.” In *Fabricate: Negotiating Design & Making*, edited by F. Gramazio, M. Kohler and S. Langenberg, 224-31. Zurich: gta-Verlag, 2014.

M. Hägele, K. Nilsson, and J. N. Pires. “Industrial Robotics.” In *Springer Handbook of Robotics*, edited by B. Siciliano and O. Khatib, 963-86. Berlin, 2008.

T. Haigh. “The chromium-plated tabulator: institutionalizing an electronic revolution, 1954-1958.” *Annals of the History of Computing, IEEE* 23, no. 4 (2001): 75-104.

K. Hamada, N. Furuya, Y. Inoue, and T. Wakisaka. “Development of automated construction system for high-rise reinforced concrete buildings.” In *IEEE International Conference on Robotics and Automation*, 2428-33. Leuven, 1998.

R. Harris, and M. Buzzelli. “House Building in the Machine Age, 1920s–1970s: Realities and Perceptions of Modernisation in North America and Australia.” *Business History* 47, no. 1 (2005): 59 - 85.

Y. Hasegawa. “A new Wave of Construction Automation and Robotics in Japan.” Paper presented at the 17th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 2000.

G. S. Hegde. *A Texbook of Industrial Robotics*. Laxmi Publications, 2006.

V. Helm. “In-situ-Fabrikation: Neue Potenziale roboterbasierter Bauprozesse auf der Baustelle.” PhD, Academy of Media Arts Cologne, 2015.

V. Helm, S. Ercan, F. Gramazio, and M. Kohler. “In-Situ Robotic Construction: Extending the Digital Fabrication Chain in Architecture.” In *Synthetic Digital Ecologies: Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, edited by J. K. Johnson, M. Cabrinha and K. Steinfeld, 169-76. San Francisco, 2012.

K. Henderson. *On line and on paper visual representations, visual culture, and computer graphics in design engineering.* Inside technology. Cambridge: MIT Press, 1999.

F. Herkommer, and B. Bley. “CAD/CAM for the prefabrication of brickwork.” *Automation in Construction* 4, no. 4 (1996): 321-29.

J. Hill. “Building the Drawing.” *Architectural Design* 75, no. 4 (2005): 13-21.

G. Hirzinger, N. Sporer, A. Albu-Schaffer, M. Hahnle, R. Krenn, A. Pascucci, and M. Schedl. “DLR’s torque-controlled light weight robot III-are we reaching the technological limits now?” Paper presented at the IEEE International Conference on Robotics and Automation, 2002.

D. Hoffmann-Axthelm. “Der Mauerziegel: Eine Faszination und ihr Objekt.” *ARCH+*, no. 84 (01.03. 1986): 58-61.

A. Hoffmann, A. Angerer, F. Ortmeier, M. Vistein, and W. Reif. “Hiding real-time: A new approach for the software development of industrial robots.” Paper presented at the IROS 2009. IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, 10-15 Oct. 2009.

I. B. Holley, Jr. “The Mechanization of Brickmaking.” *Technology and Culture* 50, no. 1 (2009): 82-102.

A. S. Howe. “Designing for automated construction.” *Automation in Construction* 9, no. 3 (2000): 259-76.

International Federation of Robotics. “World Robotics 2014 Industrial Robots.” Frankfurt am Main: International Federation of Robotics (IRF), 2014.

L. Iwamoto. *Digital Fabrications - Architectural and Material Techniques*. Architecture Briefs. New York: Princeton Architectural Press, 2009.

W. Jäger. *Mauerwerk-Kalender*. 38th ed. Berlin: Ernst & Sohn, 2013.

A. Janik. “Tacit Knowledge, Working Life and Scientific Method.” Chap. 6 In *Knowledge, Skill and Artificial Intelligence*, edited by B. Göranzon and I. Josefson. The Springer Series on Foundations and Applications of Artificial Intelligence, 53-63. London: Springer, 1988.

H. Janssen, W. Desadeleer, B. Blocken, and J. Carmeliet. “Rain penetration through thin layer mortar brick façade with open vertical joints.” Paper presented at the 13th International Brick and Block Masonry Conference, Amsterdam, 4-7 July 2004.

F. Jesus, and K. Utsav. “Unit Labor Costs in the Eurozone: The Competitiveness Debate Again.” Annandale-on-Hudson: Levy Economics Institute, 2011.

Y. Kajioka, and T. Fujimori. “Automating Concrete Work in Japan.” *Concrete International* 12, no. 6 (1990): 27-32.

R. Kangari, and T. Yoshida. “Prototype Robotics in Construction Industry.” *Journal of Construction Engineering and Management* 115, no. 2 (1989): 284-301.

“Kein Ersatz für den Maurer.” *Baublatt* 117, no. 96 (01.12. 2006): 14-15.

Keller Holding AG. “Produktedeklaration der Werke Frick und Paradies nach EN 771-1:2011.” 2014. (available online: http://www.keller-systeme.ch/bdata/files/_file_itemFile_bdataFileExt/10132_CE_Deklaration_September_14.pdf; accessed April 15, 2015)

Keller Systeme AG, “Prefabricated ceramic wall and facade elements.” KOMO certificate no. K75618/02, Netherlands: Kiwa, 2014.

S. Kieran, and J. Timberlake. *Refabricating architecture how manufacturing methodologies are poised to transform building construction*. New York: McGraw-Hill Companies, 2004.

K. Kikuchi, S. Furuta, and T. Imai. “Development and the result of practical works of concrete floor finishing robot.” In *5th International Symposium on Robotics in Construction (ISARC)*, 561-70. Tokyo, Japan, 1988.

A. Kilian. “Design Exploration through Bidirectional Modeling of Constraints.” PhD, Massachusetts Institute of Technology, 2006.

W. Knight. “Smart Robots Can Now Work Right Next to Auto Workers.” MIT Technology Review, http://www.technologyreview.com/news/518661/smart-robots-can-now-work-right-next-to-auto-workers/, (accessed April 15, 2015).

A. Kochan. “Robots help out with bricks.” *Industrial Robot: An International Journal* 24, no. 2 (1997): 149-51.

Y. Kodama, Y. Yamazaki, H. Kato, Y.Iguchi, and H. Naoi. “A robotized wall erection system with solid components.” In *5th International Symposium on Robotics in Construction* Tokyo, Japan: Japan Industrial Robot Association (Jira), cop., 1988.

