Parawood

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Framework for On-site Robotic Timber Fabrication

A PhD thesis by Jens Pedersen

Book I of II

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Fig 0.1
A robotically fabricated version of the timber-framing construction method that was developed and commercialised through the thesis.

Fig 0.2
A robotic operator programming a robot through physical drawings/markings made on a workpiece.

Parawood

Framework for On-site Robotic Timber Fabrication

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Book I of II

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PhD information (I)

Framework for On-site Robotic Timber Fabrication
Jens Pedersen

PhD Dissertation submitted: July 5th, 2023

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Summary // English (II)

Since 1980, industrial robotic arms have been explored for their potential to revolutionise the construction industry - a potential that was uncovered from the effects of implementing robotic arms in manufacturing industries, such as the car industry. Within this profession, dramatic improvements in production efficiencies and lowering of costs were observed. However, the challenge in unlocking this potential within construction could be the contrasting fabrication environment and task space; Exemplified by how car manufacturing is carried out in controlled and known factories, enabling to make copies of cars efficiently. In contrast to this, construction is performed outside at different sites, at times in an ad-hoc fashion, and very rarely are the construction tasks identical.

Mitigating this challenge is the subject of this industrial PhD project, "Parawood: Framework for On-site Robotic Timber Fabrication", carried out in close collaboration with the industry partner; Odico Construction Robotics. Odico has developed a transportable robotic fabrication concept, Factory-on-the-Fly (FotF), which this project aims to extend with new processing capabilities and instruction methods. The FotF system is a closed envelope (trailer or container) containing an industrial robot arm and a unique robotic work environment for manufacturing tasks. Instructions for the tasks are given through a software app on a tablet that configures fabrication actions for element(s). Odico's aim in developing such a system is to improve the work environment for onsite workers while improving construction efficiency.

This research is focused towards developing a solution that can assist carpenters' on-site practices, which is a construction process commonly carried out on-site. However, equipping carpenters with a robotic solution presents two challenges; 1) how can carpenters, who are usually robotic non-specialists, best instruct fabrication information, and 2) how could the robot fabricate elements that support carpenters' current practice? Thus, the project is approached from the position of the construction site, where it is explored how robotics can be intuitively used by robotic non-specialists while identifying a use-case and corresponding robotic work environment for on-site robotic timber manufacturing.

Consequently, the research develops two trajectories of equal importance that cover 1) ways in which robotic fabrication can benefit on-site practice; and 2) how ad-hoc fabrication information can be instructed to a robotic system by non-specialists.

Despite the FotF system having a method to instruct robotic actions, it can be challenged by unplanned ad-hoc fabrication requirements. Therefore, this research proposes to augment the FotF software framework with new software functionalities that allow operators to develop fabrication instructions based on physical drawings. Thus, if a challenging fabrication task arises, it is possible to create the fabrication instruction through physical drawings or markings on a workpiece. In conjunction with enabling such an intuitive instruction method, the research discusses built demonstrators that contribute to a better understanding of how FotF systems could benefit the onsite processes for carpentry, which incidentally also led to the proposal of a new timber FotF unit for Odico in 2022.

Short note: This thesis has been developed as a "PHD-by-publication" and is therefore presented as two books, namely, a first book that comprises the PhD structures, aims, background, methods and a summary of the findings across the published papers, and a second book II that contains a series of papers published using the framework of book I.

Summary // Danish (III)

Siden 1980'erne er industrielle robotarme blevet udforsket for deres potentiale til at revolutionere byggebranchen – et potentiale der blev identificeret gennem industriel fremstilling af emner, som det ses i bilindustrien. Her har man observeret en effektivisering af produktionen, som har medført en mindsket kostpris på de producerede emner. Dog har konstruktionsbranchen ikke formået at udnytte dette potentiale, hvilket kan være forårsaget af forskelle i produktionsmiljø og opgaver. Bilindustrien opererer for eksempel i nøje planlagte fabrikshaller hvor bilerne fremstilles som identiske emner. Bygninger opføres derimod udendørs, hvor ad-hoc-løsninger kan forekomme, og to bygninger er sjældent ens. Denne udfordring er målet for denne erhvervsphd; Parawood : Framework for On-site Robotic Timber Fabrication", som er udført i nært samarbejde med projektets industripartner; Odico Construction Robotics. Odico har udviklet et transportabelt robotfabrikationskoncept; Factory-on-the-Fly (FotF), som dette ph.d. projekt søger at udvide med nye fabrikations- og programmeringsmuligheder. Et FotF system er indeholdt i et lukket volumen (en trailer eller container), som indeholder en industriel robotarm, og et unikt robotarbejdsmiljø. Robotten kan programmeres via en app, der gør det muligt at konfigurere simple fabrikationsopgaver. Med dette system har Odico forsøgt at udviklet et system som kan forbedre arbejdsmiljøet samt effektivisere, hvorledes arbejde udføres på byggepladsen.

Forskningsfokusset for dette projekt har været at identificere hvorledes sådan et system kan bidrage positivt til tømrernes arbejdsproces, som normalt udføres på byggepladsen. At udstyrer en tømrer med en robotløsning giver to udfordringer; 1) hvordan kan en tømrer, som ikke er robotspecialist, programmere sådan et system, og 2) hvordan kan sådan et system producere emner som bidrager positivt til deres nuværende arbejdsgange. Projektet forsøger derfor med afsæt i byggepladsen, at identificere hvordan tømrerne intuitivt kan programmere robotter. Derudover vil projektet undersøge hvilke elementer robotterne kan producere der vil bidrage positivt til tømrernes arbejdsgang, samt identificere hvorledes robottens arbejdsmiljø skal organiseres for at muligøre fabrikationen af sådanne emner.

Selvom FotF-systemer indeholder en metode til at programmere robotbevægelser, så kan systemet blive udfordret af ad-hoc fabrikationsaktiviteter. Derfor, forslår denne forskning at udvide den nuværende FotF programmeringsmetode, med en ny der gør det muligt at programmere robotter gennem fysiske tegninger. Når der opstår en ikke-planlagt opgave, kan tømreren programmere robotten ved at tegne direkte på tømmeret som skal bearbejdes.

Samlet set vil projektet bidrage med viden om hvordanet FotF-system kan bidrage positivt til tømrerfaget, ved at anvende byggede prototyper til at demonstrere hvordan teknologien virker. Forskningsprojektet har bidraget til udviklingen af en ny træ-FotF-enhed for Odico i 2022.

En kort note; Projektet er udført som en paper-baseret afhandlingDerfor er projektet opdelt i to bøger, hvor den første bog indeholder ph.d.ens struktur, mål, baggrund, metode samt en kort beskrivelse af opdagelser og konklusioner fra de syv publikationer der er indeholdt i den anden bog.

Acknowledgements (IV)

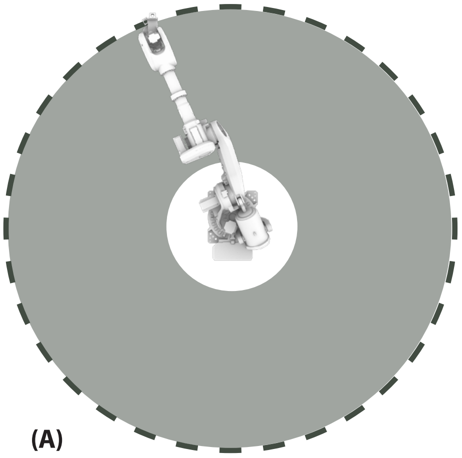
The PhD would never have come to pass without a group of special collaborators; thus this section acknowledges their special contributions to the project.

Initially, I extend my sincerest thanks to Asbjørn Søndergaard for bringing me to Odico Construction Robotics, where I was enabled to conduct my PhD studies, which have positively contributed to Odico's rich tapestry of knowledge, projects and solutions. Furthermore, my greatest appreciation is extended to both the hardware and production teams at Odico, which have supported the hardware developments that enabled the proposal of a new timber fabrication unit within the Factory on the Fly ecosystem.

Furthermore, I would like to extend my gratitude towards Anders Bundsgaard, for his support and creative input throughout the PhD and to Anetter Fjerbæk for helping make activities go smoothly.

Secondly, which goes without saying - a great and resounding thank you has to be placed with my supervisor team; Claus Peder Pedersen and Dagmar Reinhardt, Claus; thank you for your support when I felt I was on shaky grounds within the project. Dagmar, my sincerest appreciation is directed to you and your unwavering support through my project. Your continued help in finishing a multitude of papers and questioning of the project has helped fuel the project forward and got it to where it is today. And you have done it all from the other side of the world! I can't thank you enough for your continued participation in the project.

Lastly, my wife and life partner, Julie, who has been my biggest supporter throughout the project, I must to give you the biggest thank you of all. You have given me the time and space to pursue this degree, despite the project at times having taken time away from home and our two wonderful children - Eske and Hedvig. I love you all dearly and can only offer you my humblest thank you.



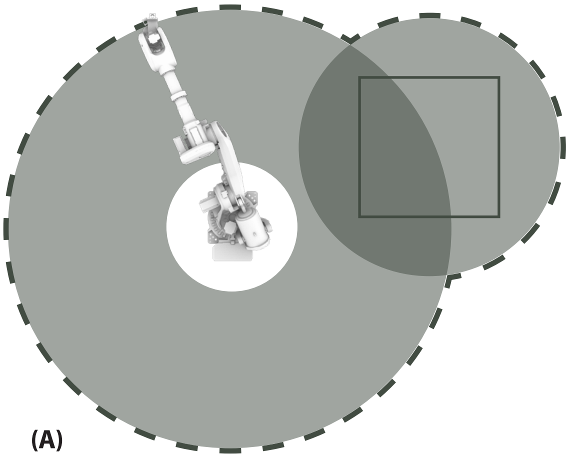
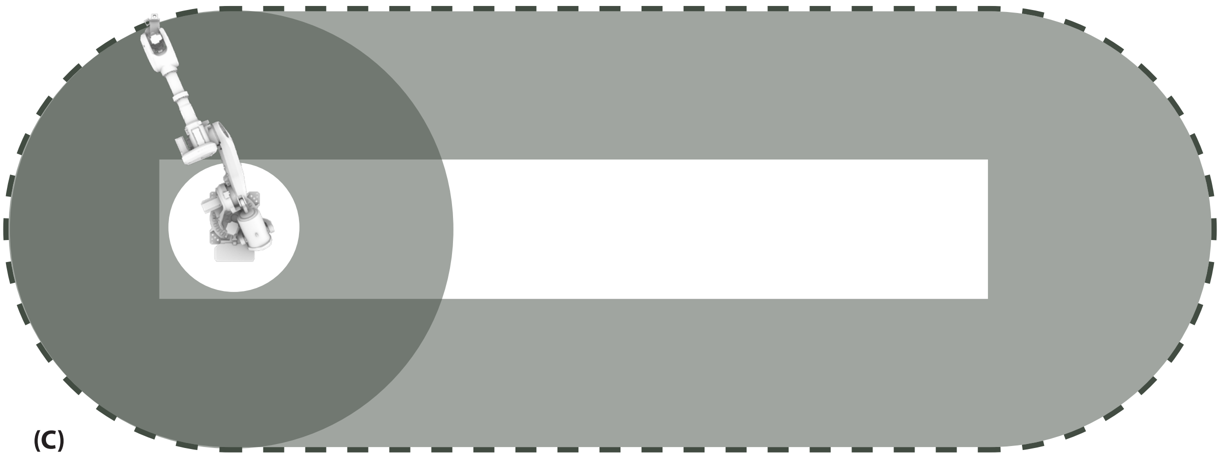


Fig 0.3
A) Conventional robotic envelope, i.e. what the robot can read from a stationary position, B) the robotic work envelope is extended through the addition of a rotary table, and lastly, C) the robotic work envelope is extended by positioning the robot on a linear track.



Definitions (V)

The thesis employs a few shorthand terms and potentially some specialised terminology outlined in the following section.

Shorthand

FotF: the Factory-on-the-Fly.
CNC: Computerized Numerical Control.

Terminology

Robot or industrial robot arm
The research uses the term "robot" or "industrial robot arm" interchangeably. Therefore, any word in reference to a robot or robotic process will always refer to an industrial robot arm.

Factory-on-the-Fly.
The research subject to develop throughout this research project. The term Factory-on-the-Fly is a registered trademark by Odico.

Workpiece
The element being machined by a robot or a CNC.

On-object-drawing
This term describes physical drawings made on top of a workpiece.

