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A Framework for Interactive Human-Robot Design Exploration

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Abstract

This study seeks to identify key aspects for increased integration of interactive robotics within the creative design process. Through its character as foundational research, the study aims to contribute to the advancement of new explorative design methods to support architects in their exploration of fabrication and assembly of an integrated performance-driven architecture. The paper describes and investigates a proposed design framework for supporting an interactive human-robot design process. The proposed framework is examined through a three-week architectural studio, with university master students exploring the design of a brick construction with support of an interactive robotic platform. Evaluation of the proposed framework was done by triangulation of the authors qualitative user observations, quantitative logging of the students' individual design processes and through questionnaires completed after finishing the studies. The result suggests that interactive human-robot fabrication is a relevant mode of design with positive effect on the process of creative design exploration.

Keywords

Design methods, robotic design processes, interactive robotics, computational design, design exploration, creativity

Introduction

During the last decade the field of architectural computing has adopted robotic fabrication as a means for exploring the potential correlations between computational driven design systems and the inherent properties of material system – a concept referred to as *digital materiality* (1). Until recently, most research in this field of robotic architecture has been based on a file-to-factory approach (2), where all the discrete steps for the fabrication are calculated and fixed before the entire fabrication sequence is transferred to the robot for execution.

This study attempts to identify key aspects for increased integration of interactive robotics within the creative design process. It does so by proposing, implementing and examining a framework for robotic-driven design exploration. By classifying six modes of designing the study traces the resulting design processes and thereby uncovers the potential impact of framing and applying relevant design methods.

An interactive approach to robotic fabrication has the potential to engage with a non-deterministic design exploration where not all aspects of the fabrication is perfected before initiating the process, but are instead solved during the fabrication process through actively engaging with the material, the robot itself, and the commands its executing. This opens for creative processes with integrated making, rather than a sequential process of design thinking, creation of representational instructions (such as drawing) and then building, as has been practiced in architecture since the Renaissance (3).

The presented study is based on previous work in the field of interactive robotic fabrication within the architectural domain. In the last decade several studies have explored interactive robotic setups that allowed collaboration between a human designer and a robotic agent. One such example, related to the specific study, with the technological objective of piling up wooden sticks, Dörfler et al.(4) explored how a simple setup with an industrial robotic arm equipped with a vacuum lifter and a table-mounted webcam for optical tracking, could be used to support an interactive human-robot design exploration. The setup allowed the user to manually place and remove wooden sticks and, based on a shape-generating algorithm calculating for structural stability, the robotic arm could continue the piling procedure. The study thereby enabled direct and transparent interaction by the user and suggested that 'the user is able to understand the causality between his action and the reaction of the system…' (4). Similar work has been showcased by Johns et al. (2) through their Mixed Reality Modeling project which featured an iterative robotic heat gun melting of wax. This project also sought to 'allow for "human in the loop" modifications' (2) during the design process and did so by allowing the user to manipulate the object by either manually removing wax or by coloring areas for subsequent robotic heat gun treatment. Recently Schwartz et al. (5) developed a new technology-based framework that enables voice control, co-speech gestures, and object recognition, thereby aiming to 'expose how robots can be turned into intelligent assistive devices that can adapt to human complex operations, changing environment parameters, and even unforeseen situations' (5). In their paper Sensors and Workflow Evolutions, Dubor et al. (6) explores a series of case studies to discuss the relevance of feedback loops and to propose a framework for human interaction and machine response. In the paper they conclude that 'collaboration between robots and human can enhance creativity and innovation by supporting designer and researcher while exploring complex material system.' (6).

The work referenced above suggests that human-robot interaction has potential for supporting designers in the exploration of material systems and their fabrication. The focus of these studies is primarily on the advancement of technology or the designed and build artifact. Through foundational research for design methods to advance of new explorative design processes, this study seeks to support architects in their exploration of an integrated architecture. A design process where material systems and their fabrication cannot be separated from their architectural performance or the visual expressive characteristics normally governing the choices of architects. This approach leads to the following research questions:

- What impact does integration of interactive robotics have on the methods and processes supporting creative design exploration?
- What skills and knowledge-sets are required of designers to adopt and implement these technological advancements and their accompanying design processes?

To investigate the potential impact of using interactive robotics to support the early design process this study developed a computational design framework that integrates parametric design of brick wall structures with acoustic simulation and robotic fabrication. The proposed design process was explored through a three-week architectural studio which instructed architecture students on master level to explore and design a brick wall construction with support of an interactive robotic platform. The design process was evaluated by qualitative user observations conducted by the author (7) and quantitative logging of the design processes conducted by the students themselves. This data collection was further supported by evaluation of the students' work with physical prototypes and computational design models. Although the design studio explored the design and fabrication of brick assemblies, including the challenging issue of bonding and interlocking, the paper will only briefly discuss this subject and mainly focus on the implications and benefits of applying the proposed framework.

The paper will present the specific design framework and the design methods used during the study, including the interactive robotic brick stacking system and the computational design methods that supported the design explorations and the interactive robotic fabrication of acoustically performative brick structures. Based on the results of the qualitative observations and the quantitative data collection the paper will discuss and reflect upon the impact of adopting an interactive human-robot approach for supporting design exploration.

Methods

The experimental setup used in this study consists of a bespoke design framework, constructed to support the exploration of a material system consisting of plywood bricks with glued-on sound absorbing foam. The framework consists of an interactive robotic system capable of performing simple brick stacking and a computational design system enabling a parametric design exploration of brick structures as well computational simulations of acoustic performance and robotic fabrication.

The design framework

Interactive robotic system

The physical setup for the robotic fabrication consisted of two identical work tables (see figure 1), each with a robotic arm (Universal Robots' UR10) equipped with a customized gripper for picking and placing the plywood bricks (one robotic arm was equipped with a pneumatic gripper and the other with a motorized gripper). Both tables contained two fixed 'storage positions', one for standard plywood bricks and one for the acoustic plywood bricks, and on both tables two momentary push buttons were installed for communicating user feedback to the computational design system during fabrication. As shown in figure 1. the length of the robots' reach allowed for a working area of 180x80 cm., restricting the study to explore and fabricate smaller wall sections at a time and solving their integration in larger assemblies. The UR robots were communicating with the computational design system by a TCP/IP connection.