M. Kohler, F. Gramazio, and J. Willmann. “Die Oparationalität von Daten und Material im digitalen Zeitalter.” In *Positionen zur Zukunft des Bauens: Methoden, Ziele, Ausblicke*, edited by S. Hofmeister and C. Hellstern, 6-19. München: Edition DETAIL / Institut für int. Architektur-Dokumentation, 2011.

B. Kolarevic, ed. *Architecture in the Digital Age - Design and Manufacturing*. New York: Spon Press, 2003.

B. Kolarevic. “Designing and Manufacturing Architecture in the Digital Age.” *In Architectural Information Management, 19th eCAADe Conference Proceedings*, 117-23. Helsinki, 2001.

H. E. Kramel. *Backstein als Gestaltungselement*. Element. Zurich: Schweizerische Ziegelindustrie, 1984.

Kuka Roboter GmbH. “Technical Data: KR 150 - KR 150 L130 -KR 150 L110.” Germany: KUKA Roboter GmbH, 2000.

KUKA System Software 5.5 - Operating and Programming Instructions for System Integrators. Augsburg, Germany: KUKA Roboter GmbH, 2010.

S. Langenberg. "Geplante Gestaltung – Gebauter Prozess. Architektur der 1960er und 1970er Jahre." *Wolkenkuckucksheim* 13, no. 1 (May 2009). Accessed April 15, 2015. http://www.cloud-cuckoo.net/journal1996-2013/inhalt/de/heft/ausgaben/108/Langenberg/langenberg.php

J. Laukemper. *Automation im Mauerwerksbau: Voraussetzungen, Verfahren, Wirtschaftlichkeit*. Schriftenreihe des Instituts für Baubetriebslehre der Universität Stuttgart. edited by P. D.-I. G. Drees. Vol. 33, Stuttgart: expert Verlag, Böblingen, 1992.

H. Lehtinen, E. Salo, and H. Aalto. “Outlines of two masonry robot system.” In *Proceedings of the 6th International Symposium on Automation and Robotics in Construction*, 143–50. San Francisco, 1989.

W. Leyh. “Optimale Zustandsregelung von Montagerobotern im Hochbau.” PhD, Technical University Munich, 2000.

S. Li. *Entwicklung eines Verfahrens zur Automatisierung der CAD/CAM-Kette in der Einzelfertigung am Beispiel von Mauerwerksteinen*. Schriftenreihe des instituts für Angewandte Informatik/Automatisierungstechnik Universität Karlsruhe. Vol. 16, Karlsruhe2007.

E. Lloret, A. R. Shahab, M. Linus, R. J. Flatt, F. Gramazio, M. Kohler, and S. Langenberg. “Complex concrete structures: Merging existing casting techniques with digital fabrication.” *Computer-Aided Design* 60 (2015): 40-49.

G. Lynch. *Brickwork history, technology and practice*. Vol. 1, London: Donhead, 1994.

G. Lynch. *The History of Gauged Brickwork*. Butterworth-Heinemann series in Conservation and Museology. edited by A. Oddy Oxford: Butterworth-Heinemann, 2007.

G. C. J. Lynch. “Bricks: Properties and Classifications.” *Structural Survey* 12, no. 4 (1994): 15-20.

I. M Rocker. “Calculus-based form: an interview with Greg Lynn.” *Architectural Design* 76, no. 4 (2006): 88-95.

J. Maeda. “Development and Application of the SMART System.” In *Automation and Robotics in Construction Xi*, edited by D. A. Chamberlain, 457-64. Oxford: Elsevier, 1994.

H. Makino, and N. Furuya. “Selective Compliance Assembly Robot Arm (SCARA).” Paper presented at the 1st International Conference on Assembly Automation ICAA, Brighton, March 25-27 1980.

E. Malinovsky, E. A. Borschewski, E. A. Eler, and V. M. Pogodin. “A robotic complex for brick-laying applications.” In *7th International Symposium on Automation and Robotics in Construction* Bristol, England, 1990.

M. McCullough. *Abstracting craft the practiced digital hand*. Cambridge, Mass.: MIT Press, 1998.

W. McGee, and M. Ponce de Leon, eds. *Robotic Fabrication in Architecture, Art and Design 2014*: Springer International Publishing, 2014.

H. Miyakawa, J. Ochiai, K. Oohata, and T. Shiokawa. “Application of automated building construction system for high-rise office building.” Paper presented at the 17th International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 2000.

Y. Miyatake, Y. Yamazaki, and R. Kangari. “The SMART System Project: A Strategy for Management of Information and Automation Technology in Computer Integrated Construction.” Paper presented at the 1st International conference, Management of information technology for construction, Singapore, 1993.

General Polygon Clipper library Version 2.32.

K. Nanba, M. Takasu, T. Sato, and S. Kojima. “Development and application of the light weight manipulator for interior finish work.” Paper presented at the 13th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 1996.

NCC. “NCC Annual Report 2006.” Solna, Sweden, 2006.

NCC. “NCC Annual Report 2007.” Solna, Sweden, 2007.

J. Neelamkavil. “Automation in the Prefab and Modular Construction Industry.” In *The 26th International Symposium on Automation and Robotics in Construction (ISARC 2009)*, 299-306. Austin, 2009.

D. F. Noble. “Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor.” *Politics & Society* 8, no. 3-4 (September 1 1978): 313-47.

S. Y. Nof, and V. N. Rajan. “Robotics." In *Handbook of Design, Manufacturing and Automation*, 259-95: John Wiley & Sons, Inc., 1994.

S. Obayashi. “Problems and effects of automation and robotization.” Paper presented at the 9th Intnternational Symposium on Automation and Robotics in Construction, Tokyo, 6-8 June 1992.

J. Ochsendorf, and P. Block. “Designing unreinforced masonry.” Chap. 8 In *Form and Forces: Designing Efficient, Expressive Structures*, edited by E. Allen and W. Zalewski. New York: John Wiley & Sons, 2009.

J. Pallasmaa. “Hapticity and time: notes on fragile architecture.” *Architectural Review* 207, no. 1239 (May 2000): 78-84.

J. Pallasmaa. *The thinking hand existential and embodied wisdom in architecture*. Chichester: Wiley, 2009.

R. Pedreschi. *Eladio Dieste*. The engineer’s contribution to contemporary architecture. edited by A. Macdonald and R. Pedreschi London: Telford, 2000.

G. Pfeifer, R. Ramcke, J. Achtziger, and K. Zilch. *Mauerwerk Atlas*. 6th ed. Basel: Birkhäuser Verlag für Architektur, 2001.