Robotic work envelope
This term is used to describe the envelope within which the robot can reach - commonly, this is referred to as the robotic "reach". But the envelope can be extended through secondary axis systems that either move the robot or the element being machined. This process doesn't extend the reach of the robot but enables it to reach within a larger envelope, thus the use of the term robotic envelope (fig 0.3).

Robotic Work Environment
This term describes additional elements accessible to the robot within its work envelope. This can be subsidiary systems that extend the reach of the robot, or processing stations (fig 0.3).

Demonstrators
Within this research the term "demonstrator" is used in reference to either a physically built entity or a software system. The demonstrator then becomes a description of the knowledge demonstrated to present a given entity - whether it is digital or physical.

Automation Technologies
This is used in reference to describing technologies aimed at automating tasks within architecture, where this thesis primarily uses this term in reference to technologies such as CNCs or industrial robotic arms.

Contents

Fig 1.1
A Factory-on-the-Fly system, enquired by a client that wished to explore both robotic 3D printing and robotic milling.

Chapter 1

Introduction

Chapter 1 Overview

This first chapter introduces the research project and its aims and objectives, alongside an overview of the project's industrial context, and how the aims of the industrial partner have informed research toward developing new knowledge. As the leading industrial PhD supervisor, Odico aimed to add new functionalities to their transportable robotic concept, the 'Factory-on-the-Fly' (FotF). Hence, the research identified two interlinked research trajectories to develop, trial and expand this concept across academia and practice through a series of demonstrators, which centre on 1) the requirements for robotic non-specialists to intuitively use robotics; and 2) the use case and corresponding robotic work environment for robotic timber manufacturing in a carpentry context for 1-2 storey housing. This exploration has resulted in a multi-disciplinary project anchored in architecture, with intersecting knowledge from the domains of manufacturing and fabrication, engineering, computer science and construction robotics. This chapter introduces the research questions and methodological framework rooted in research through design, augmented through action research, to respond to the research questions. Lastly, the chapter outlines the scope and limitations of the project, before introducing project collaborators and executed workshops.

1.1 Introduction

On-site construction processes have seen little to no innovation throughout history, and while some technologies have improved, the construction process remains the same [Balaguer & Abderrahim, 2008, McKinsey 2015, McKinsey 2017, Berger, 2016]. In contrast, manufacturing industries have seen an increase in innovation, as exemplified by the automotive industry, where human labour is being substituted with industrial robotic arms, resulting in boosted production efficiencies and an overall reduction in costs of both cars and robotic technologies [Hasegawa 2006, Balaguer & Abderrahim 2008, McKinsey 2015]. However, the AEC industry has neglected such innovations and digitisation, which has left an unfulfilled potential to be optimised through robotic technologies [Hasegawa 2006, Balaguer & Abderrahim 2008, McKinsey 2015, McKinsey 2017, Berger, 2016]. The AEC industry did explore this potential in the 1980s [Hasegawa 2006, Yoshida 2006], whereas today, digital fabrication technologies, CNC or robots, in construction, are primarily seen in off-site facilities producing modules for on-site assembly [Popovic, & Winroth 2016, Rauch et al. 2015]. Furthermore, the specialist knowledge available in off-site factories is not available at the construction site, thus presenting a technical divide that requires bridging to implement on-site robotic frameworks successfully.

An example that brings robotics to the construction site while bridging the technical divide is the 'Factory-on-the-Fly' (FotF) [Odico2] concept by Odico Construction Robotics, which through a proprietary configurator software [Neythalath 2021, Neythalath et al. 2021] aims to allow non-specialists to shift off-site efficiencies to the construction site. However, the current software has a preset of defined functionalities that can be challenged by unplanned fabrication actions, which are expected to be part of on-site construction practices. Therefore, effectively facilitating using a FotF system requires augmenting the current software solution to allow robotic non-specialists construction workers to instruct ad-hoc fabrication to mitigate the uncertainties of as-built elements. Additionally, it is required to understand how such a system can positively benefit on-site construction processes through digitally manufactured elements. These two areas, what/how elements are made and how/who is instructing the system, define the field in which this research aims to contribute with knowledge.

1.2 Research context

This thesis is developed within the Danish system of an industrial PhD project; in collaboration with the industry partner; Odico Construction Robotics [Odico1] and at the Aarhus School of Architecture [Arkitektskolen Aarhus], where financial support has been given by the Danish Innovation fund [Innovationsfonden]. A short background to the industry partner is given here: Odico is an industry leader in robotic fabrication of elements for casting concrete in the construction industry, much to the credit of clever use of robotic wire cutting [Søndergaard 2014, Søndergaard & Feringa 2012, Søndergaard et al. 2016]. Since 2018 they have expanded the company strategy to include the development of transportable robotic units under the umbrella term 'Factory-on-the-Fly' (FotF) (fig 1.2), developed to support on-site construction processes. The system contains the following physical components: a transportable work environment (trailer or container), an ABB robotic manipulator, and a tablet with software components for instructing the robot to configure a closed list of actions and tasks.

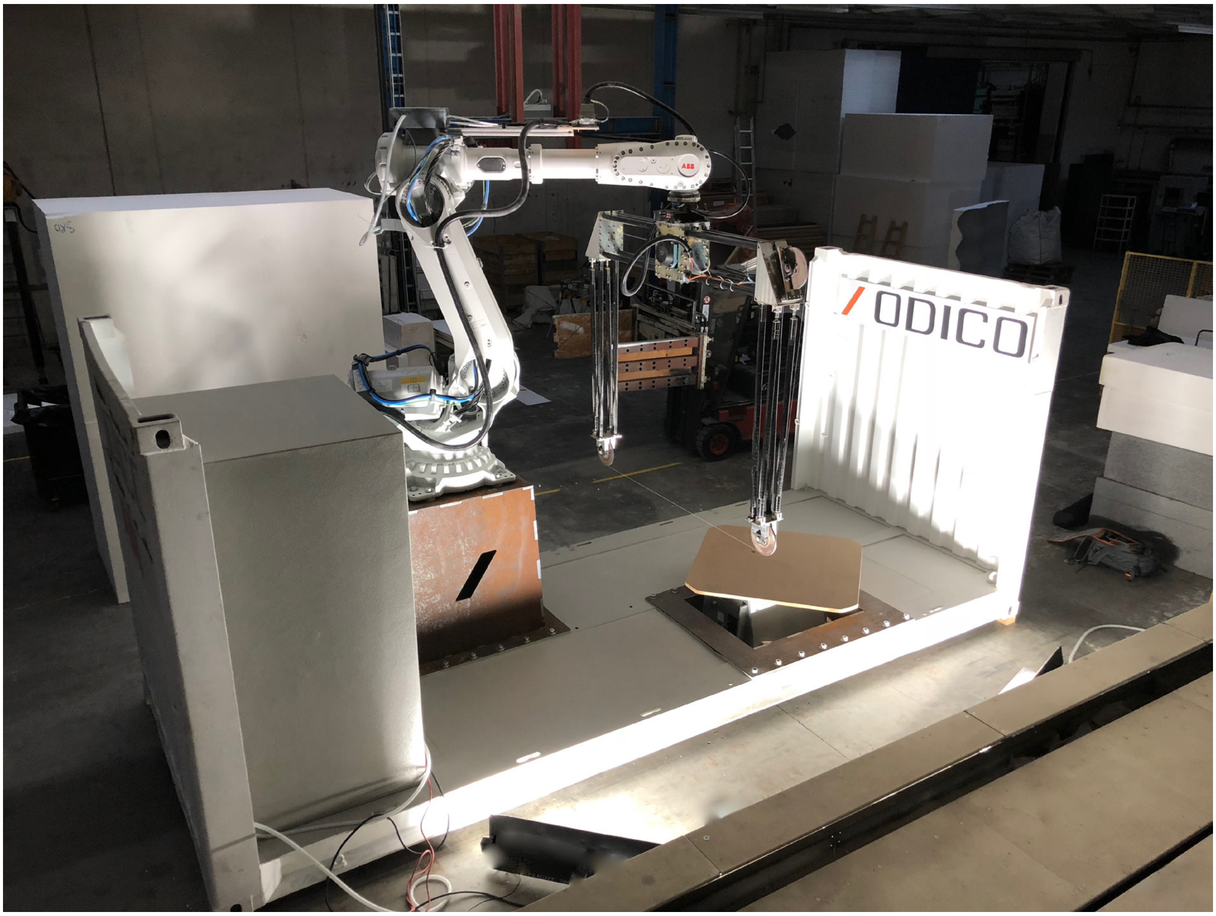


Fig 1.2
A Factory-on-the-Fly system, equipped here for robotic abrasive wire cutting.

As an industrial-based PhD, this research has adopted the FotF system as a base premise and research context and aligns to develop a new solution for a growing set of FotF solutions. The FotF system has already shown promise for successful industrial applications, as demonstrated by a fully commercialised solution that assists pavers in cutting pavement tiles while improving the overall working environment for the pavers by minimising noise and dust pollution [Odico3]. In this FotF application, the pavers instruct the robot with fabrication actions through a configurator software hosted on a tablet (fig 1.3) [Neythalath 2021, Neythalath et al. 2021, Neythalath et al. 2021]. In understanding the full system, and how it creates value for Odico, it is possible to position the FotF system in an abductive framework (fig 1.4), which enables it to isolate important research areas pertaining to the FotF solution.

Fig 1.3
A) A paver positioning a pavement stone in the robotic work environment. B) A snapshot of the software which enables pavers to instruct cuts to the robotic unit, and C) the full system, where the robot is positioned within a trailer environment, making it highly transportable.

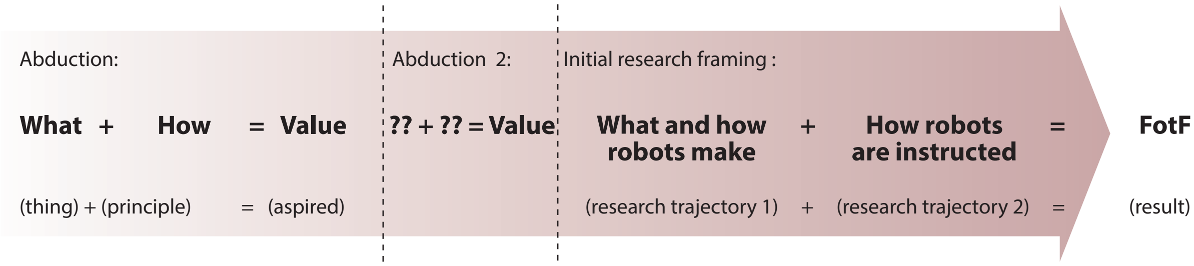


Fig 1.4
This abductive diagram identifies the elements that enable the FotF system to create value for Odico. The basis for the 'abduction 2' method is described by Groat and Wang [Wang & Groat 2015].

This analysis determined that the research would be conducted using two separate research paths, which are pursued simultaneously. The goal is to combine these paths into a cohesive FotF system eventually.

Research trajectory I has, in unison with the industry partner, been focused towards robotic timber fabrication. Thus, the research aims to identify how timber elements made with a FotF system can support on-site carpentry processes. A prerequisite of this line of enquiry is to identify how such elements can be made within a FotF unit. The project chose to focus on timber due to the increased focus on constructing with timber globally since it is a renewable resource that sequesters carbon within its building mass. Furthermore, material and engineering innovations have enabled to replace or minimise concrete use in buildings when replaced with mass timber modules (CLT) [Dangel, 2016].

However, despite timber being renewable, we should explore resource-efficient timber construction methods compared to CLT members (fig 1.5). If we were to replace 25 % of current concrete consumption with timber, we would need to replant a forest 150 % of the area of India each year [Zeitung 2021]. The project, therefore, focused on resource-efficient timber construction methods such as timber framing [Timber framing 2022, Munch Andersen 2018, Dangel 2016] or the half-timbered construction system [Benzon 1984, Jensen 1933, Vejlby 1991], both are construction types executed on-site by carpenters [Timber framing 2022, Vejlby 1991]. These construction methods are usually used for 1-2 story housing, which accounts for upwards of 60-70 percent of the yearly built square metres in Denmark [Danish Statistics], of which 20-30 percent are commonly made from wood. These could be made from locally sourced wood annually [Danish Wood]. This equates to roughly 12-18 percent of annual builds in Denmark alone. Thus, this presents a significant market share to propose a robotic solution for. Thus, research trajectory I aimed to develop a FotF solution that can migrate manufacturing efficiencies from the factory to the construction site while manufacturing elements that assist carpenters in making the structure of timber houses. Developments within this research trajectory revolve around built demonstrators.