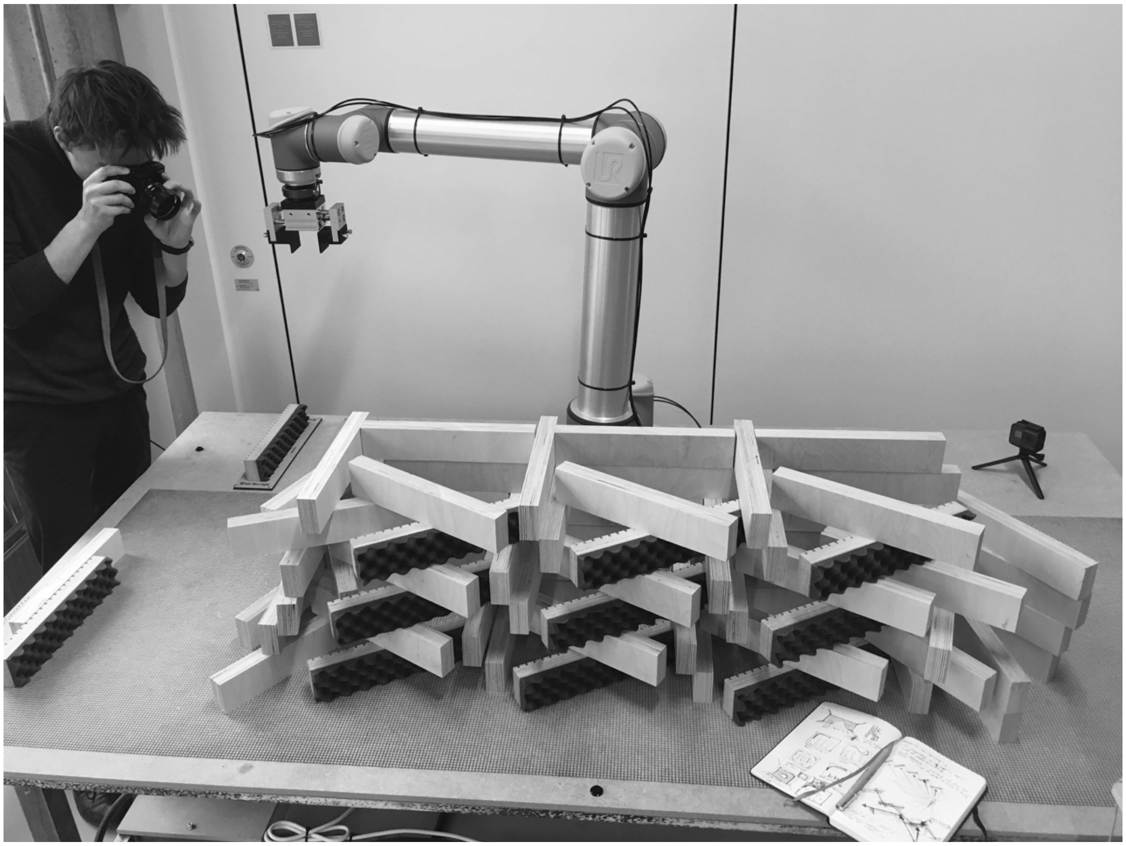


Fig. 1. Photo of the robotic setup used during the study. The setup features a UR10 robot arm, two push-buttons (one placed front-center and one back-left), and two storage positions (back-left) for the two types of bricks. On the table a brick structure has been stacked by the robot using the 300x60x30mm plywood bricks.

The material and geometric system

To enable a parallel design exploration utilizing both analog and computational modes of working a material system comprised of geometrically simple elements was chosen. Consisting of discrete plywood bricks (300x60x30mm), with the option of having a 15mm thick foam block glued onto one of the bricks' two largest sides, the material system allowed for an examination of complex assembly logics for horizontal stacking of interconnected double wall structures. This supported an exploration of brick formations and their sequential building process comprised of discrete fabrication steps. The option of using either standard plywood bricks or the sound absorbing plywood bricks with an attached foam block, allowed for differentiation in the acoustic performance of the brick formations, with the foam material having a higher sound absorption level.

The geometric aspect of the material system allows for the design and robotic stacking of rather simple rule-based assemblies as long as the overall shape of the wall is straight and the brick bond is kept to a strict formation. However, introducing curvature to the surface of the wall and exploring more elaborate brick bond patterns, highly increases the level of complexity and introduce challenges in structural feasibility and inter-collision between brick elements. The demand for interconnections between the two wall structures served the purpose of increasing structural stability, and from a didactic view ensured a level of complexity in brick composition and assembly logics that challenged the students' computational design skills and their spatial intelligence. Solutions for the interconnection within the double wall structures could range from a physical interlacing of the two wall structures or through the use of "binder bricks" spanning the interior gap between the walls. Examples of these two structural typologies can be seen in figure 8.

The computational design system

To establish an integrated computational design system that enabled the students to fluently move between a mode of designing and a mode of fabrication, the parametric CAD environment Rhino+Grasshopper (8) was used. After two days of intense teaching in Grasshopper, the students were introduced to a generic Grasshopper definition containing the logics for three main design processes: 'Brick Wall Design', 'Acoustic Simulation' and 'Robotic Fabrication'.

The sub-system for the 'Brick Wall Design' contained an open framework for designing a double wall formation based on a contoured guide surface controlling the position and orientation of each individual brick in the layered brick formation. The output of this process was both a geometric representation of potential brick formations, the comprised plywood and foam surfaces ready for acoustic analysis with the Rhino-plugin Pachyderm (9), as well as all the target planes for the robotic fabrication.

Within the 'Acoustic Simulation' the individual brick surfaces were organized into two sets – one for plywood (lower sound absorption) and one for foam (higher sound absorption) – informing the acoustic simulation of their material properties related to acoustic performance. An intentional distribution and orientation of the two brick types allowed for a design exploration that also considered acoustic performance. By running acoustic simulations in Pachyderm the students were able to test the acoustic performance of the brick formation against changes in brick formation, distribution of acoustic bricks, location of sound emitter and receiver, as well as placement of the brick formation within a given room. Depending on the students' own choice for the acoustic purpose of the room, it could be optimized against a specific acoustic design. The use of acoustic simulations moves the study from simple geometric stacking to a design complexity where the designer is considering multiple and potential conflicting conditions that are better understood during a 'live' design making process – enabled by the robotic setup.