D. T. Pham, and S. S. Dimov. “Rapid prototyping and rapid tooling—the key enablers for rapid manufacturing.” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 217, no. 1 (January 1, 2003): 1-23.

A. Picon. “Architecture and the virtual : Towards a new materiality?” *Praxis: Journal of Writing+Building*, no. 6 (2004): 114-21.

A. Picon. “Robots and Architecture: Experiments, Fiction, Epistemology.” *Architectural Design* 84, no. 3 (2014): 54-59.

J. N. Pires. *Industrial Robots Programming Building Applications for the Factories of the Future*. 1. Ed. ed. New York: Springer, 2007.

M. Polanyi. *Personal knowledge towards a post-critical philosophy*. Ed. 1962 ed. London: Routledge & Kegan Paul, 1962.

W. Poppy. “Driving forces and status of automation and robotics in construction in Europe.” *Automation in Construction* 2, no. 4 (1994): 281-89.

G. Pritschow, M. Dalacker, J. Kurz, and M. Gaenssle. “Technological aspects in the development of a mobile bricklaying robot.” *Automation in Construction* 5, no. 1 (1996): 3-14.

G. Pritschow, M. Dalacker, J. Kurz, and J. Zeiher. “A mobile robot for on-site construction of masonry.” In *IEEE/RSJ/ GI International Conference on Intelligent Robots and Systems (IROS)*, 1701-07. Munich, 1994.

D. Pye. *The nature and art of workmanship*. Cambridge: University Press, 1968.

J. Rieffel. “Evolutionary Fabrication: The Co-Evolution of Form and Formation.” PhD, Brandeis University, 2006.

R. A. Rihani, and L. E. Bernold. “Computer Integration for Robotic Masonry.” *Computer-Aided Civil and Infrastructure Engineering* 9, no. 1 (1994): 61-67.

Y. Rosenfeld, A. Warszawski, and U. Zajicek. “Full-scale building with interior finishing robot.” *Automation in Construction* 2, no. 3 (1993): 229-40.

S. Sakamoto. “Mechanical planning and actual test results of a robot for painting the exterior walls of high-rise buildings.” *Advanced Robotics* 5, no. 4 (1990): 457-66.

S. Sakamoto, and H. Mitsuoka. “Totally Mechanized Construction System for High-Rise Buildings (T-UP System).” In *Automation and Robotics in Construction Xi*, edited by D. A. Chamberlain, 465-72. Oxford: Elsevier, 1994.

M. T. Salim. “Bringing an old concept into the future: The Maeda MCCS Analysis.” Paper presented at the CIB IAARC W119, Munich, Germany, 24th October 2012.

V. D. Scheinman. “Design of a Computer Controlled Manipulator.” PhD, Stanford University, 1969.

F. Scheurer. “Architectural CAD/CAM - Pushing the Boundaries of CNC-Fabrication in Building.” In *Manufacturing Material Effects - Rethinking Design and Making in Architecture*, edited by B. Kolarevic and K. Klinger, 211-22. New York: Routledge, 2008.

C. Schindler. “Ein architektonisches Periodisierungsmodell anhand fertigungstechnischer Kriterien, dargestellt am Beispiel des Holzbaus.” PhD, ETH Zurich, 2009.

F. Schumacher. *Das Wesen des neuzeitlichen Backsteinbaues*. Reprint der Originalausgabe 1920 ed. München Callwey 1985: Callwey, 1920.

T. Schwartz. “HAL: Extension of a visual programming language to support teaching and research on robotics applied to construction.” In *first international conference on robotic fabrication in architecture, art, and design, Rob|Arch*, edited by S. Brell-Cokcan and J. Braumann, 92-101. Vienna: Springer, 2012.

G. Semper. *Der Stil in den technischen und tektonischen Kuensten, oder praktische Aesthetik*. 2 vols. Vol. 1, München: Bruckmann, 1860.

G. Semper. “Entwurf eines Systemes der vergleichenden Stillehre.” In *Kleine Schriften*, 259-91. Berlin & Stuttgart: Spemann, 1884.

M. Sharp, ed. *The Transformation of the Industry – Open Building Manufacturing*, Proceedings of the 1st International Conference. Rotterdam, 2007.

SIKA. “Product Data Sheet - Sikadur-30.” http://gbr.sika.com/en/solutions_products/document_download1/construction-downloads/structural_strengtheningpds.html, (accessed April 15, 2015).

SIKA. “Product Data Sheet - Sikadur-330.” http://gbr.sika.com/en/solutions_products/document_download1/construction-downloads/structural_strengtheningpds.html, (accessed April 15, 2015).

H. A. Simon. “Style in Design.” In *Second Annual Environmental Design Research Association Conference - EDRA TWO*, edited by J. Archea and C. Eastman, 1-10. Pittsburgh: Dowden, Hutchinson & Ross, Inc., 1970.

A. H. Slocum, and B. Schena. “Blockbot: A robot to automate construction of cement block walls.” *Robotics and Autonomous Systems* 4, no. 2 (1988): 111-29.

Statistisches Bundesamt. “Bauen und Wohnen - Baugenehmigungen von Wohn- und Nichtwohngebäuden nach überwiegend verwendetem Baustoff Lange Reihen ab 1980.” Wiesbaden: Statistisches Bundesamt, 2013.

Statistisches Bundesamt. “Produzierendes Gewerbe -Produktion des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden.” Wiesbaden: Statistisches Bundesamt, 2013.

German Institute for Standardization. “Clay masonry units - Part 100: Clay masonry units with specific properties.” DIN German Institute for Standardization, 2012.

International Organization for Standardization. “Robots and robotic devices - Vocabulary.” 2012.

R. Steinmetzger. “Neue Baumaschinen-Generationen mit Einsatz modernster Kommunikationstechnik.” Paper presented at the 2. Tag des Baubetriebs 2002, Bauhaus Universität Weimar, 2002.

J. Stenerson. *Fundamentals of programmable logic controllers, sensors, and communications*. Englewood Cliffs, New Jersey: Regents/Prentice Hall, 1993.

C. Syverson. “What Determines Productivity?” *Journal of Economic Literature* 49, no. 2 (2011): 326-65.

T.Honda, T.Okana, H.Nomura, T.Matsumoto, H.Wada, and Y.Yuzaki. “A material-handling system in the building site.” Paper presented at the 9th International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, Japan, 1992.

N. Tanaka, M. Saito, K. Arai, K. Banno, T. Ochi, and S. Kikuchi. “The Development of the ‘Mark II’ Mobile Robot for Concrete Slab Finishing.” Chap. 25 In *CAD and Robotics in Architecture and Construction*, 249-57. New York: Springer, 1986.