Such a system will be instructable from the current FotF software framework [Neythalath 2021], which has documented use of configuring simple parameters for fabrication tasks, such as fabricating formwork for stairs or specifying parameters for specific pavement cuts [Neylath 2021]. However, such an approach might be challenged by ad-hoc challenges that can emerge on the construction site, as exemplified by how modules from off-site factories may need adjusting when arriving on the construction site [Rauch 2015]

Consequently, research trajectory II focuses on the user and how the current FotF software could be augmented with a new instruction method to enable for ad-hoc instructions to be developed by robotic non-specialists. This trajectory develops knowledge for how skills can be adopted from different user groups (robotic non-specialists), and direct how physical inputs can allow for ad-hoc fabrication action, where developed methods are tested through design-led user studies and built demonstrators.

This places tension between research trajectories I and II, since I is aimed at developing a solution that becomes an efficient file-to-factory system. In contrast, research trajectory II emphasises an alternative method to instructing robotic actions, whereby robotics could become an extension of creative practice. This tension unfolds through the research, where the aim is to combine the two trajectories towards the end of the project.

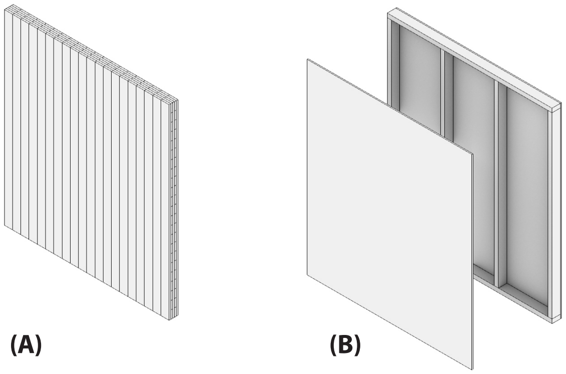


Fig 1.5
Shows the difference between a mass timber wall segment and a timber framed element. A) Is a mass timber wall segment, which has a 270 % higher material use compared to the timber-framed wall segment in B).

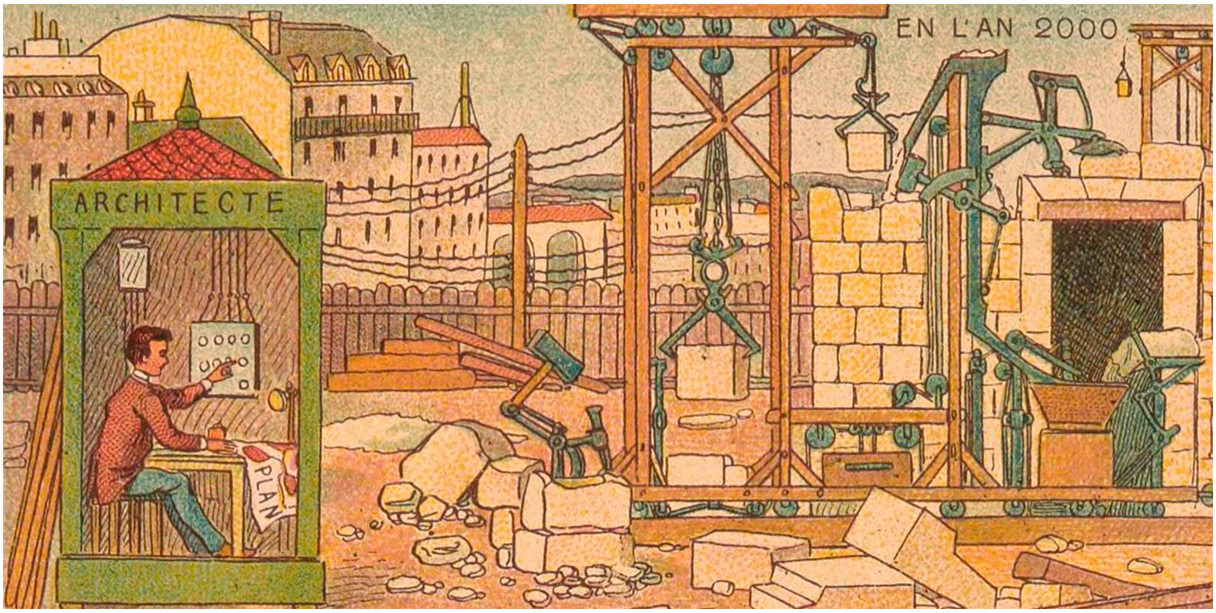


Fig 1.6
The future architect Anno “2000” was imagined by a French cartoonist in the early 1900s. It depicts how he imagined the future to be. A future where architects work on the construction site using automated systems [Asimov & Cote 1986].

1.3 Research Motivation

The research aims to explore the potential of digital fabrication technologies in enhancing on-site construction processes. As a result, this project has become an extension of my personal quest to become a ”digital craftsman,” embodying a combination of digital and physical craft techniques and seamlessly navigating between them. This pursuit led me to collaborate with Odico Construction Robotics, the industry partner for my PhD, which embraces computational and digital fabrication tools as integral components of craft techniques, blurring the boundaries between them.

Another factor that sparked my interest in this research is my personal affinity for working with wood and my experience in academia, where I have conducted various workshops on robotic fabrication. During these workshops, I observed that many participants faced difficulties due to the significant amount of new knowledge they needed to acquire, such as McNeelRhinoceros3D (Rhino) and Grasshopper3D (GH), before utilising a robotic cell effectively. As a result, I aspired to leverage my PhD to develop an intuitive approach to working with digital fabrication technologies specifically tailored to woodwork.

1.4 Research Background

The project builds upon a background of multiple fields but is anchored in architecture. The description of these fields unfolds through three sections in Chapter 2, as reflected in fig 1.7. The initial section details a reflection on how construction information is instructed on the construction site, informing the premise of the new robotic instruction method to make it intuitive to construction workers (section 2.1). Following the reflection is a section that details the technical framework to enable such an instruction method (Machine Learning and Computer Vision), which leads to a description of how previous projects have employed a similar instruction process and how this project differs from them (section 2.2).

Lastly, section 2.3 details the state-of-the-art of robotic timber fabrication for both on- and off-site facilities since very few such on-site systems exist. This section aims to understand the robotic work environments employed in different projects. This analysis revealed that two approaches to robotic fabrication have emerged over the past twenty years, each with unique robotic work environment features. These unique characteristics are analysed to identify which of the two approaches is best suited for on-site robotic fabrication work.

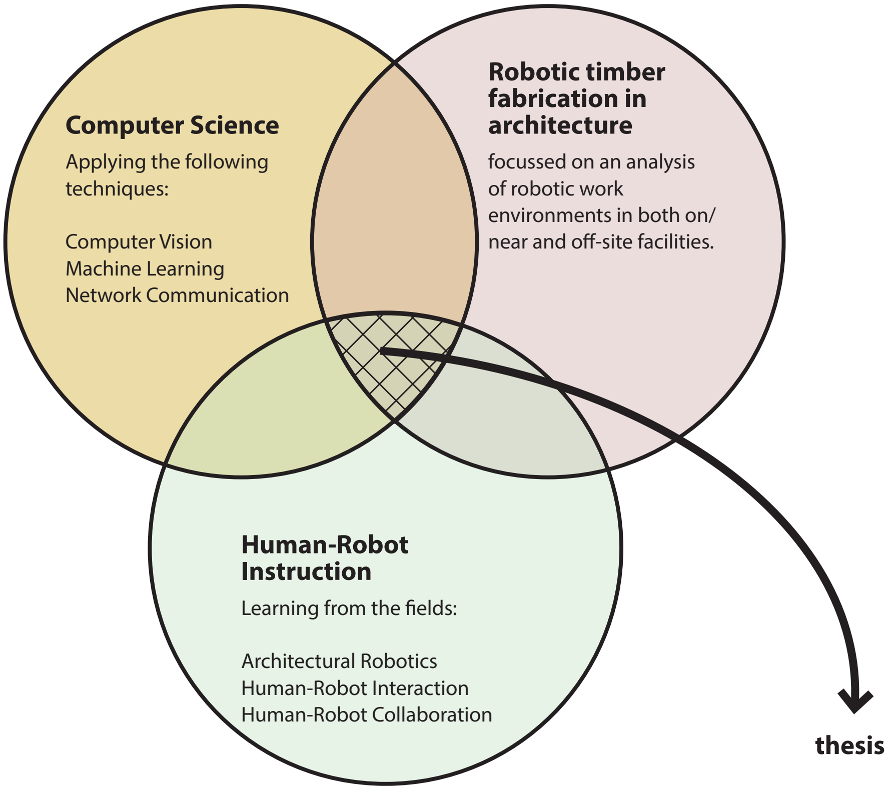


Fig 1.7
This illustration highlights the interdisciplinary background employed through the thesis, which comprises Robotic Timber Fabrication, Human-Robot Instruction and Computer Science.

1.5 Research Questions

The research is motivated by the following research question:

R: How can robot programming be made intuitive and accessible to a non-specialist user in the context of timber fabrication for construction?

It should be noted that while the research explored the problem of intuitive robot instructions, this was done in conjunction with another research trajectory running parallel throughout the project. Thus, research questions are posed in pairs for either research trajectory to identify how a new timber FotF could benefit the carpentry profession, and how fabrication actions can be intuitively instructed.

Consequently, the sub-questions for research trajectory I address the "what" (i.e. the content) the new FotF will make, and the "how" (i.e. the method) by which it will manufacture elements:

Can onsite robotic systems contribute positively to the manual carpentry processes? (RQ 1.1)

How can on-site robotic fabrication systems be designed to influence the construction industry? (RQ 1.2)

Similarly, sub-questions for research trajectory II focus on understanding how robotic non-specialists are enabled to instruct robotic fabrication actions:

How can robots be instructed by users with limited knowledge about robotics? What are the critical aspects and methods that enable such a system to function? (RQ 2.1)

Can instructing robotic information through physical drawings, allow robotic non-specialists, to instruct ad-hoc robotic fabrication information? (RQ 2.2)

1.6 Research Methodology

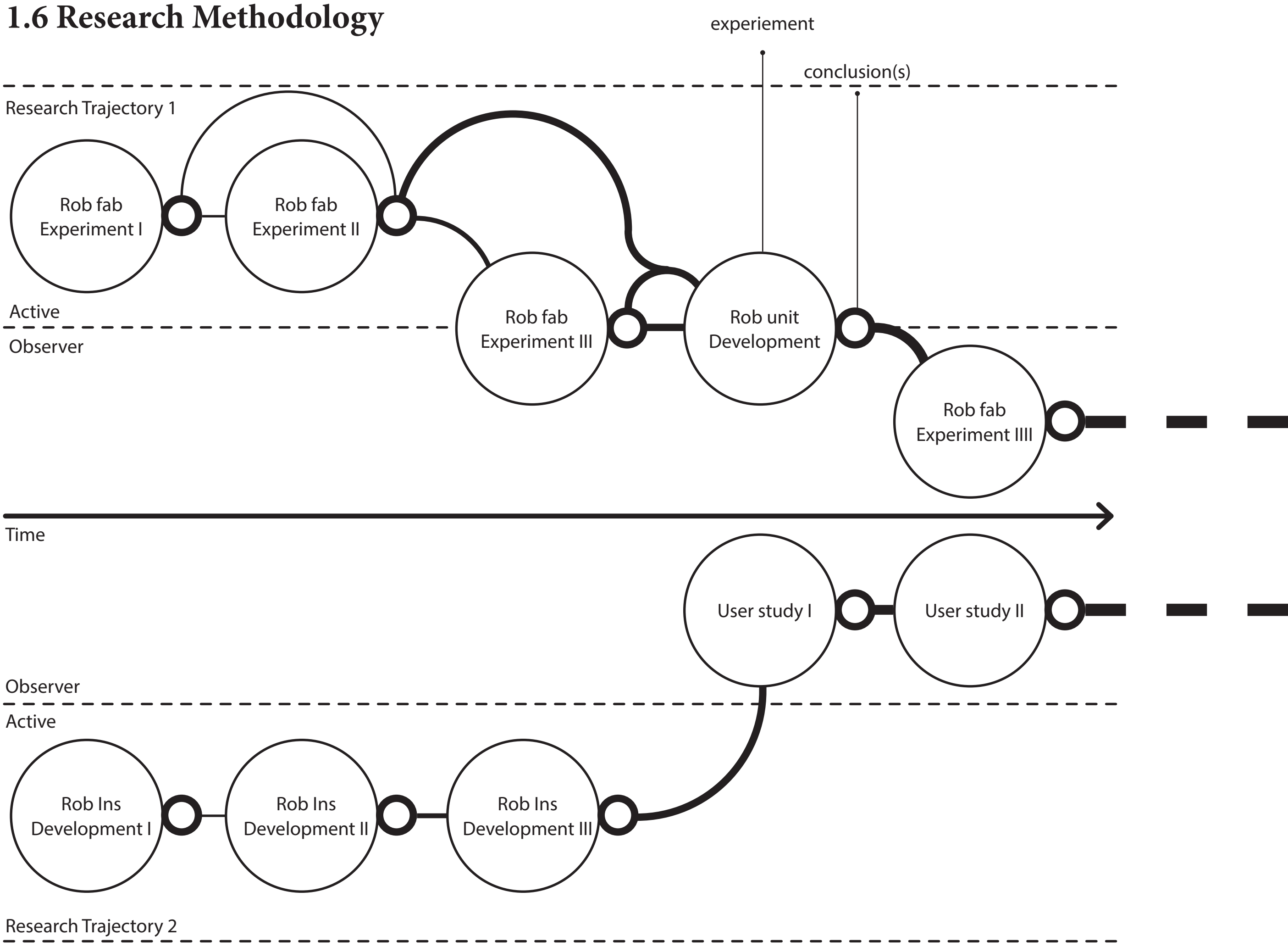


Fig 1.8
This diagram details the research design, and how it has been carried out through a series of parallel experiments in two individual research trajectories. The position of the experiments signifies the position of the researcher - namely if they have been an observer, active or a hybrid.