The 'Robotic Fabrication' contained all the logics for creating target planes and transferring instructions (robot control code) to the robotic arm. The Grasshopper add-on Robots (10) was used for simulation of the robotic fabrication process and communication with the UR10 robot. Based on the target planes generated in the 'Brick Wall Design' the sub-tasks for picking and placing the individual bricks were automated, but instead of transferring the complete set of commands to the robotic arm the system allowed for three different modes of communicating with the robot. The design of the different modes for robot interaction enabled design exploration and robotic fabrication of the stacked brick formations. The three modes, for which the logics are visualized in the flow chart in figure 2, are; *Auto-stacking (Mode 1),* where the robot automatically picks up a brick, moves it to an already determined position, and places it. This mode can be run fully automatic or with the need for human acknowledgements before brick pick-up and placing. *Adjustable-stacking (Mode 2)*, where the robot automatically picks up a brick and moves it to an already determined positions based on the supplied target planes. Before the robot places the brick the designer can manually move the robot/brick (this process is shown in the top-left picture in figure 3 and takes advantage of the free drive mode built into the UR-robot) or digitally (by changing slider values in Grasshopper) alter the position and orientation of the robot/brick in a more precise numeric fashion. The final position of the brick is recorded and updated in Rhino+Grasshopper. *Free-stacking (Mode 3)* where the robot automatically picks a brick and present it to the designer and he/she will manually hand-guide the brick (again using the robot's free drive mode) to a desired position. The position of the brick is recorded and updated in Rhino+Grasshopper. It is important to note that for each of the three interaction modes the design intention and decision-making lies solely with the human designer – the robotic arm, and the interactive system driving it, only responds through preset interaction scenarios.

The design framework, established by the combination of the physical robotic setup, the material brick system, and the computational design system, allows the designer to engage in a human-robot-material design process and can, by utilizing the three suggested modes for robotic interaction, perform design explorations with varying degree of determinism.

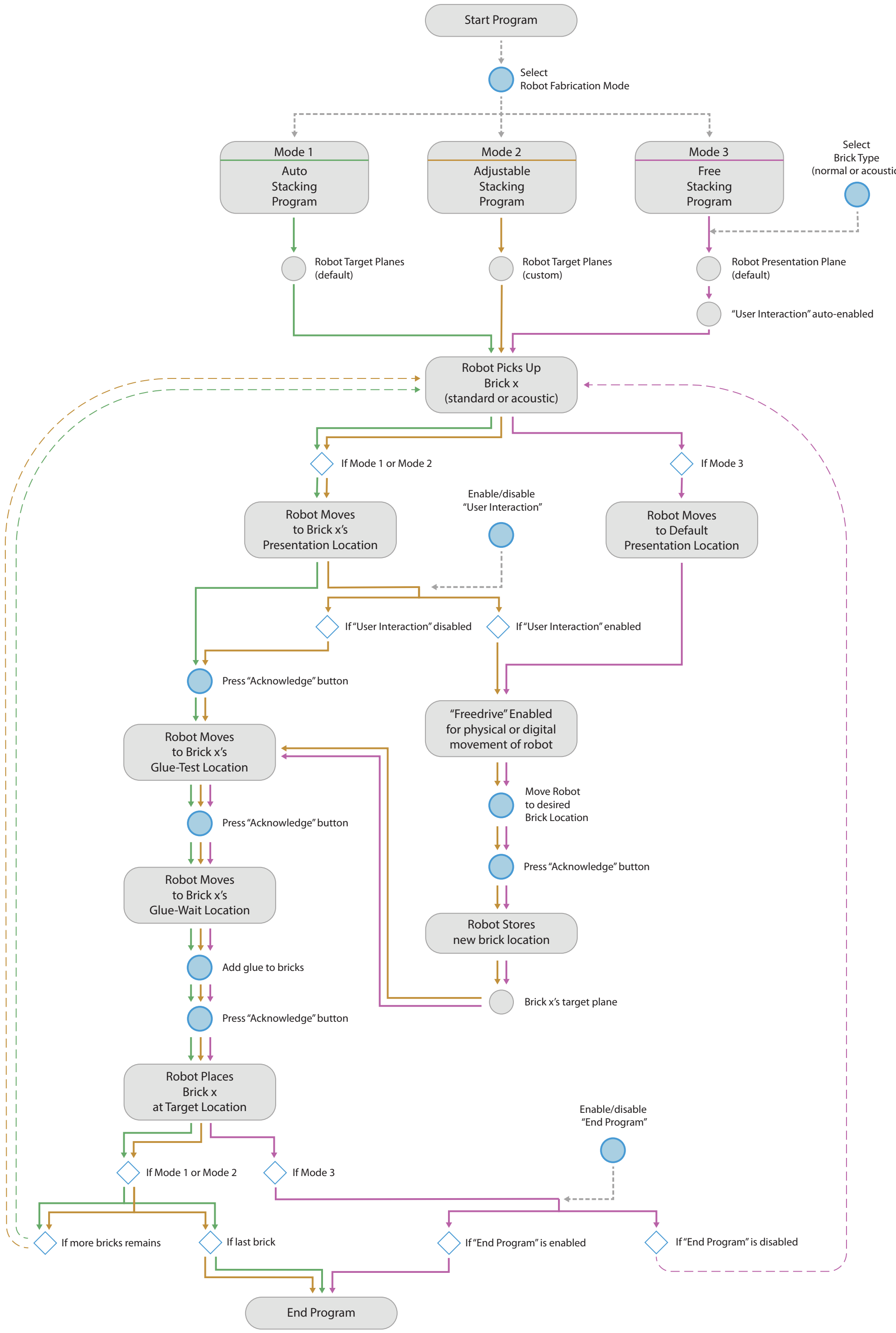


Fig. 2. Flow chart showing the logical steps for each of the three robotic interaction modes. The blue circles represents the specific locations where the user/designer can interact with the robotic fabrication process. At some of these locations the designer merely acknowledge that the fabrication process is proceeding as planned, but at other locations the designer needs to engage actively in the fabrication process by ex. adding glue manually or by moving the placement of bricks, thereby altering the design trajectory.

Architectural studio

To evaluate the impact of introducing interactive robotics to the creative design exploration the described design framework was exposed to 19 master level students during a 3-week architectural studio. All participating students had little experience in computational architecture and no experience with robotics. The studio guided them through the design process in three distinct phases:

- Week 1: introduction to the interactive robotic-based design framework focused on the design and assembly of simple brick structures.
- Week 2: exploration of acoustic performance related to the arrangement of brick structures and the material properties of the individual plywood+foam brick.
- Week 3: parallel exploration of interactive robotic fabrication and acoustic simulation of brick structures for a specified contextual setting.

Throughout the studio the students had unlimited access to the robotic setup and the wooden bricks were available for exploring both manual hand stacking and robotic stacking.

User observations and logging of design work modes

To investigate and evaluate the design framework a user observation strategy was implemented which, besides the author's qualitative observations of the students, utilized image and video recordings of the students' design process including their use of physical models, hand sketches, prototypes, interactive robot fabrication and computational design models.

Design work modes

The observations were supported by quantitative logging of the students' individual design processes, structured through the implementation of a daily personal log (see table 1.) in which all students registered their own daily alternation between six different 'design work modes'. The six work modes were manual brick stacking, interactive robotic stacking, parametric design modeling, acoustic simulation, robotic simulation, and hand sketching (see figure 3.).