M. Taylor, S. Wamuziri, and I. Smith. “Automated construction in Japan.” *Proceedings of the ICE - Civil Engineering* 156 (2003): 34-41.

S. Terauchi, T. Miyajima, T. Miyamoto, K. Arai, and S. Takizawa. “Development of exterior wall painting robot capable of painting walls with indentations and protrusions.” Paper presented at the 10th International Symposium on Automation and Robotics in Construction (ISARC), Houston, 24-26 May 1993.

D. A. Turin. “Construction and development.” *Habitat International* 3, no. 1-2 (1978): 33-45.

A. M. Turing. “On Computable Numbers, with an Application to the Entscheidungsproblem.” *Proceedings of the London Mathematical Society* s2-42, no. 1 (January 1, 1937): 230-65.

A. R. J. P. Ubbelhode. “The Beginnings of the Change from Craft Mystery to Science as a Basis for Technology.” Chap. 23 In *A History Of Technology*, edited by C. Singer, 663-81. Oxford: Clarendon Press, 1958.

H. Vekemans, and R. v. d. Pluijm. “Daas-ClickBrick: Dry stack clay bricks for façades.” Paper presented at the 13th International Brick and Block Masonry Conference, Amsterdam, 4-7 July 2004.

T. Wakisaka, N. Furuya, Y. Inoue, and T. Shiokawa. “Automated construction system for high-rise reinforced concrete buildings.” *Automation in Construction* 9, no. 3 (May 2000): 229-50.

A. Warszawski, and R. Navon. “Implementation of Robotics in Building: Current Status and Future Prospects.” *Journal of Construction Engineering and Management* 124, no. 1 (1998): 31-41.

L. S. Wesley. “The History of Robotics.” In *Robotics and Automation Handbook*: CRC Press, 2004.

J. Willmann, M. Knauss, T. Bonwetsch, A. Apolinarska, F. Gramazio, and M. Kohler. “Robotic timber construction — Expanding additive fabrication to new dimensions.” *Automation in Construction* 61 (2016): 16-23

N. Wirth. “The programming language pascal.” *Acta Informatica* 1, no. 1 (March 1, 1971): 35-63.

Y. Yamazaki, and J. Maeda. “The SMART system: an integrated application of automation and information technology in production process." *Computers in Industry* 35, no. 1 (1998): 87-99.

T. Yoshida. “A Short History of Construction Robots Research & Development in a Japanese Company.” Paper presented at the 23rd International Symposium on Automation and Robotics in Construction (ISARC), Tokyo, 2006.

T. Yoshida, T. Ueno, M. Nonaka, and S. Yamazaki. “Development of spray robot for fireproof cover work.” Paper presented at the 1st International Symposium on Automation and Robotics in Construction (ISARC), Pittsburgh, 1984.

S.-N. Yu, B.-G. Ryu, S.-J. Lim, C.-J. Kim, M.-K. Kang, and C.-S. Han. “Feasibility verification of brick-laying robot using manipulation trajectory and the laying pattern optimization.” *Automation in Construction* 18, no. 5 (2009): 644-55.

G. Zenobi, and P. Reinshagen. *Vorfabrikation mit Backstein*. Element. Zurich: Schweizerische Ziegelindustrie, 1973.

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APPENDIX 1: Tests structural adhesive

Shear test Kelesto-Clinker 240/115/61 with Sikadur 330

Table 1. Results shear test Kelesto-Clinker 240/115/61 with Sikadur 330.

Nr	Adhesive Sikadur	Gluing area mm^2	Glue g/ mm^2	Thickness mm^2	Compression of gluing area	Age h	Fracture load$^{1)}$ kN	Shear stress$^{1)}$ N/mm^2	Fracture load$^{2)}$ kN	Shear stress$^{2)}$ N/mm^2
A	330	18,400	0.00055	<1	yes	48	60.00	3.26	35.00	3.80
B	330	18,400	0.00083	1~2	no	48	131.34	7.14	109.19	11.87
C	330	18,400	0.00083	1~2	no	120	80.05	4.35	71.85	7.81
Avargare								**4.92**		**7.83**

1) Failure of first glued surface
2) Failure of second glued surface

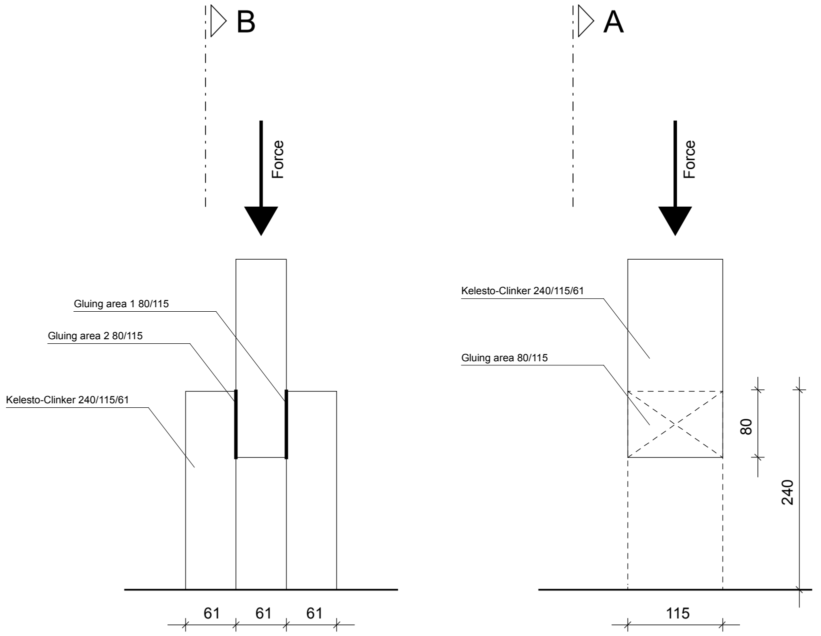


Figure 71. Scheme of shear test set-up: (left) Section A; (right) Section B.