The research questions have been addressed through an epistemological framework that embraces the contrasting aims of the two research trajectories. However, both trajectories commonly use design to develop knowledge, which anchors the project within a design-led research method [Frayling 1993, Lenzholser et al. 2013]. Here the practice of design is used to develop knowledge, whereas a secondary framework is used to structure research trajectory II design experiments (1.6.2).

Thus, research in either trajectory is developed through demonstrators built physically in 1:1 or made as functioning digital systems. Each demonstrator develops knowledge that informs subsequent demonstrators. Research trajectory I derives knowledge from built demonstrators to propose a new FotF system from analysing the robotic work environments that fabricated the demonstrators. Research trajectory II develops an intuitive instruction method through a cyclical development process, which is tested through design-led user studies or built demonstrators. Thus, design is attributed a central role in how this project develops technologies by designing construction processes, a robotic system, an instruction method and corresponding software functionalities.

The research design for this process is outlined in (fig 1.8), where the research trajectories and their experiments are described with links between them to explain how they have influenced one another. Despite the experiments being carried out concurrently, the aim is to merge the trajectories towards the end of the thesis.

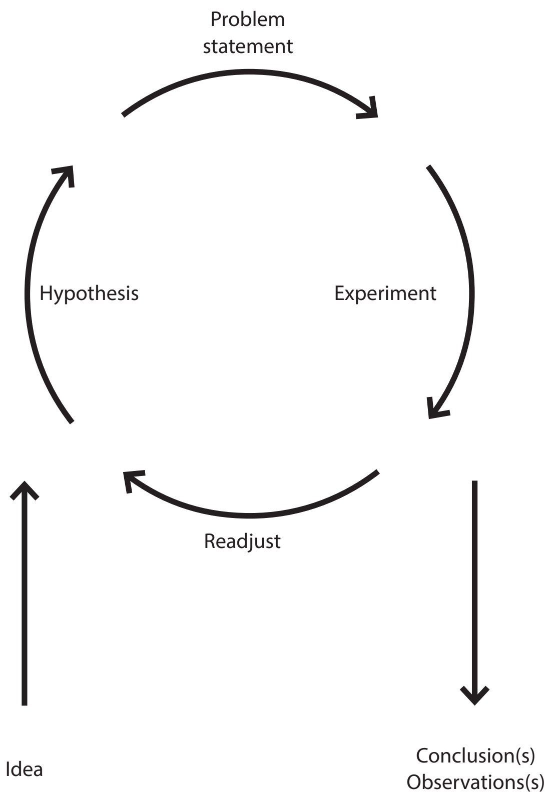


Fig 1.9
A description of the cyclical approach applied in the project.

1.6.1 Research through Design

Design-led research has a high versatility and consequently has been applied across multiple unaffiliated fields as a method for research, such as landscape architecture [Lenzholser et al. 2013] or Human-Computer Interaction [Zimmermann et al. 2007 and 2010]. Thus, this thesis adopts design research as a well-suited method to be applied within the multidisciplinary field of this research. Frayling describes how design-led research can be carried out through three different approaches; Research into Design, Research through Design and Research for Design [Frayling 1993]. This research follows the Research Through Design (RtD) method, where designing and making leads to demonstrators that constitute a body of knowledge. As Frayling and Zimmermann argue, this enables an iterative research approach where thinking and doing are inseparable elements (fig 1.9) [Frayling 1993, Zimmerman 2003].

Within the RtD framework, Frayling describes how RtD can be applied in "material research", "development work", or through "Action Research". Due to the nature of this research, the thesis follows RtD aimed towards development work, which is described as; "...customising a piece of technology to do something that no - one had considered before, and communicating the results." [Frayling 1993]. However, a challenge in following this approach is that knowledge can become internalised within made demonstrators if their process and findings aren't carefully documented. Thus, this research uses photos and video that are logged in progress reports that formed the basis for the publications in book II [Frayling 1993, Zimmerman et al. 2010].

The RtD development approach has been applied to both research trajectories, where research trajectory II has structured the research through a cyclical action research framework (1.6.2). Research trajectory I has followed the iterative process of fig 1.9, to develop knowledge towards proposing a new FotF system for fabricating linear timber elements.

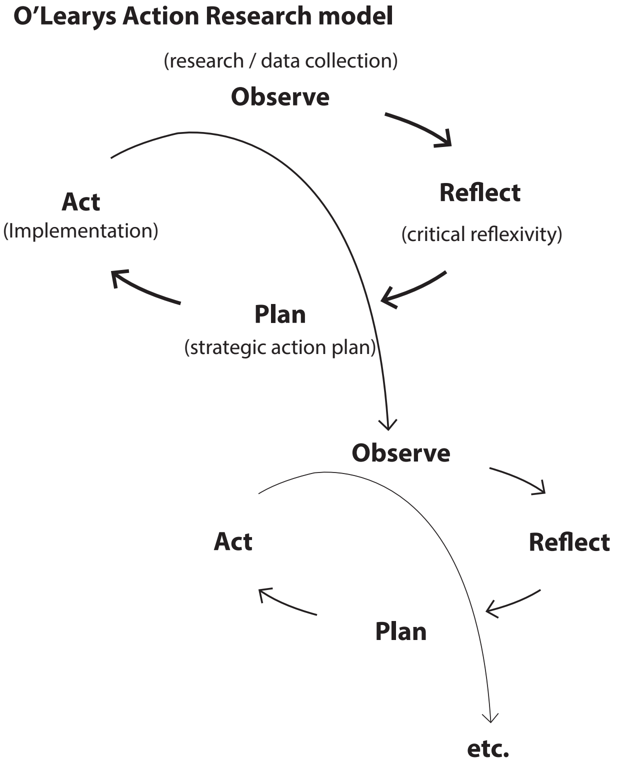
This process centres around built demonstrators that test, or retest, a series of established principles that have been identified from an analysis of how robotically fabricated elements could positively influence the construction industry. These principles are based on isolated topics from the McKinsey reports [McKinsey 2015, McKinsey 2017], which can be mitigated or tested through a process of making. The demonstrators are evaluated towards, how well they were found to mitigate the identified principles, where positive findings can be re-applied in new demonstrators to refine the response to how a principle is expressed.

This process, as this thesis discusses, enabled to identify what a new transportable robotic unit should make, and consequently how it is made, based on an analysis of the robotic work environments that enabled fabricating the demonstrators. The pre-requisite for this approach is that both the findings in relation to the tested principles are documented alongside the robotic work environment that enabled fabricating the given demonstrator.

1.6.2 Action Research

Research trajectory II augments the RtD process through an action research framework to develop a new instruction method for robotic fabrication. Action research is often employed by academics engaged in practice research, resulting in research informing practice and vice versa [Frayling 1993, Avison et al. 1999]. Action research seeks to implement change in a context through a cyclical research process [Zimmerman et al. 2007, Zimmerman 2010, Avison et al. 1999], where the studies follow a defined sequence of observation, plan and act [O'Leary 2004]. Over the years, action research has primarily been used as a framework for research - meaning that multiple versions of the framework have emerged [Avison et al. 1999]. Of the many versions, this research has focused on O'Leary's action research framework that, through a cyclical process, addresses Observe, Reflect, Plan and Act [O'Leary 2004]. Through repeated cycles, the research moves towards a given "optimum", where a solution to a given contextual challenge is found.

For this research, it has been chosen to modify O'Leary's model, so each cycle contains the following steps; Analyse, Hypothesise, Plan, Act (fig 1.10). The aim of this shift is to initiate the research through an analysis/synthesis process, which identifies what the new instruction process should be. Subsequent cycles begin by analysing the previous cycle, before progressing through the other steps. Cycles can be evaluated through personal tests of the developments or user studies with questionnaires or semi-structured interviews. Each cycle is documented through photos and progress reports that have formed the basis for papers.


O'Learys Action Research model

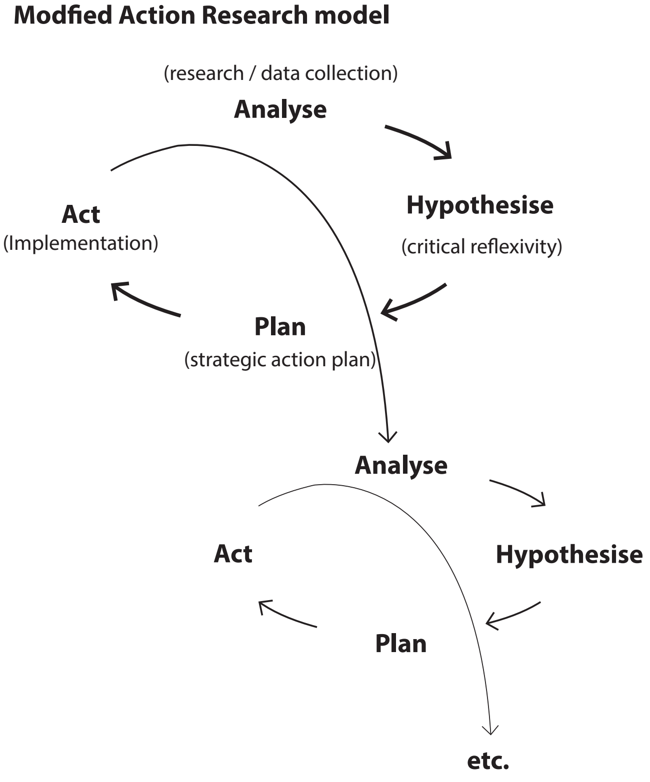

Modfied Action Research model

Fig 1.10
A description of how O'Leary's action research framework has been modified to meet the requirements of Research Trajectory II.

1.6.3 Implementation of the Research Methods

The sum of sections 1.6.1 and 1.6.2 describes the epistemological framework that has enabled to respond to the two research trajectories. The different approaches have been applied as described in Table 1.1, which outlines the research and evaluation methods for the total of nine experiments carried out through the thesis. Additionally, the table outlines how the experiments are used in response to different research questions.

number	study	method	analysis method	Research question
1	rob ins experiment 01	RTD	action research	RQ 2.1
2	rob ins experiment 02	RTD	action research	RQ 2.1
3	rob ins experiment 03	RTD	action research	RQ 2.1
4	rob ins user study 01	Qualitative participatory Questionaires	participatory design , Deduction	RQ 2.2
5	rob ins user study 02	Qualitative questionaires	participatory design, Deduction	RQ 2.2
6	Rob Fab 01	RTD	deduction	RQ 1.1
7	Rob Fab 02	RTD	deduction	RQ 1.1
8	Rob Fab 03	RTD action research, participatory design	deduction	RQ 1.1
9	Rob fab design 01	RTD	deduction	RQ 1.2

Table 1
A table describing the method and evaluation method from the epistemological framework that has been employed for each individual experiment.

1.7 Scope and Limitations

While the research explores what and how an onsite robotic timber unit should fabricate; and how robots can be intuitively instructed with information, the research project has, however limitations in scope, as discussed in the following:

The use of digital fabrication technologies in research trajectory I is primarily focused on robotic technologies due to the company profile of Odico, which through their 10+ year history, have emphasised the use of industrial robot arms within the AEC industry. However, the project acknowledges the great potential of CNC machines, where Hundeggers are considered the industry standard for timber fabrication. Furthermore, the project limits its focus on linear timber elements such as glulam or off-the-shelf timber members. Lastly, fabrication studies within this trajectory are instructed through the 3D modelling platform McNeel Rhinoceros3d [rhino] and the scripting plug-in Grasshopper3d [GH] software package since it was decided to focus on developing the hardware setup for the FotF, as opposed to adding a new configurator software for timber fabrication as well.