Table 1. Example of the daily log showing one student's registrations of the alternation between design work modes. Each student did their individual registrations throughout the 3-week studio.

| | | Mo | | | | Tu | | | | | | We | | | | | | | | Th | | | | | | | | | | | | | |
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	3
MODE A	**Manual Stacking**						x							x																				
MODE B	**Robotic Stacking**			x																x			x			x								
MODE C	**Parametric Design**	x						x		x						x		x			x			x			x		x		x		x	
MODE D	**Acoustic Simulation**					x			x		x		x															x		x		x		
MODE E	**Robot Simulation**		x														x		x			x			x									
MODE F	**Hand sketching**				x							x			x																			

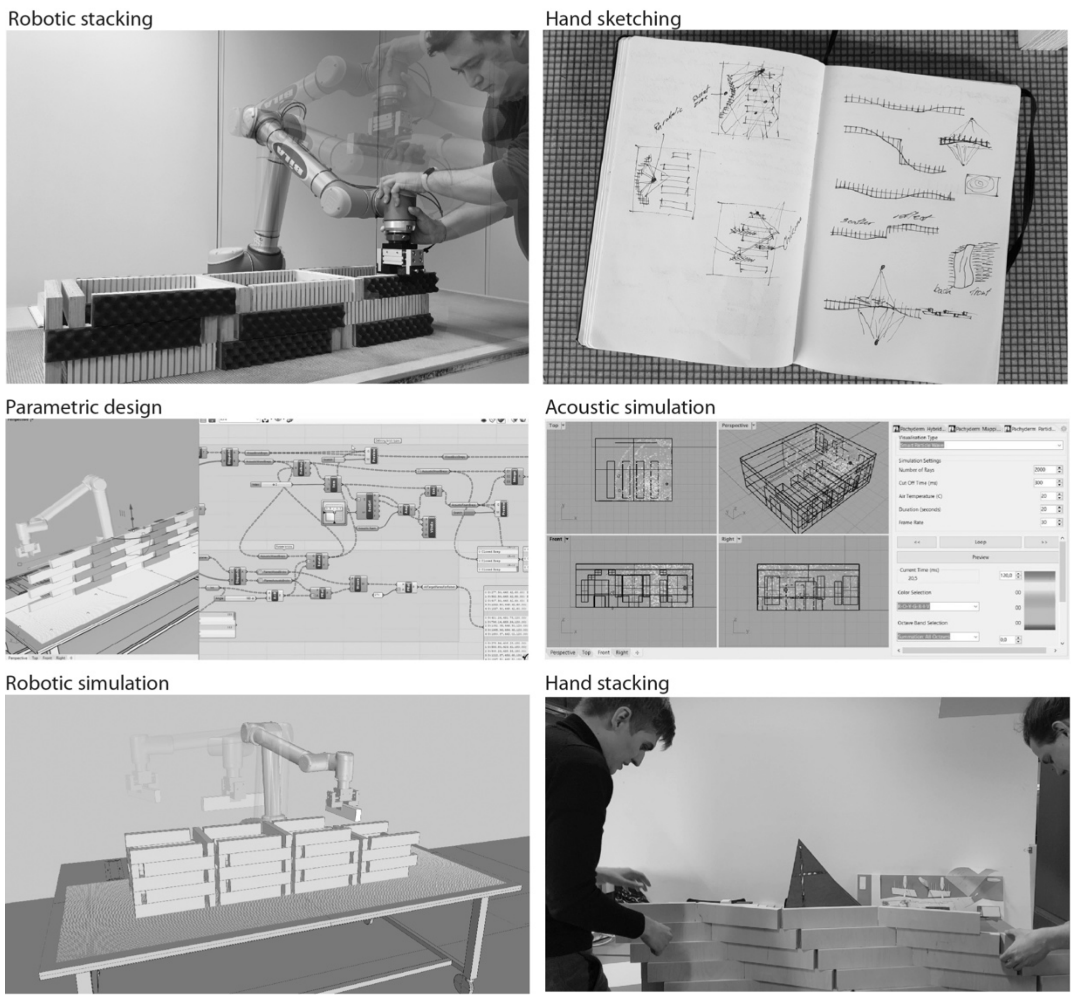


Fig 3. The six design work modes used during the study

Data collection and mapping

To understand the impact that the implementation of an interactive human-robot fabrication system has on the way novice designers engage with the described design work modes a graphical mapping of the recorded data was performed. The data recorded in the students' personal logs was represented through three different graphs (see figure 6.), each depicting a specific aspect of the data (please note, that as the first week of the architectural studio did not contain individual design explorations, this week is not accounted for in the students' daily logs and therefore not part of the represented data). It is important to note that completion of the daily personal logs was administered by the students themselves and the data entry is therefore subject to carelessness and misunderstandings of the logging procedure. To ensure validity of the data collection it is based on triangulation (11) of three different methods for data acquisition and the results will only be used for capturing trends and patterns within the design process.

"Daily freq./mode", the bottom graph in figure 5, shows the average percentage of times each work mode was used each day, thereby suggesting how active a given mode has been in the students' daily iterative design cycles.

"Daily shifts/user", the graph in the middle, depicts how each student shifts between the work modes represented by one continuous polyline per student. The graph thereby highlights the "path" for each students' daily design process and visualizes the sequential use of the different work modes – potentially showing if specific alternation sequences (ex. if robotic simulation being followed by robotic stacking) occurs more often at the beginning than at the end of the design process.

"Total daily freq.", the last graph at the top, shows the average amount of alternation occurring between the six work modes, while also visualizing the frequency range between the least alternating student and the most. The graph thereby makes visible if certain periods during the creative design exploration is linked with a distinctive incline or decline in work mode alternation.

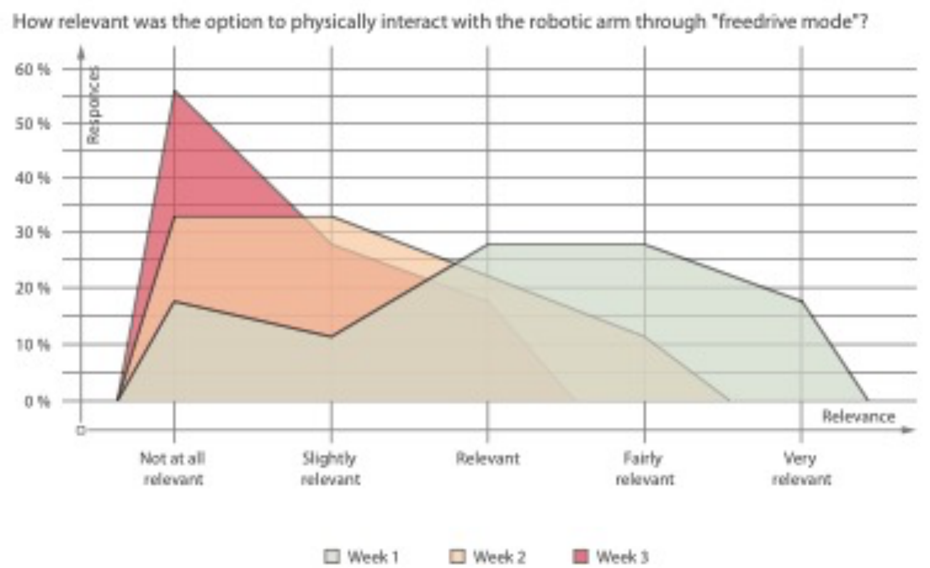
The graphical mapping was performed to visually spot trends and patterns in the collected data and it is important to note that the logged data does not contain the amount of time used in a given design work mode, but only how frequently the mode was used.