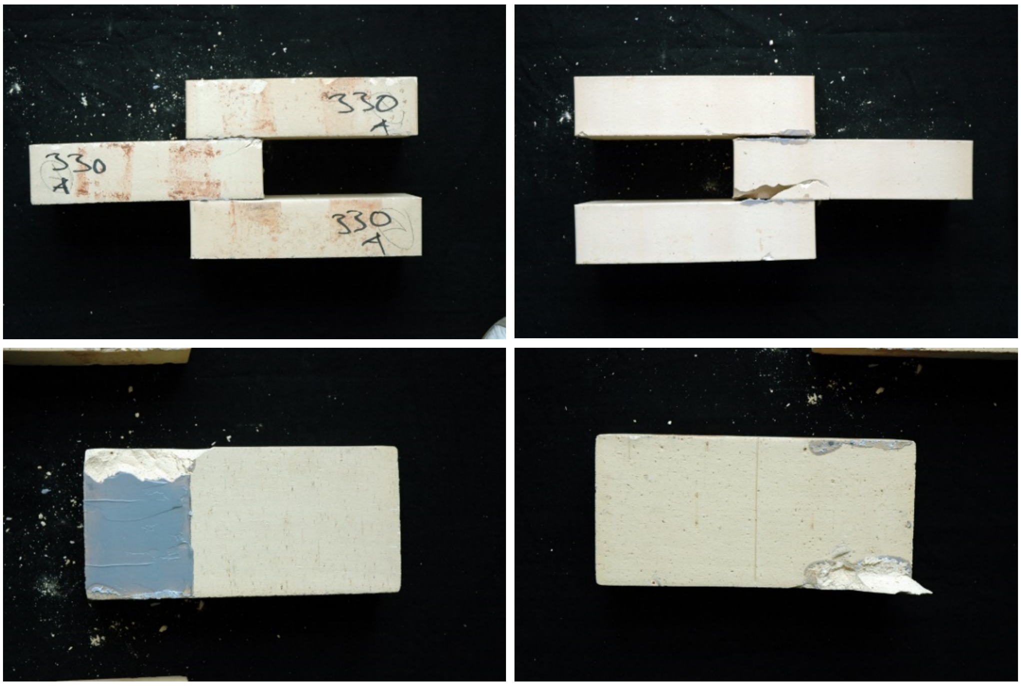


Figure 72. Line of breakage Sample A.

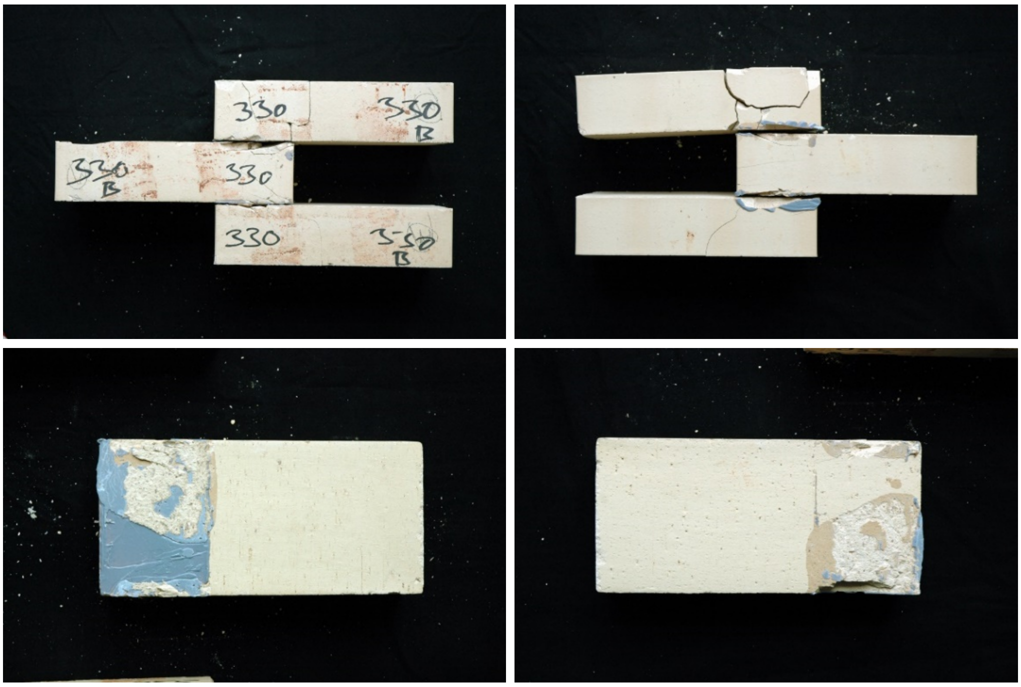


Figure 73. Line of breakage Sample B.

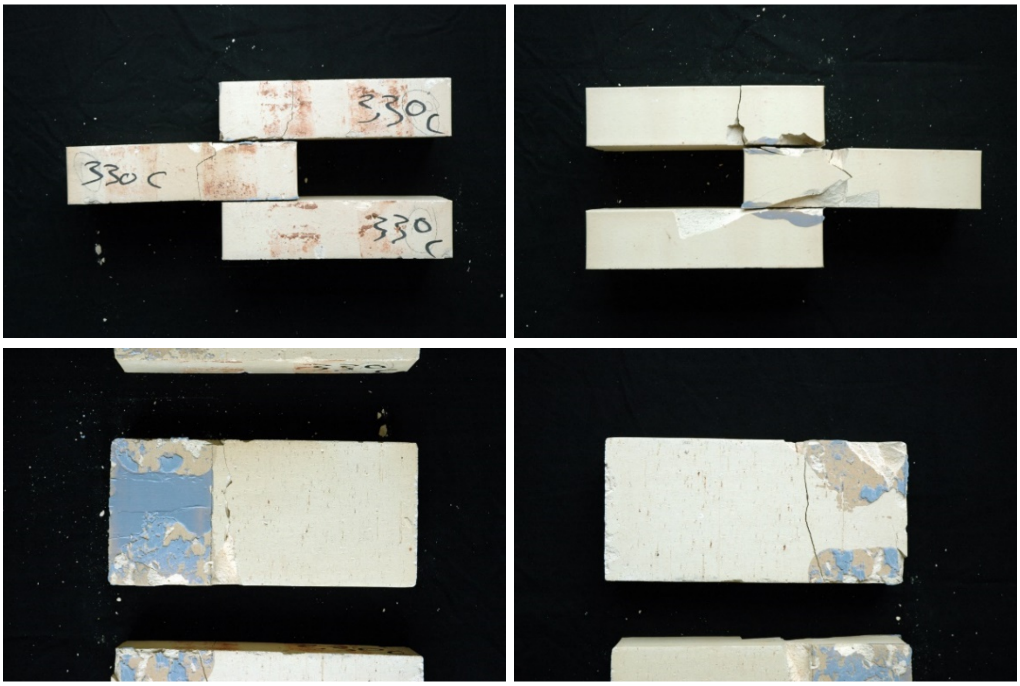


Figure 74. Line of breakage Sample C.