The scope of research trajectory II is limited to identifying and developing the technical framework for a new instruction method that can augment existing FotF instruction possibilities. The new instruction method is tested through personal- and user studies. A by-product of the development process of the instruction method is a tablet interface that manages different functionalities of the instruction method. This has been built on top of a work-in-progress version of the FotF software. However, the focus of the user studies has yet to be to optimise or improve the design of the interface.

Fig 1.11
A photo showing a conventional robotic fabrication workshop, where a lot of time is spent behind laptops before robotic action is instructed.

1.8 Workshops and User Group Description

As has been discussed, the research aims to develop a transportable robotic work environment for the carpentry profession, where research trajectory II focuses on what and how such a system can produce. The thesis determined the user group for this research as participants with experience and background in the carpentry trade, which in a Danish context follows 4.5 years of education, containing a mixture of working as an apprentice and being at an educational institution. When carpentry students are in school, they are instructed in practices of the construction site and safe use of different mechanised tools, and receive little training in CAD software [Aarhus Tech]. There is no mention of training in computational design techniques or digital fabrication technologies, hence, carpenters can be considered a user group consisting of robotic and computer non-specialists.

This generalised position on the carpentry profession, namely them being robotic non-specialists, has informed that a general user group of robotic non-specialists can be used to test the developed instruction method from research trajectory II. Testing the instruction method against multiple professions can reveal different potentials of the method. This position has informed the identified user studies described in Chapter 4, where a user group totalling twenty-seven participants of either researchers, tutors, architectural students, or cabinet makers from the Aarhus School of Architecture tested the instruction method. The majority of these participants were found to be robotic non-specialists. Ideally, the user group would have consisted of carpenters, which would have been able to qualify if the method had relevance for them. But due to the limited time and possibilities to organise user studies, the aim of the two studies was simply to test if others than the researcher could use the developed instruction method.

1.9 Thesis by Publication and Thesis Structure

As described, the PhD unfolds through a thesis by publication, where seven papers have been written and are listed in chronological submission order, where ‘1’ is the most recent. Five papers have been disseminated in three journals and two in conference proceedings (3-7). Two papers await peer-review (1-2) from relevant journals they have been submitted to.

Peer-reviewed journal papers:
P1 **Pedersen, Jens**, and Reinhardt, Dagmar (2023) ‘Design Method for Transportable Robot Units (TRU): Using experience to identify new work environments for TRUs.’ Automation in Construction and Advances in Manufacturing (submitted, awaiting review).

P2 **Pedersen, Jens,** and Reinhardt, Dagmar (2023) ‘The robots see red: Instructing industrial robots with on-object drawings.’
Human-Robot Interaction journal (submitted, awaiting review).

P3 **Pedersen, Jens**, and Reinhardt, Dagmar (2023) ‘Computationally enabled material management: Learning from three robotically fabricated demonstrators’. Submitted for and accepted by the UIA conference.

P4 **Pedersen, Jens**, and Reinhardt, Dagmar (2023) ‘Robotic Drawing Communication Protocol: A Framework for Building a Semantic Drawn Language for Robotic Fabrication’. Construction Robotics, 23 January 2023. https://doi.org/10.1007/s41693-022-00089-w.

P5 **Pedersen, Jens,** Olesen, Lars and Reinhardt, Dagmar, ‘Timber Framing 2.0’. In Towards Radical Regeneration, edited by Christoph Gengnagel, Olivier Baverel, Giovanni Betti, Mariana Popescu, Mette Ramsgaard Thomsen, and Jan Wurm, 320–31. Cham: Springer International Publishing, 2023. https://doi.org/10.1007/978-3-031-13249-0_27.

P6 **Pedersen, Jens,** Søndergaard, Asbjørn and Dagmar Reinhardt. ‘Hand-Drawn Digital Fabrication: Calibrating a Visual Communication Method for Robotic on-Site Fabrication’. Construction Robotics 5, no. 2 (1 June 2021): 159–73. https://doi.org/10.1007/s41693-020-00049-2.

P7 **Pedersen, Jens,** Neythalath, Narendrakrishnan, Hesslink, Jay, Søndergaard, Asbjørn, and Reinhardt., Dagmar, ‘Augmented Drawn Construction Symbols: A Method for Ad Hoc Robotic Fabrication’. International Journal of Architectural Computing 18, no. 3 (1 September 2020): 254–69. https://doi.org/10.1177/1478077120943163.

Structure of the PhD

All the papers are presented in Book II, which are organised in a reading order corresponding to the chapters within this book. The reading order deviates from the publishing sequence because the project unfolded through simultaneous experiments in two research trajectories (section 1.6, and fig 1.8). Therefore, the following details how this book has been structured and how the papers are summarised through different chapters.

Chapter 1 introduces the research field by describing the project context, background and collaborators. *Chapter 2* gives an account of the project background, which includes a reflection on how construction information is instructed on the construction site, followed by a state-of-the-art section on both; how robots can be intuitively instructed and robotic timber fabrication. *Chapter 3* unfolds through three sections that describe how research trajectory I have developed knowledge that leads to three papers (1,3,5). Section 3.2 summarise findings from papers 3 and 5, to present how on-site carpentry practices could benefit from robotically fabricated elements. The following section 3.3 summarises paper 1 to describe how the robotic work environment for a new FotF system has been developed based on findings from three different demonstrators. *Chapter 4* describes the development and testing of the new instruction method through three sections, which lead to four papers (2,4,6,7) and a patent application (additional publications). Section 4.2

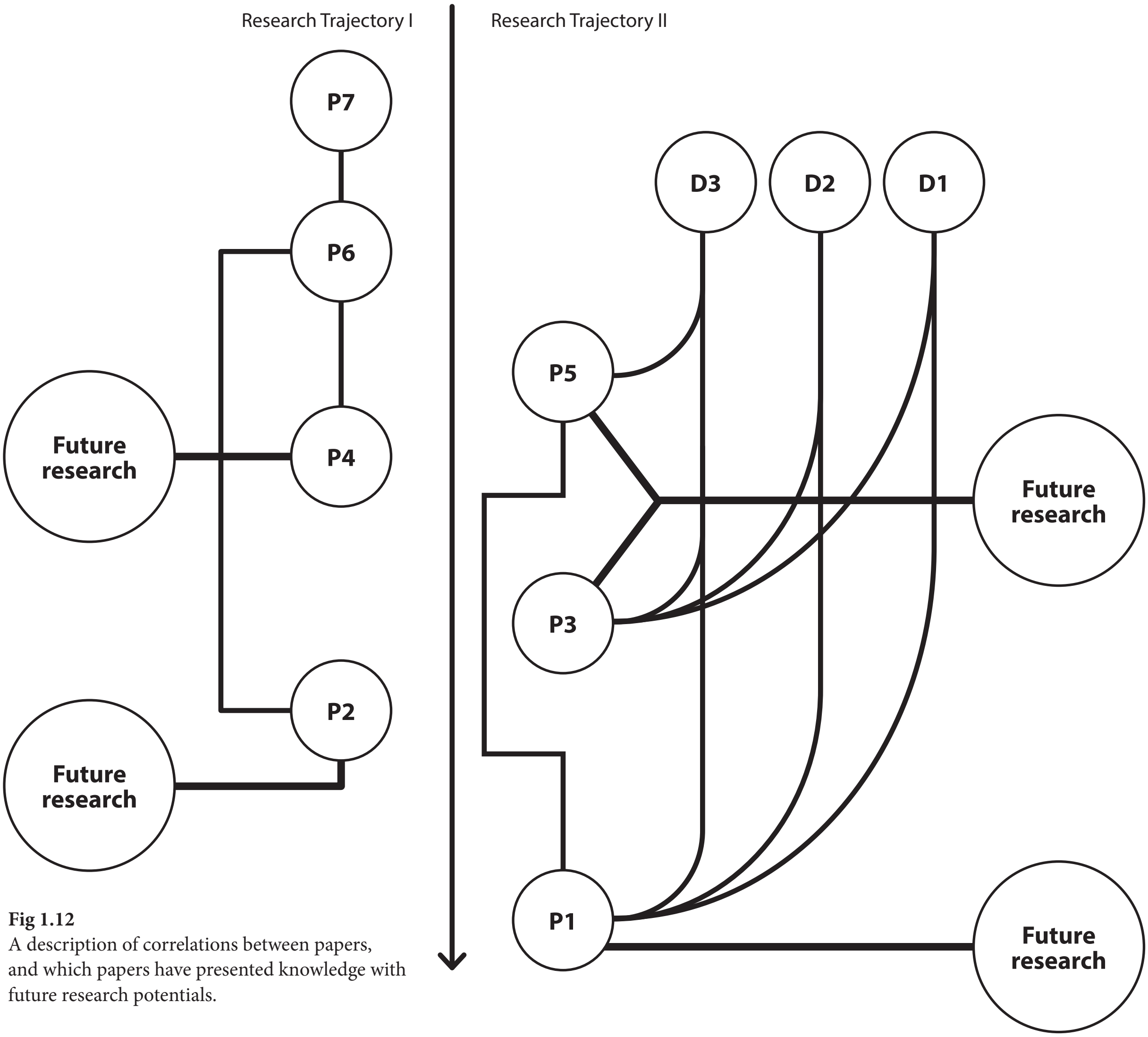


Fig 1.12
A description of correlations between papers, and which papers have presented knowledge with future research potentials.

describes how the patent was used to plan the development of the instruction method, which is summarised through the three papers (4,6,7) that detail the development of the method. Section 4.3 describes the first user studies, where paper 1 is summarised to describe the findings briefly. *Chapter 5* discusses the research findings through three topics; On/near Site robotic fabrication (5.1)? Instruction method, software or robotics (5.2)? Resilient Robotics (5.3). Lastly, *Chapter 6* concludes the research while presenting future research to be carried out

Additional Publications

Chapter in the RIBA book titled “Intelligent Control; Disruptive Technologies”

I was invited to submit a chapter for the book, where it was decided to describe the past, present and future of Odico. The section on the future focus on the research developed through this PhD. The article is not included in book II, due to publishing rights retained by RIBA, but it does not contain knowledge that isn’t available within the included papers.

Pedersen, Jens and Søndergaard, Asbjørn, ‘PROFILE: Scaling Construction Robotics: Odico Construction Robotics’. Hyde Rob, Filippidis, Filippos. Intelligent Control: Disruptive Technologies (RIBA Publishing, 2021).

Patent

The robotic instruction method developed as part of the PhD thesis was used as the basis for a patent application by Odico that is currently under review with patent number EP4165483A1 [Pedersen et al. 2023]. The patent application described the technical framing of the instruction method and became the guiding principle for the development process (Chapter 4). Book II contains the diagrams from the patent application alongside small text fragments that give a principal description of the diagrams. The text submitted alongside the patent application is precluded from the secondary booklet due to its technical phrasing and resulting readability, but it is accessible online [Pedersen et al. 2023].

1.10 Industry Collaborations with Stakeholders

The project's primary stakeholder is Odico Construction Robotics, enabling the thesis project to access robotic facilities and support in relation to hardware developments. This support aided the development and realisation of the new timber FotF system based on an outline of required functionalities derived from the research. Through a collaboration with Odico's hardware team, an alpha version of the FotF was realised and is currently being tested in their off-site facilities.

Throughout the project, other industry collaborators emerged from other companies, such as Brav Engineering [Brav Aps] and CS byggefirma [CS Byggefirma Aps]. These were collaborative partners of a project within the PhD - the Olaf Ryes Gade project, which is detailed in Book II and Chapter 3.

Chapter 1 Summary

This chapter has provided an overview of how the project aims to contribute to the field of architecture through an interdisciplinary approach, with the goal of making an impact in both industry and academia. After the introduction, the chapter explained how the project is positioned at the intersection of industrial and academic research. This positioning has led to developing an epistemological framework that leverages experiences and user studies in a design-led research approach, utilising physical and digital demonstrators to generate empirical knowledge.

In the subsequent chapter, the focus shifts to the background, where the first section delves into a short reflection on how construction information is instructed on the construction site, to identify the basic concept for the instruction method. The following section describes a technical framework to enable the development of the identified instruction method, followed by an analysis of projects that have developed alternative approaches to instructing robotic fabrication information. Lastly, the first section delves into the application of robotic timber fabrication, examining its use both on and off construction sites. The primary objective of this analysis is to extract principles related to the work environment of robotic solutions and understand how these principles facilitate specific fabrication actions.