Applicability of human-robot interaction modes

As previously explained the proposed computational design system contains a method for interactive robotic fabrication, which allows for three different modes of human-robot interaction (free-stacking, adjustable-stacking, and auto-stacking). To gain insights regarding the applicability of these three interaction modes and their relevance during the design process, the planning of the qualitative observations contained continuous registration of the students' work at the two robotic work tables. To avoid researcher bias and subsequent loss of objectivity the results of the qualitative observations was supported by questionnaires - distributed to all students in the beginning and end of the architectural studio (see attached file with research data from the complete questionnaire). To acquire the students' opinion regarding the applicability of the interaction modes one subset of the questionnaire dealt with the experienced relevance of each interaction mode during each of the three weeks of the studio. The result of these questions is expected to reveal if the interaction modes are found to be of equal relevance throughout the design exploration – a result that can then be further explained and contextualized based on the outcome of the qualitative observations.

Results

Evaluation of the design framework was done by a triangulation of the authors qualitative user observations, the data from the students' daily logs and from the answers collected through the questionnaires. From these three sources the following results can be drawn.



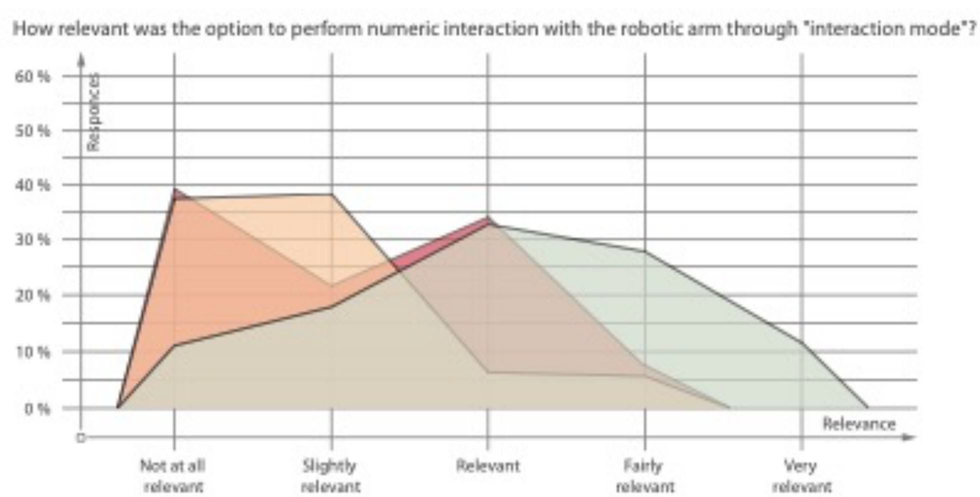


Fig. 4. Graphs showing the distribution of the students' answers for two of the questions in the survey. The chart in the top shows the relevance of "*free-stacking*" and the bottom chart shows the relevance of "*adjustable-stacking*".

Creative impact of interactive robotics

The opportunity for designers to interact with the robot during the fabrication process allowed for a non-deterministic approach to robotic-driven design and had a positive effect on the explorative design process, especially during the first days of design exploration. This result is based on the answers in the questionnaire relating to the questions of how relevant the interaction mode was during the design exploration. As can be seen in the graph in figure 4, the answers indicate a high relevance concerning the use of the interactive robotic setup for the first week of the studio, which then decays during the following two weeks. This result is supported by the qualitative user observations where most students were observed to be engaged in interactive robotic-based design explorations in which various brick formations were fabricated and investigated without any dependence on preconceived design concepts. The authors' observations therefore suggest that design exploration continued within the robotic fabrication work mode. The students' ability to interact with and influence the fabrication process allowed for creative interruptions in the otherwise linear and deterministic robotic fabrication process. The design process thereby shifted from a series of creative non-deterministic activities stitched with linear deterministic robotic fabrication processes (approach B in fig. 5.) to a process in which the designer, by supplying new input to the robotic system, continuous the non-deterministic design exploration during the robotic fabrication process (approach C in fig. 5.).

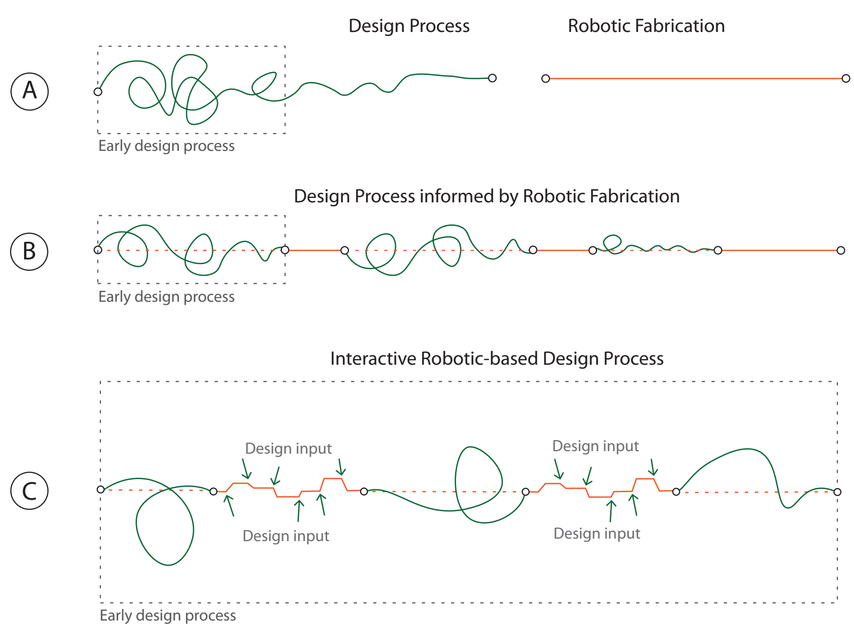


Fig. 5. Illustrates three approaches for integrating design processes with robotic fabrication. A) No integration, the non-deterministic design process is carried out and the final design is fabricated using a deterministic robotic-based process. B) Periods of linear/deterministic robotic fabrication (prototyping) is informing periods of non-linear design processes. C) Periods of non-linear/indeterministic interactive robotic fabrication is informing non-linear design processes.