Shear test Kelesto-Clinker 240/115/61 with Sikadur 30 LP

Table 2. Results shear test Kelesto-Clinker 240/115/61 with Sikadur 30 LP.

Nr	Adhesive Sikadur	Gluing area mm^2	Glue g/ mm^2	Thickness mm^2	Compression of gluing area	Age h	Fracture load1) kN	Shear stress1) N/mm^2	Fracture load2) kN	Shear stress2) N/mm^2
D	30 LP	18,400	0.00166	1~2	no	120	47.23	3.26	57.22	6.22
E	30 LP	18,400	0. 00166	1~2	no	120	206.48	7.14	91.13	9.91
F	30 LP	18,400	0. 00166	1~2	yes	120	41.97	2.28	x	x
Avargare								**5.36**		**8.06**

1) Failure of first glued surface
2) Failure of second glued surface

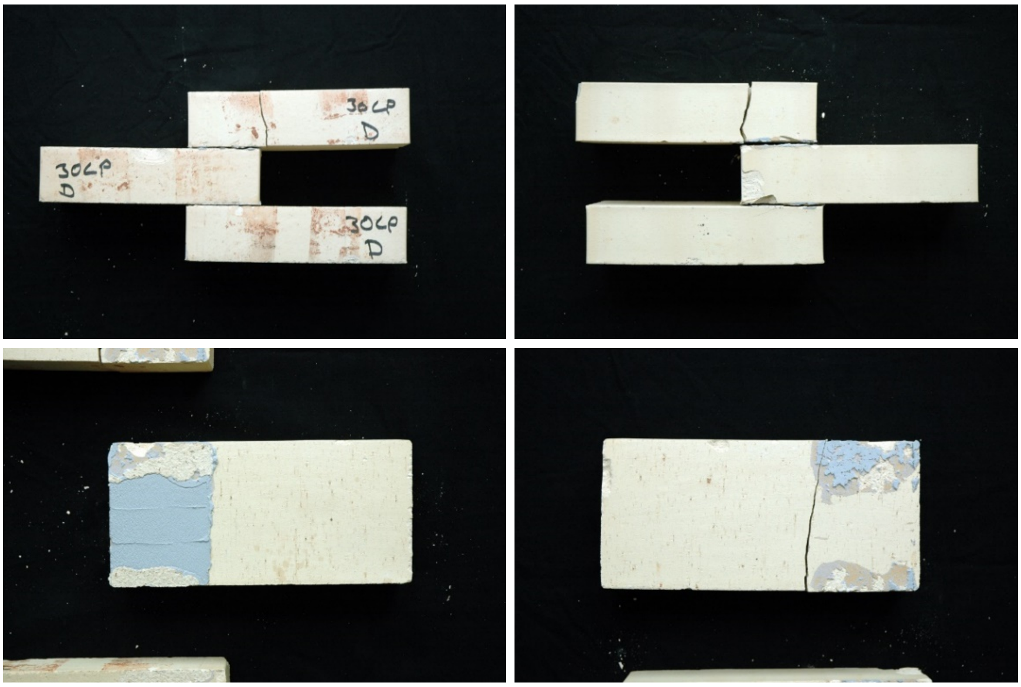


Figure 75. Line of breakage Sample D.

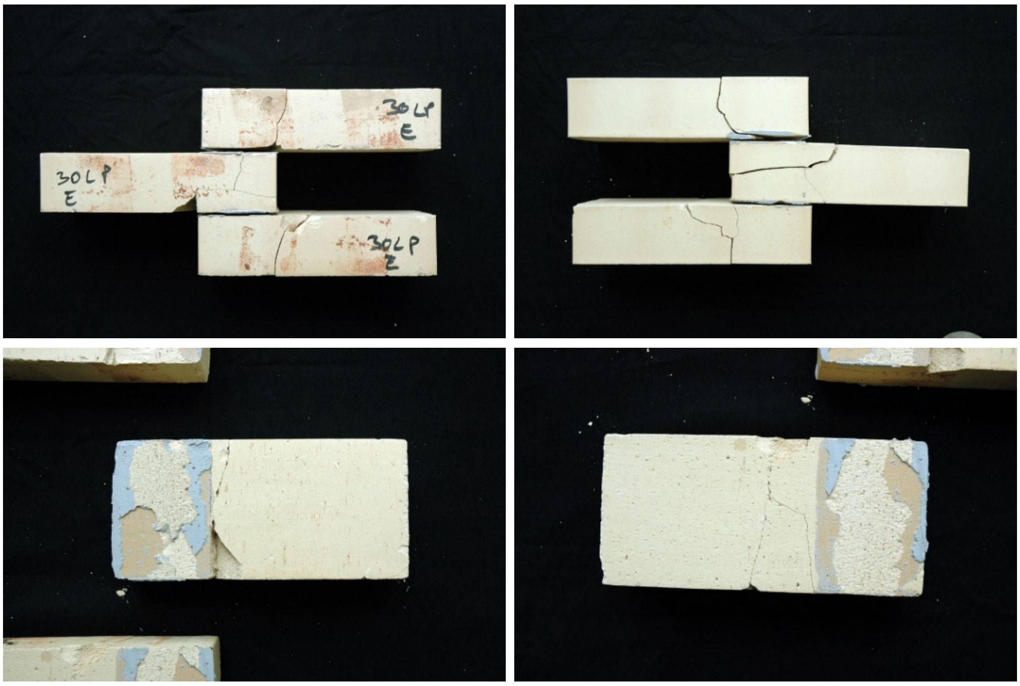


Figure 76. Line of breakage Sample E.