Chapter 2
Background

Chapter 2 Overview

This chapter provides a background to the research at the intersection of three topics. The first section reflects on construction instructions and how this reflective process has influenced the development of a methodology for intuitively instructing a robotic system (2.1). The following section details the requirements to develop an alternative instruction process for robotic fabrication (2.2) and describes the state-of-the-art in Robotic Timber Fabrication (2.3).

Section 2.2 explores the realisation of the intended instruction process, whereby physical drawings are interpreted through a developed visual system that equips a robot with visual perception and understanding capabilities. This section also showcases projects from fields, such as Architectural Robotics and Human-Robot Interaction, where alternative and intuitive methods for instructing robotic actions have been developed. The knowledge gathered from these projects guides the thesis towards incorporating computer science techniques such as Computer Vision (CV), network communication, and Machine Learning (ML) to enable robotic instruction through physical drawings.

Lastly, section 2.3 derives the current state-of-the-art robotic timber fabrication in both off-site and on-site facilities to comprehend how specific hardware principles facilitate different fabrication actions. The analysis of these findings focuses on their compactness and transportability, informing the design of the robotic work environment for a new timber Factory-on-the-Fly (FotF) system.

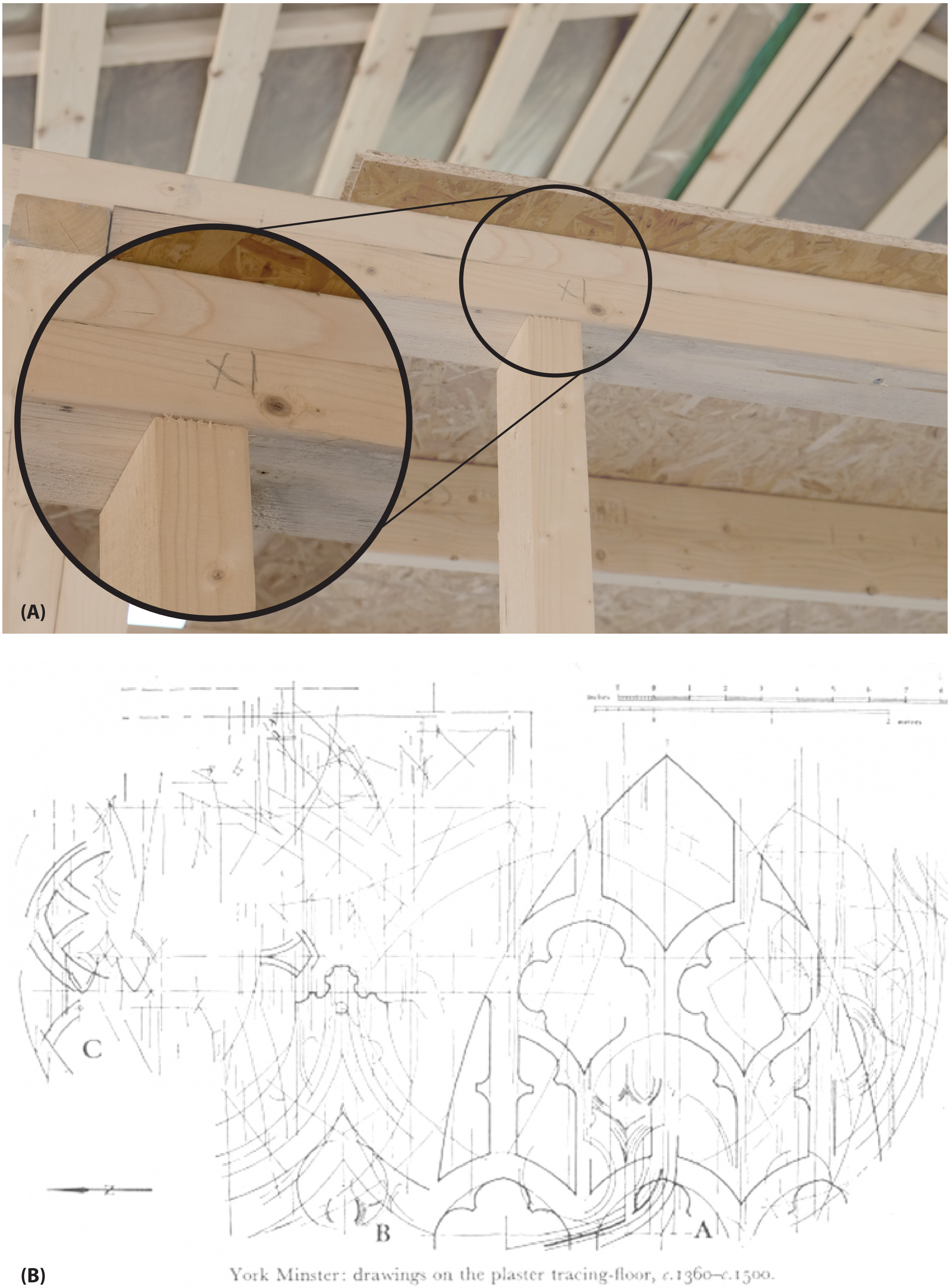


Fig 2.1
A) Image from a construction site visit, where it was revealed that carpenters communicate information among one another through hand-drawn symbols. B) a tracing by AR Whitakers of the tracing floor in York Minster, which was an integral part of onsite construction practice, centred around 1:1 drawings that conveyed construction information for jiggs or building components.

2.1 Domain: Instructing Construction Information

This section describes the inspiration for a new robotic instruction method that was informed by the process of instructing construction information for onsite construction work (current and historical) and how carpenters convey construction information among workers.

Instructing Construction Actions

The point of departure to identify how to instruct robotic fabrication information is anchored in today's current method of instructing construction information. Namely, through drawings printed from various CAD programs or otherwise made externally and delivered on the construction site to instruct construction tasks [Disney et al. 2022, Gregory 1966]. This process is inflexible to change and can lead to miscommunications between construction workers and architects [Disney et al. 2022].

Unlike today, construction instructions used to be a dynamic on-site process, where the architect or master craftsman etched information into a dedicated floor on the construction site. These floors were made in plaster or stone and were referred to as "tracing floors", wherein construction information for jiggs or building components were etched in 1:1 [Harvey 1997, Calvo Lopez et al. 2013] (fig). Compared to the processes of today, this approach is highly dynamic and can adapt to changes within a given construction process.

Interestingly, among carpentry workers, drawings/markings made on timber elements instruct construction or assembly information as part of timber construction. Historically, this has been exemplified by the half-timbered construction system, where physical markings on elements instruct construction, manufacturing and assembly information [Benzon 1984, Vejlby 1991, Jensen 1933]. Whereas today in timber framing, physical markings are made on top/bottom beams to convey positional information for posts (fig 2.1). This indicates that instructing constructing information through physical drawings has been, and to some extent still is, an active method on the construction site.

Therefore, this research argues that for robotic fabrication to become fully integrated into the construction process, it should be possible to instruct a robot with a simple ruler and marker dynamically. This process emulates how construction workers have been observed communicating construction information with one another.

2.2 Domain: Instructing Robotic Fabrication Actions

In section 2.1, physical drawings or markings were recognised as an intuitive instruction process inspired by carpentry. Hence, this section delves into the description of a technical framework that enables a robot to both ”see” and ”understand” a physical drawing. To accomplish this, the project outlines the development of a vision system that imparts a level of visual perception to the robot. This involves creating a computational framework that can comprehend the visual information captured by the robot.

Additionally, a subsection highlights the importance of a communication protocol that allows different elements of the instruction method to interact and exchange information effectively. Furthermore, this section showcases two projects that have successfully utilized ”drawing” as a means to instruct robotic fabrication actions.

Technical Framework

Enabling digital systems to perceive visual information can be approached from two perspectives: one is through the utilisation of scanning technologies to capture three-dimensional information [Kinnect1, Kinnect2, Real Sense]; or through 2D cameras that can be analysed by existing computational libraries for images or video [openCv, Emgu]. Approaching the challenge of identifying a physical drawing through scanning technologies could be approached similarly to Johns, 2014 [Johns, 2014], where objects were isolated within a 3D scan based on colour, indicating that 2D colour information could be sufficient. Therefore, the project follows a similar approach by using images/video as 2D information, where existing computer vision libraries enable parsing camera data efficiently [Emgu, openCV].

Recent years have seen a surge in computational techniques centred around “artificial intelligence”, wherein multiple technical frameworks can enable digital systems to “understand” data ranging from text to images or video. In 2020, a group of researchers reported on a method to achieve the highest documented classification score off the MNIST library [An et al 2020]. The MNIST library [mnist] is a collection of hand-drawn digits from 0-9, which are used to test training methods when dealing with a similar classification problem. Since this research aims to classify hand-drawn markings, some of the techniques presented by An et al. (2020) are followed. Classifying a drawing into specific types holds various procedural advantages, as will be described in Chapter 4. This classification process facilitates the development of a robotic/operator language, where drawn symbols convey particular fabrication actions. Consequently, this enables a similar instruction process for robots, akin to how carpenters communicate construction information using symbolic representations, as discussed in section 2.1.

Other researchers who have pursued alternative robotic instruction methods have found it necessary to use a server to enable communication between systems composed of multiple devices [Dörfler et al. 2012, Andraos 2015]. This research has adopted a similar approach since it was available within the existing software framework [Neythalath 2021]. In addition to facilitating communication between devices, Andraos [2015] emphasises how this approach enables a double confirmation of instructions. This means that any erroneous or flawed data can be identified and rectified before potentially harmful instructions are issued to the robotic system.

Instruction Through Drawing State of the Art

The project has found a few examples of deliberately using the drawing process to instruct robotic actions, where relevant examples are the work by Cubero et al. 2021 and the Tracepen by Wandelbot [tracepen] (fig 2.2).

Cubero et al. [2021] have described a collaboration with an artist that explored robotics in relation to her art practices, which required rethinking how robotic instructions were given. They used a collaborative robotic system (cobot), to enable free interaction with the cobot since these systems can be used without safety fencing [Bauer et al. 2016]. Through this process, they enabled the artist to instruct the cobot through dancing, but more importantly, by drawing with a stylus on a digital drawing tablet. The artist could draw on the tablet through this process, where the cobot would copy or augment the drawing [Cubero et al. 2021]. Despite their developed process being intuitive, it is tough to understand the scale and appearance of the drawing in the process because it is first visualised when drawn by the robot.

An analogous approach to the one mentioned above is the tracepen [tracepen], which is utilised in various industries. The tracepen resembles a pen-like device that can be manually moved in space while simultaneously recording its positions. These recorded positions are displayed on a digital device, allowing the traced path to be modified and verified before being transmitted to the robot as instructions. This approach is highly intuitive and finds application when an additional process needs to be applied to an existing object. However, it is important to note that although the process involves drawing to scale and visualizing it digitally, it can only provide instructions on a per-element basis, as the drawn path becomes an immediate robotic instruction. In contrast, using physical drawings will enable both to draw in scale, while "pre-programming" elements, because the program is read from the drawing. The development of such a process is detailed in Chapter 4.