Alternations between design work modes

Analysis of the data logging of the students' alternation between 'design work modes', combined with qualitative observations, shows two tendencies. The first was that the interactive robotic fabrication was used throughout the design period and that its relevance was highest in the first days of the design exploration. The other tendency was that the design exploration was centered around the parametric design model, including both the acoustic and robotic simulation (see figure 6).

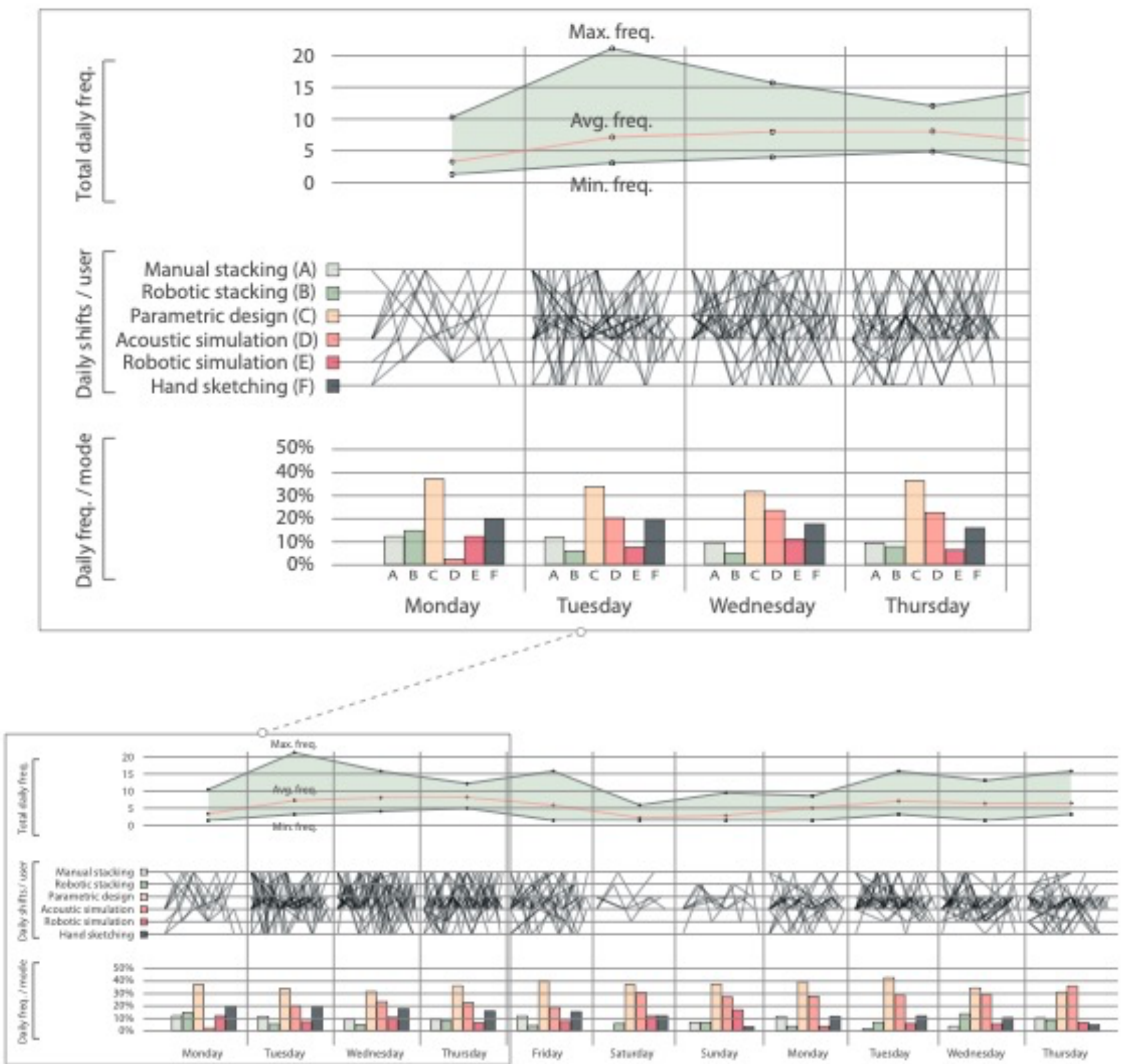


Fig. 6. Combined graphical representation of all students' registrations of their 'shift between design work modes'. The first graph 'Total daily freq." shows the highest and lowest number of shifts between design work mode recorded for each day. The middle graph "Daily shifts/user" tracks the history of each student's shifting between specific work modes. The bottom bar chart "Daily freq./mode" displays how many times each work mode was used by the students per day.

Complexity in brick assemblies

A difference in geometric complexity can be observed in the students' design solutions when working with manual brick stacking as opposed to robot-based brick stacking. Based on the images in figure 8 it is evident that the computationally generated and robotically stacked brick formations are very limited in their structural complexity and dominated by very strict and procedural expressions.

Discussion

Impact of human-robot interaction in design exploration.

Through a discussion of the data collected throughout the study, including both the students' subjective tracking of their shifting between design work modes, their subjective answers to the questionnaires, and the authors qualitative observations on the progression of the individual design processes, this section presents answers for the first of the two research question.

During the first days of the 3-week studio the robotic fabrication setup was introduced and the established modes for human-robot interaction was explored. Hands-on investigations of the robotic-based brick stacking process resulted in very valuable understanding of the potentials and limitations of robotic fabrication. Furthermore, it was observed that hands-on knowledge of how data from the computational design system needed to be structured and transferred to the robot system (i.e. structuring the target planes and I/O-commands and sending these to the robot as either one complete file or as individual brick-specific packages) is fundamental for successful use of the design framework.

The opportunity for the students to physically interact with the fabrication process (see figure 7) increased their insight and supported subsequent explorations of the relationship between material system and robotic fabrication. Based on the authors' observations it was evident that initial challenges regarding the location of 'placement targets', leading to potential collision with neighboring bricks, were overcome through the option of interactive adjustments/repositioning of the bricks. This meant that instructions for the robot did not have to be fully determined. Correction of unforeseen events during the robotic fabrication process and incomplete instructions (ex. rotating the brick before placing) could be done by either hand guided or numeric interaction. This allowed students to use the robotic system without specifying and controlling all steps of the fabrication sequence, thereby supporting a trial-and-error based approach that aided the students' freedom during design exploration. Referring back to "approach C" in figure 5 one can argue that this interactive robotic-driven design process allowed for reflection-in-action, as defined by Schön (12), to take place also during the fabrication process, thereby enabling this design work mode to support the simultaneous act of thinking and doing. The study therefore suggests that an interactive robotic approach can support the explorative "what-if" questions that are fundamental to the creative and iterative design process.