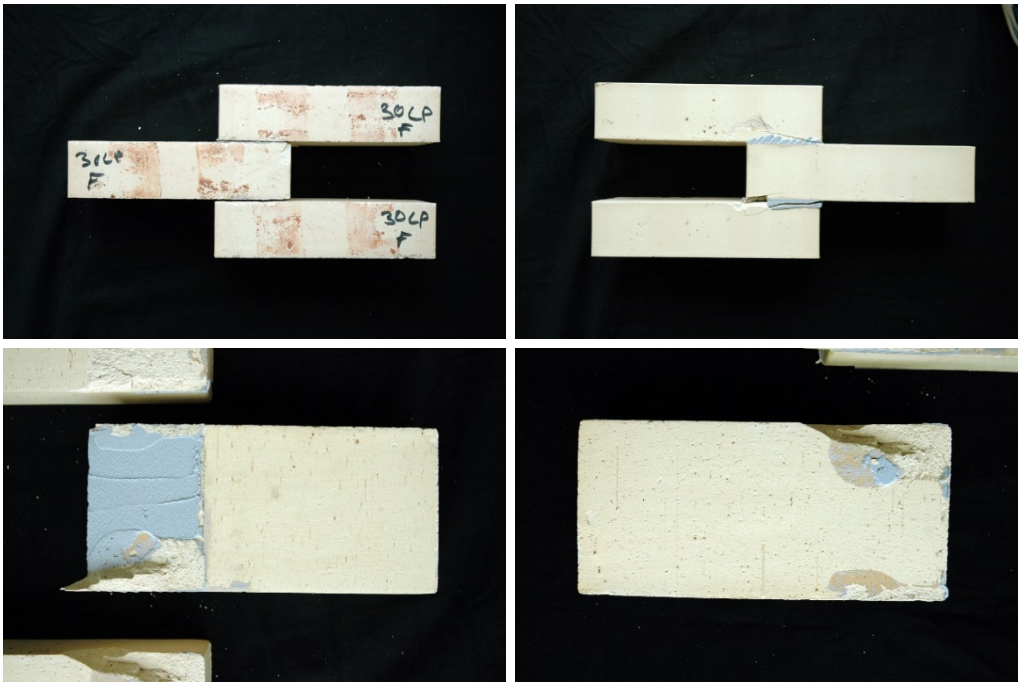


Figure 77. Line of breakage Sample F.

Bending test façade elements Gantenbein Winery

Material: Kelesto-Clinker 240/115/61 with Sikadur 330.

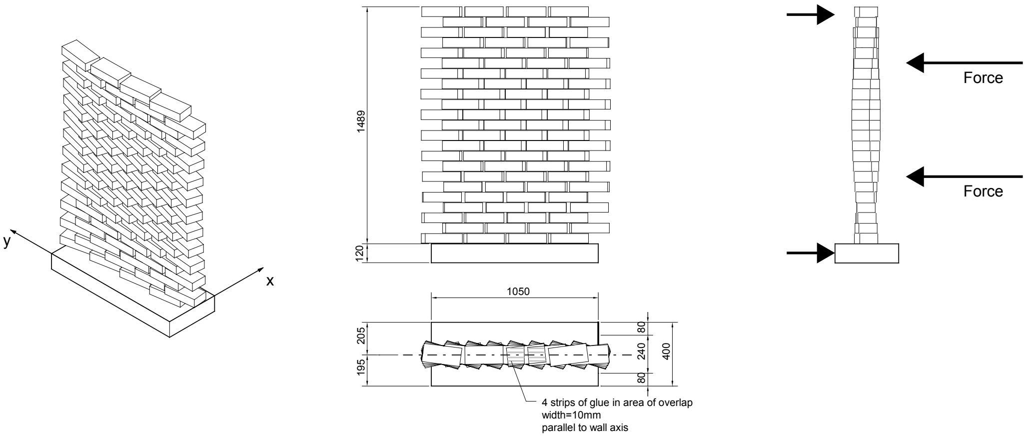
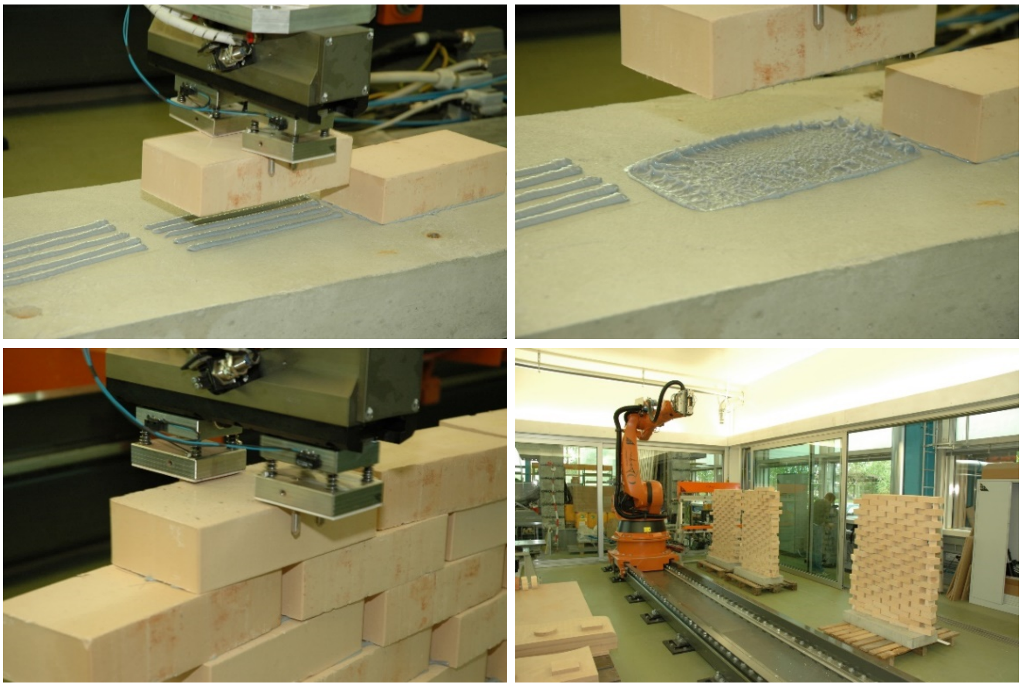


Figure 78. Scheme of bending test Gantenbein Winery.