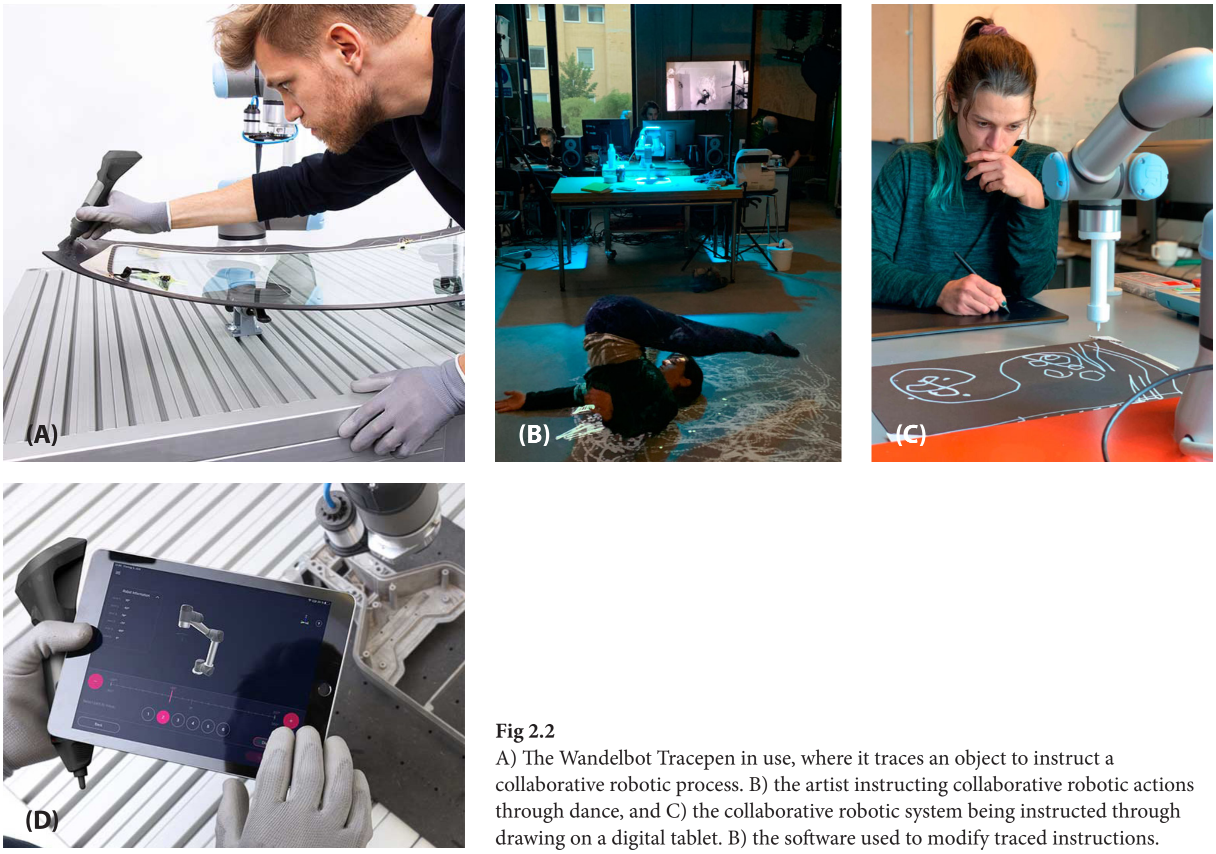


Fig 2.2
A) The Wandelbot Tracepen in use, where it traces an object to instruct a collaborative robotic process. B) the artist instructing collaborative robotic actions through dance, and C) the collaborative robotic system being instructed through drawing on a digital tablet. B) the software used to modify traced instructions.

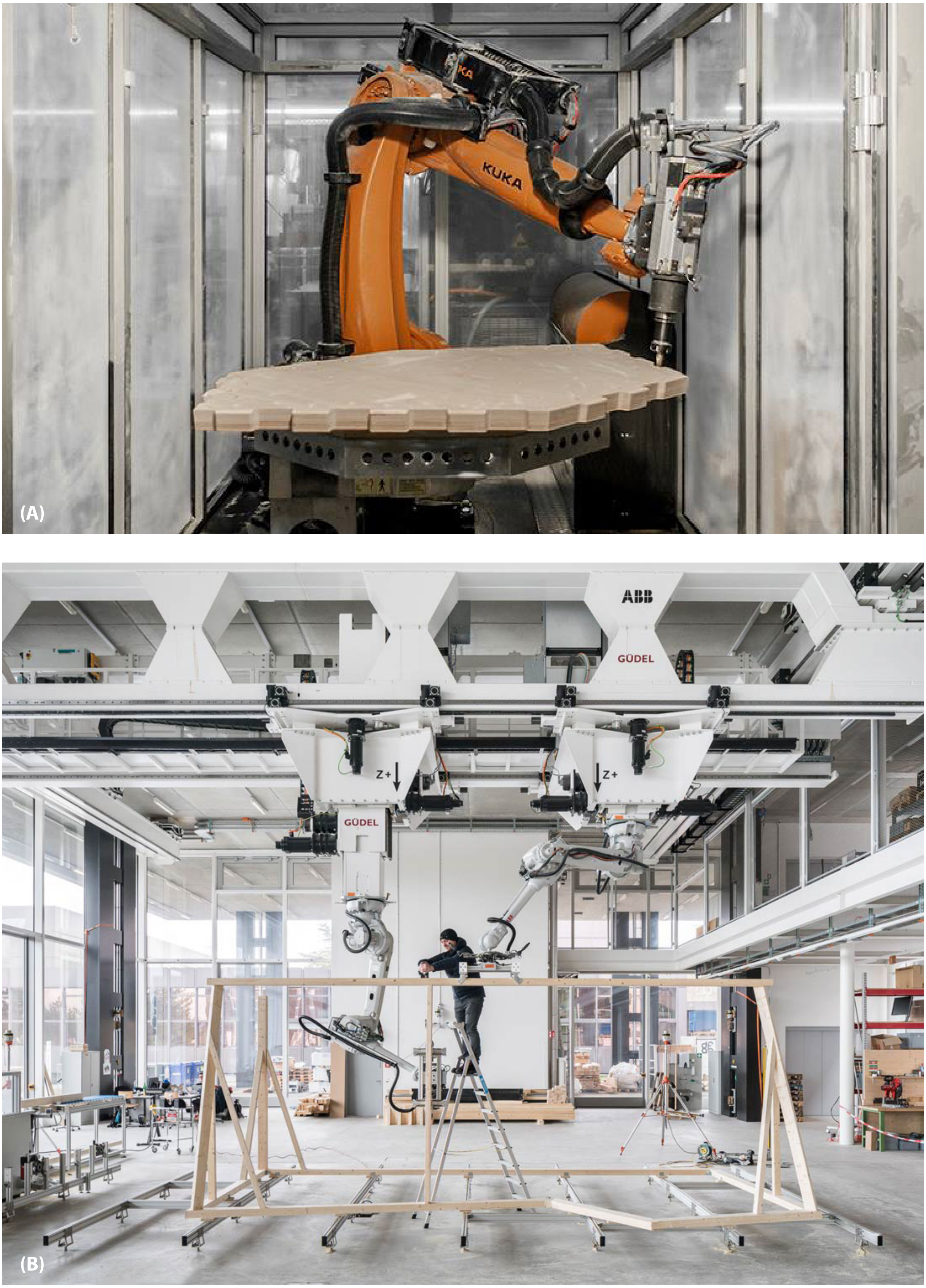


Fig 2.3
A diagram showing the two individual approaches to robotic fabrication. A) Illustrates the 'fabricator' approach to robotic fabrication, image from the fabrication of the Landesgartenschau Exhibition Hall, 2014, © ICD/ITKE/IIGS University of Stuttgart. B) illustrates the 'assembler' approach from the Spatial Timber Assemblies project, 2018, © NCCR Digital Fabrication / Roman Keller.

2.3 Domain: Robotic Timber Fabrication

This section aims to identify new hardware principles for a FotF system to process linear timber elements, from an analysis of existing on- or off-site robotic facilities. Such a process commonly begins by analysing similar projects, but only a few on-site systems exist across academia and practice. Thus, the following section identifies the current state of the art in robotically fabricated timber elements from off-site facilities, revealing two approaches to robotic fabrication - using the robot either as an 'assembler', or a 'fabricator'. Either approach has unique robotic work environments that can be analysed for their potential to be positioned in a compact and transportable robotic fabrication unit. The subsequent section (onsite or 'near-site' robotic work environments) describes robotic work environments designed for on- or near-site robotic fabrication of timber or other material systems and how they relate to knowledge gained from the section: two schools of thought.

Since 2009 industrial robot arms have been used to machine and, in some instances, assemble timber elements into complex formations [Oesterle,2009], as exemplified by the vast array of realised projects [Waimer et al. 2013, Krieg et al. 2015, Apolinarska et al. 2016, Eversmann et al. 2017, Thoma et al. 2018, Robeller 2019]. From these efforts, it is argued that two approaches, or two 'schools of thought', for using robotic fabrication systems to machine timber have emerged.

The first approach is robotic systems as an 'assembler', where robotic arms are used to assemble elements into complex formations. This approach is exemplified through multiple research efforts [Oesterle,2009, Apolinarska et al. 2016, Eversmann et al. 2017, Thoma et al. 2018]. Using a robot as an 'assembler' begins with a 1) robot picking a timber element with a gripper, then 2) the element is passed through (multiple) processing stations positioned within the robot's work envelope, before 3) the element is positioned within a robotically assembled structure. Using the robot to assemble elements is limited to structures that fit within the work envelope of the robotic system. Arguably this process emulates how the car industry uses robotics or how humans conventionally process an element through (multiple) processing stations before it is ready to be positioned within a given construction.

The second approach uses robotics as a 'fabricator' where components are robotically machined to a final shape before being assembled by a human [Waimer et al. 2013, Krieg et al. 2015, Bechert et al. 2016, Alvarez et al. 2018, Robeller 2019, Buckling et al. 2022]. The approach allows fabricating elements that can be enclosed within the work envelope of the robotic unit, but there is no limit to the size of the final structure - because it is assembled by humans that can be assisted by cranes, lifts and other such tools.

Both scenarios establish different propositions for task distribution, and it is important to distinguish which approach is followed when proposing a new robotic work environment for the FotF system. Common for both approaches is a careful consideration regarding the environment surrounding the robot, which in the case of industrial robotic arms, needs to be fenced off physically or with light barriers for safety [Bauer et al. 2016, Europe safety]. Therefore, the robot's environment should contain everything necessary to carry out a given fabrication task, i.e. different tools, external axis or assembly area - through this research, such an environment is referred to as the Robotic Work Environment. Thus, this section aims to extract knowledge about the specific nature of robotic work environments for either an 'assembler' or 'fabricator' approach to robotic timber fabrication to propose a new robotic work environment for a timber FotF (fig 2.3).

Precedent Study: Timber Fabrication and Assembly

Multiple researchers have explored the 'assembler' process [Oesterle 2009, Helm et al. 2016, Leung et al. 2021, Helmreich et al. 2022], where a robot handles, machines and assembles elements in a closed loop. This approach has yielded impressive large-scale projects such as the sequential roof [Apolinarska et al. 2016] and the Spatial Timber Assemblies project that made the timber framed modules for the dFab house [Thoma et al. 2018, Adel et al. 2018].

Adopting the 'assembler' approach reveals the crucial role of calibration, as any discrepancies between the digital twin and the fabricated element will introduce additional complexities when it comes to the robotic assembly of the structure. This is exemplified by research from Helm et al., 2016, where a timber structure was made through the following process; 1) a robot picks up a timber element, 2) passes the element through a processing station, and 3) assembles the element into the designed timber structure. Through this process, they documented deviations between the manufactured elements and their digital twin, which complicated the robotic assembly process. Following this realisation, the researchers introduced an external laser sensor to inform the digital twin with physical information and update subsequent fabrication and assembly information through a computational framework [Helm et al. 2016].

A prominent example for robotic timber fabrication, is the *Spatial Timber Assemblies* project that fabricated and assembled the timber framed modules for the DFAB house (Gramazio Kohler Research, ETH, Zürich, 2016). These were fabricated and assembled using two six-axis robotic units mounted upside down on a three-axis gantry system in the ceiling, which resulted in a robotic work envelope totalling 3.75 m width by 8.2 m length and 3.5 m height. Wherein a three-axis CNC was positioned to cut timber elements to length and at given angles [Thoma et al. 2018, Adel et al. 2018]. The fabrication and assembly of elements follow this principle sequence; 1) the robot picks up the timber element, 2) the timber element is passed through the CNC station, 3) the timber element has assembly details milled, 4) the timber element is positioned within the structure, before 5) a human fixates the element with either screws or bolts (fig 2.2). Similarly to Helm et al., 2016, the

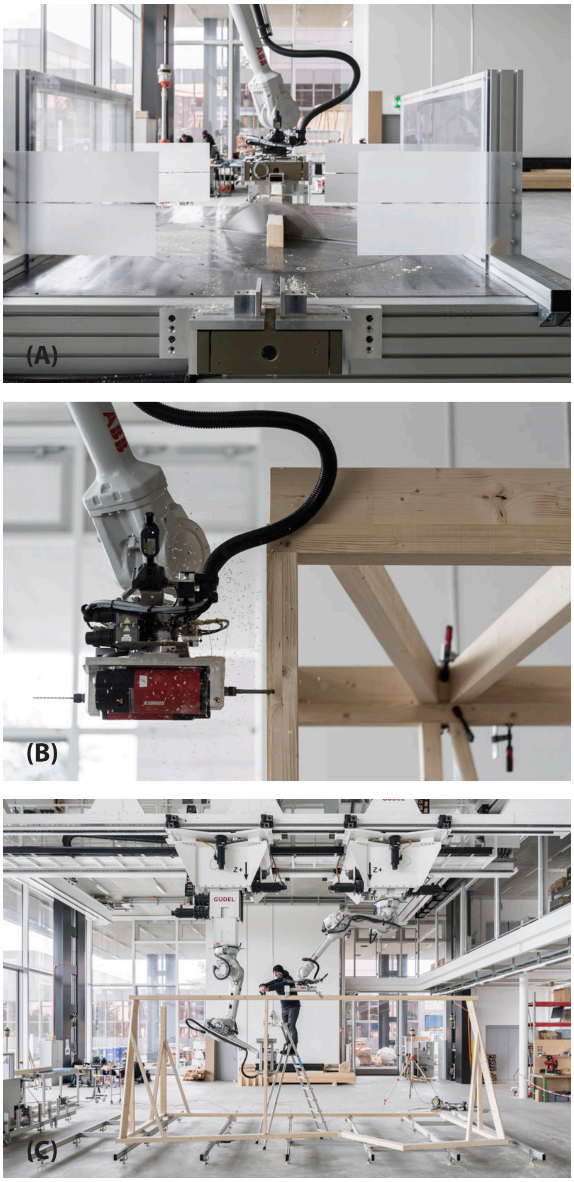


Fig 2.4
A) a Robot processing a piece of timber on the external CNC saw, B) A robot milling details, and C) Robots holding elements in place, while a human screws the elements together. All images are from the Spatial Timber Assemblies project, 2018, © NCCR Digital Fabrication / Roman Keller.