However, the results of the study also showed that the need for interacting with the robotic fabrication process declined during the 3-week studio. While most of the student actively interfered with the robotic brick positioning process during the first days of the studio, this option was registered to be of less value as the design process advanced. The reason for this development can be found in the acquisition and accumulation of specific design knowledge and understanding of the design variables at play. The first days of interactive robotic-driven exploration of the brick-based material system allowed the students to effectively identify the inherent design variables and constraints, thereby establishing a firm understanding of the associated problem-solution space, as defined in the co-evolution model by Dorst and Cross (13). Furthermore, as the material system featured simple and identical wooden bricks it did not contain unknown or unstable parameters, making the shift to robotic simulation relatively unproblematic. The combination of a well-understood human-robot-material system and the option of simultaneous computer simulation of brick assemblies and robotic fabrication allowed the students to engage in a highly iterative computational design process. Further exploration of the physical robotic fabrication was still needed when the design exploration challenged the established boundaries making the result of the computer simulations inconclusive and unreliable. This explains the results of the shifting between design modes shown in figure 5, but also suggests that increased applicability of interactive robotics can be achieved by exploring material systems with more complex inherent properties that are more difficult to predict and control during the fabrication process.

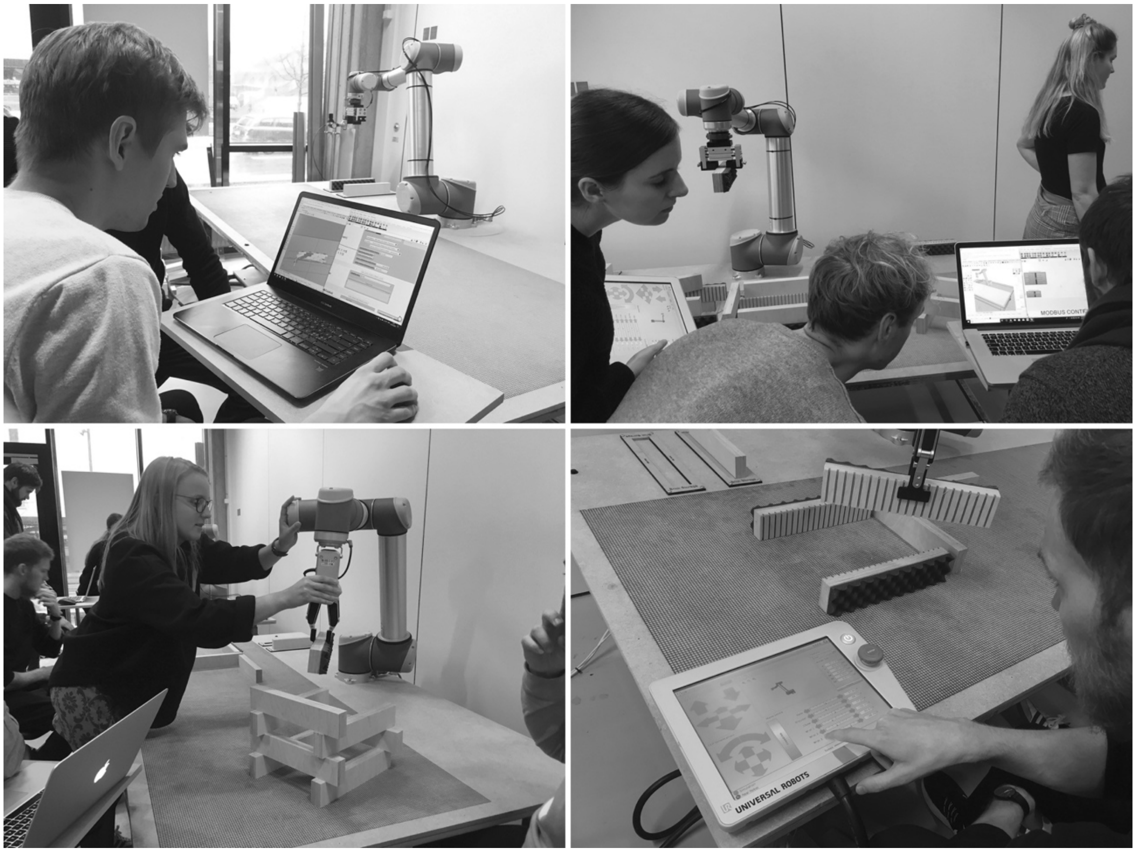


Fig. 7. Student-robot interactions.

Implementation of robotic fabrication did not however render traditional modes of designing obsolete or redundant. The use of hand drawing and manual brick stacking was frequently registered by the students and observed by the authors to support the design exploration throughout the studio. This suggests that varying aspects of the robotic driven design process was explored by applying the work mode that best suited the task at hand; brick patterns were quickly explored through hand stacking; possible relationships between geometries, acoustic performance and the situated context was explored through hand sketches; effects of gradual changes in brick positioning was tested through the precision of robot stacking. It should of course be noticed that during the study parametric design was a newly introduced mode of working and the students were therefore likely to seek familiar modes of designing when they could not overcome challenges due to lack of knowledge and experience.

During the study the students were introduced to a design framework that allowed them to explore a certain problem-solution space, but the system, due to its level of computational complexity, also confined the students and hindered both expansion and reconfiguration of this problem-solution space. Reflecting on the design outcome it is apparent that the design framework affected the individual design processes. Overall the design proposals had a strong integration of the project-specific design requirements and the students demonstrated a high level of comprehension concerning the relationship and effect of the various design variables at play. This suggests that the design framework supported the students in dealing with what Lawson would describe as a multi-dimensional design problem (14). While aiding the students in the integration of multiple performance criteria the approach seemed to inhibit their exploration of non-standard brick compositions and the aspects of interlocking and bonding of bricks were left unchallenged. The answer for this unfortunate impact on the creative design process is multi-faceted and one can argue that part of the answer can be found in the restrictions defined by the fabrication setup, the choice of robot and tool/gripper, or the limitation posed by the fixed dimensions of the wood/foam bricks. The author would argue that removing these restrictions would not benefit the design exploration, but on the contrary this would lead to an even larger solution space and contradicts the strategy of narrowing down the range of possible solution as argued by Lawson (14). Instead, this study would argue that the negative impact on the design process is mainly caused by the students' lack of computational design skills and their experience within computational design thinking.

Computational design skills and knowledge

Introducing a design framework that incorporates robotic technology in a computational modeling environment generates new demands for the creative designer. Through a reflection on the challenges that faced the students during the study, this section seeks to answer the second research question.