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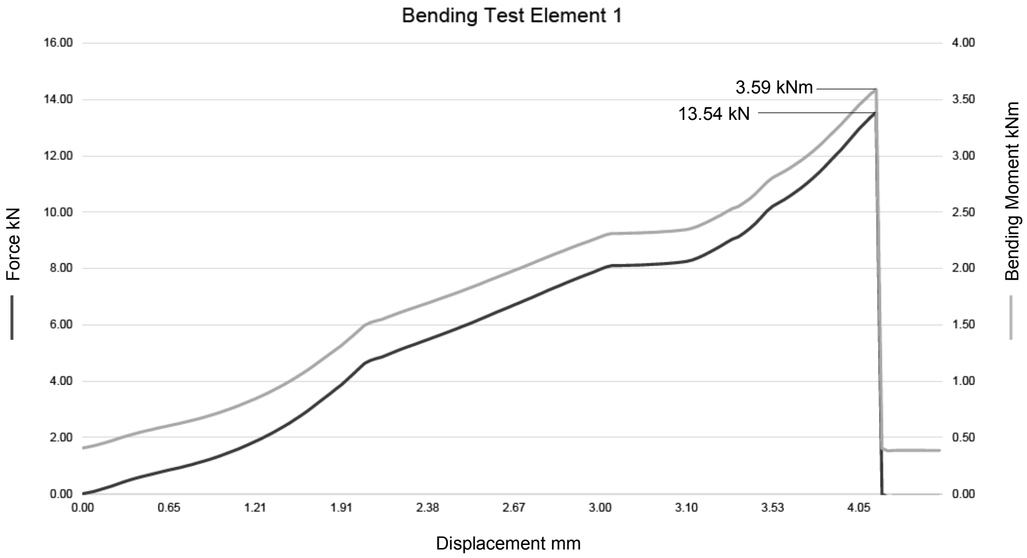

Figure 80. Results bending test for Element 1.

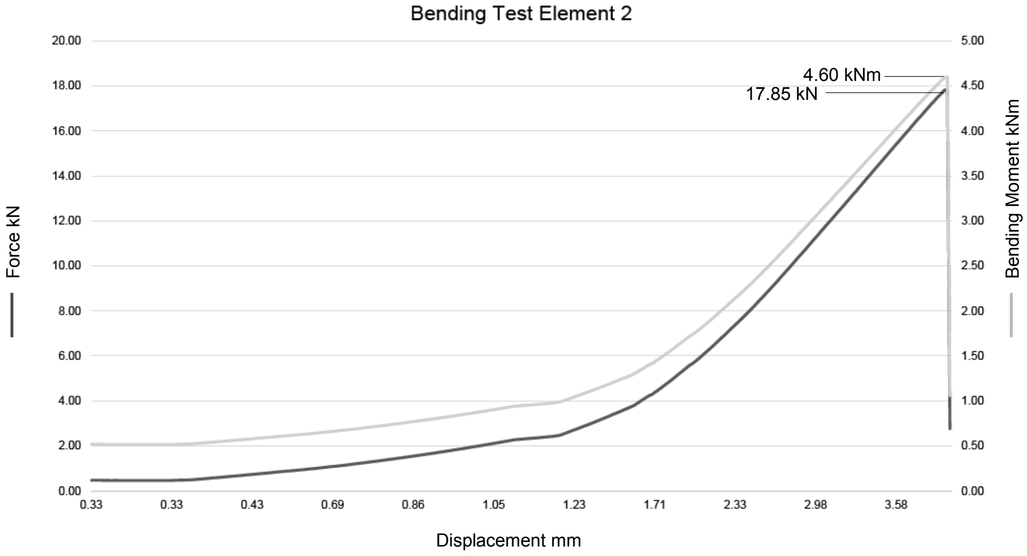

Figure 81. Results bending test for Element 2.

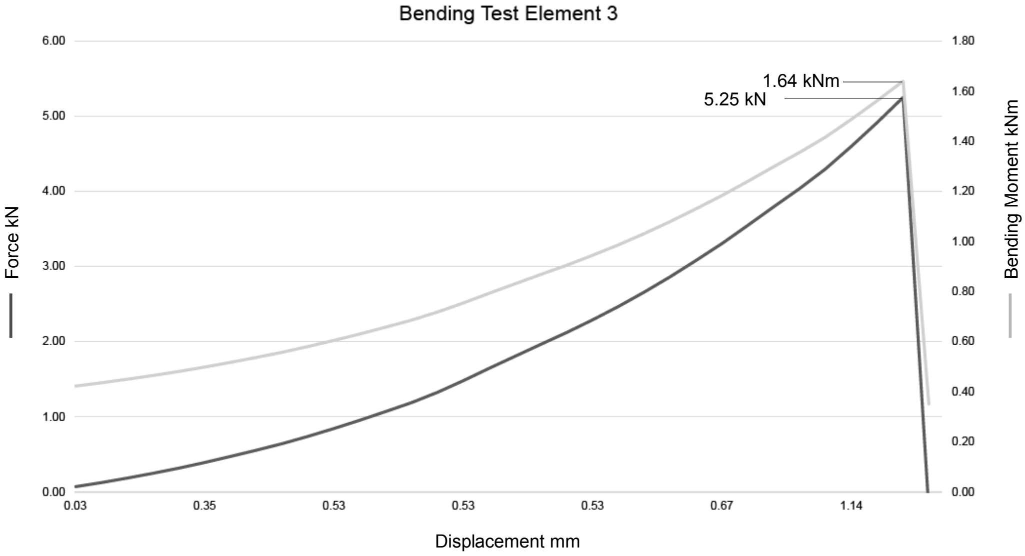

Figure 82. Results bending test for Element 3.

Figure 83.Bending Test: (left) Element before load; (right) failure of element.

APPENDIX 2: Credits experiments and projects

The experiments and projects discussed in this thesis have been conducted within the group of Gramazio Kohler Research at ETH Zurich, under the guidance of Professor Fabio Gramazio and Professor Matthias Kohler.

Experiment 1

The Programmed Wall

Gramazio Kohler Research:
Tobias Bonwetsch (project lead)
Daniel Kobel
Michael Lyrenmann

Students:
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Michael Knauss
Kocan Leonard
Gonçalo Manteigas
Silvan Oesterle
Dominik Sigg

Industry partner:
Keller AG Ziegeleien

Experiment 2

Gantenbein Winery

Gramazio Kohler Research:
Tobias Bonwetsch (project lead)
Daniel Abraha
Stephan Achermann
Christoph Junk
Michael Knauss

Andri Lüscher
Michael Lyrenmann
Silvan Oesterle
Martin Tann

Architecture project:
Bearth & Deplazes Architects, Chur and Gramazio Kohler Architects, Zurich

Industry partner:
Keller AG Ziegeleien

Experiment 3

ROB Unit

Gramazio Kohler Research:
Michael Lyrenmann (project lead)
Tobias Bonwetsch
Dr. Ralph Baertschi

Industry partner:
Bachmann Engineering AG

Structural Oscillations

Gramazio Kohler Research:
Michael Knauss (project lead)
Dr. Ralph Baertschi
Gregor Bieri
Tobias Bonwetsch
Michael Bühler
Nadine Jerchau
Michael Lyrenmann
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Curator:
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Sponsors:
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Kuka Schweiz AG
Sika Schweiz AG