As seen in figure 8 the results of the parametric (computational) exploration of brick formations during the study showed to be limited in complexity, when compared to the results of the manual (physical) brick stacking. Based on these observations this study argues that the computational design skillset is crucial if designers are to fully utilize the potential of human-robotic design processes – in the same manner as hand drawing skills are important when exploring design solutions through sketching. To examine the importance of experience and domain-specific knowledge/skills future studies with human-robotic design processes should also include expert-designers as prospective users.

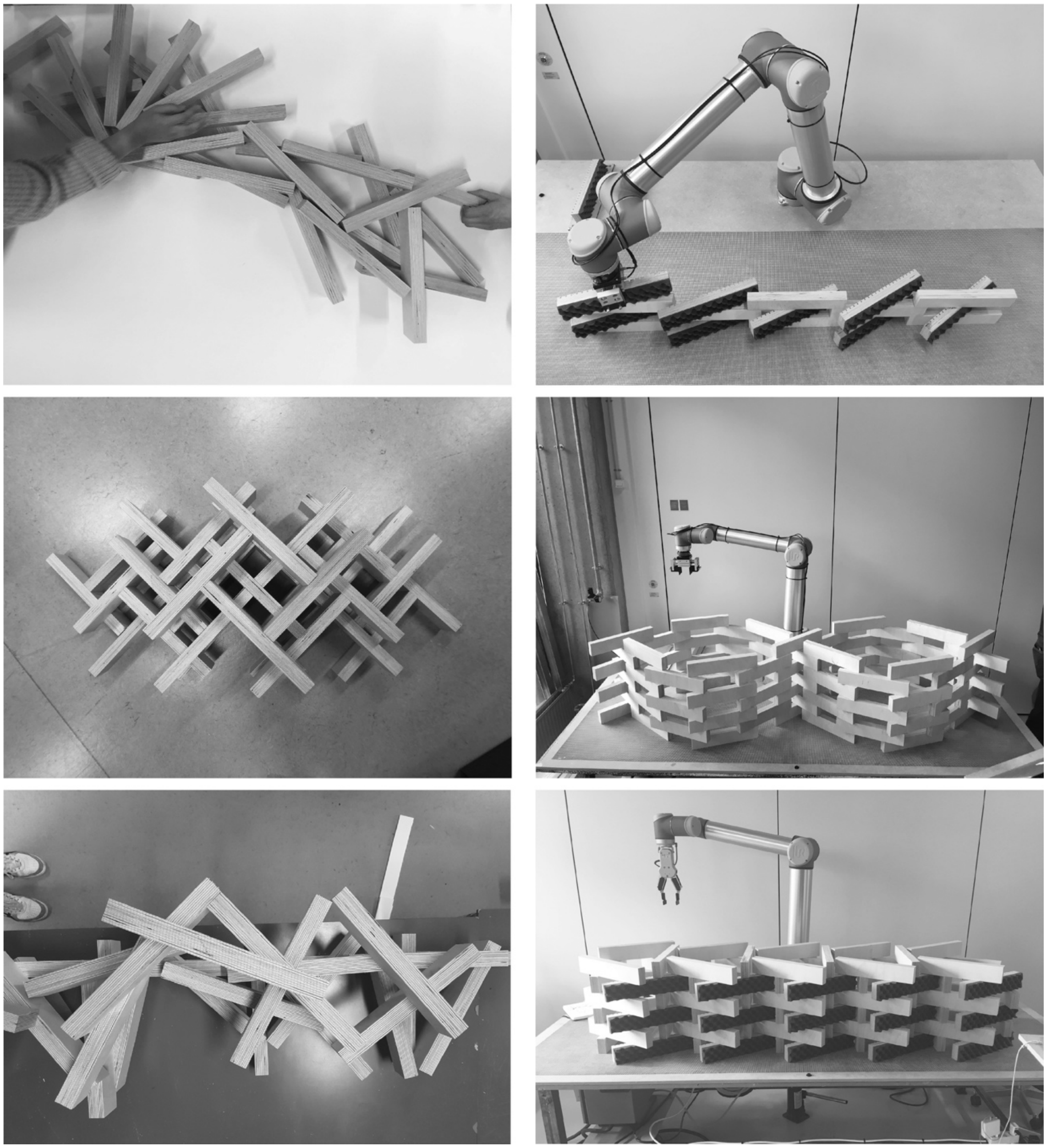


Fig. 8. Examples of brick formations stacked manually by hand (left column) and by robotic fabrication (right column).

The results of the study also suggests that it is the skills and knowledge of the student designers and not the software that restricts the design exploration. For some students limited computational design skills resulted in a negative influence on their ability to exploit the robotic fabrication setup and thereby challenge the material system. Interaction with the robot during the preliminary design exploration did not pose a problem for any of the participants, but challenging their design process with increasing requirements for acoustic performance, structural integrity and fabrication constraints, resulted in the desire for more advanced brick formations, which were unsolvable with their computational skillset and knowledgebase.

The robotic setup that enabled the students to explore the fabrication aspects, also confined them to a certain set of logical design procedures that they were able to alter and manipulate, but not radically change or divert from. This advocates for a need for computational designers with the skills to explore the material system and overcome the restrictions of the computational/robotic system. In the same manner as Frei Otto constructed physical machines/devices for exploration of material design systems, designers in the field of computational-robotic design needs the capability to build their machines/devices for design exploration (15).

Robots as creative co-designers

As has been argued above, the interactive human-robot design framework presented in this paper supports a non-deterministic design approach that allows for a more integrated, and even physically closer, collaboration between designer and robot. But is the robot really "collaborating" or is it merely executing commands already anticipated by the designer? Are precision and repeatability the only advantages of applying robotics in an architectural design process? What happens if the robot engages with the material system as a medium for suggesting alternative design outputs based on aspects that are perhaps more clear for the robotic system (ex. based on acoustic or thermal simulations) than it is for the designer? In the presented design processes it is the designer that supplies new design suggestions and the robot that reacts on them – the designer suggest a new placement of a brick and the robot places the brick as suggested. For a designer to engage with a collaborating robotic system it needs to be able to pose design suggestions – it needs to continue the iterative "what-if" process. To realize this iterative process of human-robot co-designing the robotic system needs to base its suggestions on the current state of the material system, which might change due to actions of the human designer, and therefore needs to be capable of repeatedly sensing its environment. But maybe the robotic system should not necessarily try to "sense the world" in the same way as its human co-designer. Sensing the world differently might lead to novel design suggestions.

Fig. 9. Shows the human-robot fabrication process.

Fig. 10. Shows a full-size demonstrator of the double-wall brick system.

Fig. 11. Shows a full-size demonstrator of the double-wall brick system.

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