Fig 2.5
Module for the dFab housing being craned into position by humans 2018 © Gramazio Kohler Research, ETH Zurich.

researchers found that the timber deviated from its intended position, especially long members, which instead of sensors were mitigated by the dexterity of humans that readjusted the position of such elements [Adel et al. 2018].

A constraint of following the 'assembler' process is the limit to dimensions of an assembled structure that must sit within the described work envelope of the system. Therefore, using the 'assembler' approach has been limited to modular construction, whereby humans subsequently are to assemble the robotically made timber modules (fig 2.5). Furthermore, such a robotic work environment is nearly impossible to make transportable since it occupies such a large envelope to accommodate the size of assembled modules and elements being moved through the air by robots.

Fig 2.6
Robotically assembled timber-only jointed structure on-site in Japan 2019-22 © Gramazio Kohler Research, ETH Zurich.

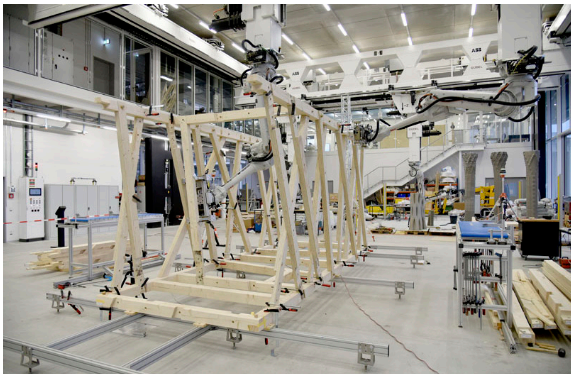


Fig 2.7
The robotic setup used for both the Spatial Timber Assemblies project, and the assembly of timber elements for the timber-only jointed structure in fig 2.6, 2020 © Gramazio Kohler Research, ETH Zurich.

In contrast to the manufacturing of the timber-framed modules for the DFAB house [Adel et al. 2018, Thoma et al. 2018], other researchers [Leung 2021, Helmreich et al. 2022] used the same robotic setup to robotically assemble a timber-only structure robotically. The structure consisted of five modules (fig 2.6), each consisting of 52 - 57 elements made on a Hundegger CNC from glu-laminated spruce, for later robotic assembly [Leung 2021]. The assembly of the premade timber elements were carried out using the robotic setup for the dFab house, that were assisted by a series of 'distributed clamps', which were used to push joints together and compensate for an expected positional accuracy of +- 6 mm [Leung 2021]. The assembly process was documented to take 48 hours pr module, which will be used as a point of comparison for human assembly times [Helmreich et al. 2022]. Furthermore, their research underlines the findings of Helm et al. from 2016, because positional accuracy when assembling elements robotically remains a challenge.

Thus, the 'assembler' approach requires a large envelope encompassing the assembled structure and surrounding processing stations. Secondly, the positional precision of the system requires either human intervention or other subsidiary systems to function, which indicates that it would be challenging to implement such a system on the construction site.

In contrast to the previous research, the ‘fabricator’ approach mounts the processing tool at the end of the robot arm, and humans load/unload workpieces in the robotic work environment before being machined to a finished shape that can be assembled by humans. This approach’s robotic reach and work envelope can be significantly enhanced by positioning workpieces on rotary tables [rotary axis] or placing the robot on a track that moves it back and forth [track]. This fabrication process has been adopted for multiple projects [Waimer et al. 2013, Krieg et al. 2015, Bechert et al. 2016, Alvarez et al. 2018, Robeller 2019, Buckling et al. 2022]. Despite highlighted projects primarily fabricating elements from wooden sheet material, the robotic work environment of the ICD research pavilion in 2011 [Waimer et al. 2013] and Landesgartenschau exhibition hall (2014) [Krieg et al. 2015] is of specific interest. Because both projects employed a compact robotic work environment, consisting of a stationary robot that machines elements with a mounted spindle, where the robotic work envelope is extended by positioning workpieces on a rotary table (fig 2.8). Although these projects were not made from linear timber elements, recent research by Buckling et al. 2022 has used a similar robotic work environment to fabricate prototypes consisting of linear timber elements (fig 2.8, C). Thus, the principle of the ’fabricator’ approach (stationary robot, workpieces on external axis) will inform the development of a robotic work environment for a new timber FotF.

Fig 2.8
A) The robotic setup used to mill joinery details for the Landesgartenschau Exhibition Hall, 2014, B) the Landesgartenschau Exhibition Hall, 2014 C) The robotic setup for milling linear timber elements 2022, D) The robotic setup for the 2011 ICD research pavilion, and D) the 2011 ICD research pavilion, 2011. All images belong to © ICD/ITKE/IIGS University of Stuttgart.

Precedent Study: Onsite or 'Near-site' Robotic Work Environments

The previous section on approaches to robotic timber fabrication found that the fabricator approach would be the most eligible to be situated in a transportable robot system due to its compact work environment. In this context, it is interesting for the research to understand how on- or near-site systems have addressed the robotic fabrication of timber elements or modules. Unfortunately, the research has found that very few systems for near/on-site robotic fabrication systems exist, specifically for linear timber machining [Wagner et al. 2020]. Therefore, the project extracts knowledge on 'compactness' and 'transportability' from available robotic solutions while understanding how their robotic work environment could be relevant for fabricating linear timber elements.

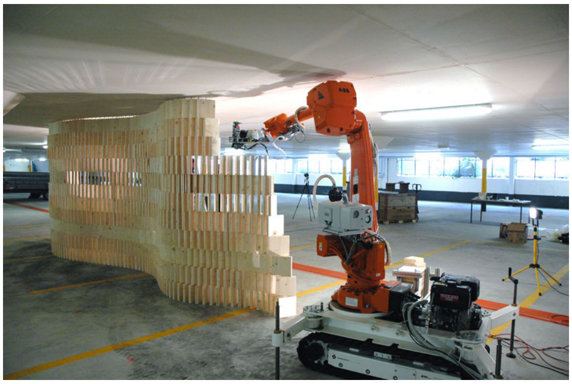


Fig 2.9
The dimRob setup is being used within the Ecord project series.
2011 - 2012 © Gramazio Kohler Research, ETH Zurich.

One identified framework is the dimRob [Helm et al. 2012], which later became the in-situ-fabricator [Sandy et al. 2016, Gifthaler et al. 2017]. Here, an industrial robotic arm is mounted on a mobile platform that is dimensioned to enable the system to navigate through the tight quarters of a construction site. Elements or objects needed as part of a work process can be positioned on the platform. The system has been used for different on-site assembly tasks; such as positioning bricks [Helm et al. 2012, Sandy et al. 2016] or plywood blocks [Helm et al. 2012] into geometrically complex configurations. To carry out these tasks, the researchers have developed different techniques to derive positional information to enable the robot to assemble structures accurately within a physical context [Sandy et al. 2016]. Thus, the system has primarily been used as an on-site version of the 'assembler' approach, which the previous section documented could require a large work envelope if processing linear timber elements. Therefore, despite the system being compact and transportable, it is expected to be time-consuming to implement on the construction site for linear timber fabrication while requiring a large work envelope.

Fig 2.10
The R-O-B setup on-site in New York, USA, 2009 to assemble the Pike Loop project © Gramazio Kohler Research, ETH Zurich.

Another approach to on-site robotic fabrication is the R-O-B container unit described by Bonwetsch in 2015 [Bonwetsch 2015]. The system comprises a robot on a linear track [track] and a brick dispenser inside a container. The system aims to assemble brick formations outside of the container environment, resulting in two complex brick projects; the 'Pike Loop', 2009 [Pike Loop] and 'Structural Oscillations', 2008 [Structural Oscillations]. The pike loop was assembled directly on the construction site, where the container unit sat on a lorry that moved forward as sections were assembled. Differently from this approach, the Structural Oscillations project assembled modules that, when finished, were moved into a dedicated exhibition space with a forklift. This approach to on- and near-site fabrication or assembly of elements, where a robotic unit and workstations are enclosed, presents potential. Still, the research believes the system would be challenged by carrying out the assembler approach with long linear timber elements, within the dedicated work area.

Fig 2.11
The Buga pavilion is a research pavilion made out of LVL cassettes from a near-site robotic process, Bundesgartenschau Heilbronn, Germany, 2019, © ICD/ITKE/IIGS University of Stuttgart.

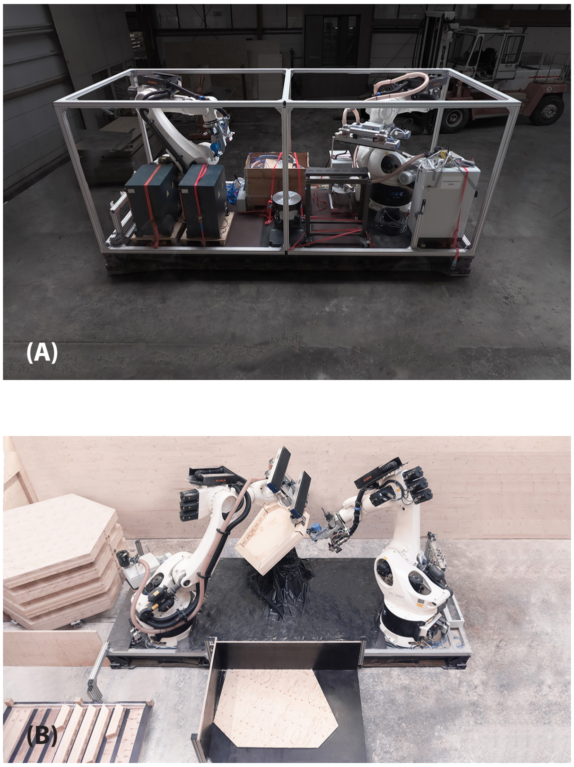


Fig 2.12
A) The TIM framework in its transportation configuration, and B) the TIM framework unpacked and operational in a near-site facility, Germany, 2019, © ICD/ITKE/IIGS University of Stuttgart.

Similarly to the R-O-B framework, a recent publication by Wagner et al. 2020 presented a near-site solution to manufacture the final stages of timber modules for the Buga pavilion. The 'TIM' system consists of two KUKA robots, where their associated tools and workstations are positioned on a twenty-foot container bed. The system hybridised the 'assembler' and 'fabricator' approach, where elements for the Buga modules were prefabricated on a Hundegger CNC. The premade pieces are positioned in a dedicated work area, from which the robot picks up elements and assembles them on a central rotary table through a developed sequence. Once all elements for a module have been assembled, it is larger than its digital shape, which is removed through a subsequent machining process where any excess material is removed. Once the machining process concludes, the module is moved from the rotary table to a 'finished' pile by a robot. The finished modules were transported to the construction site for human assembly.

The system is found to be challenged by its deployment time. Because, despite workstations and tools being able to fit on the container bed when being transported, some must be positioned outside the container when being deployed and thus require recalibration (fig). The researchers found the recalibration process alone to take roughly one day. Therefore, the system is only deployable through the use of specialist knowledge that is assumed not to be available on- or near the construction site. The researchers have made this a subject of future research, but it limits the system's transportability. Furthermore, since the robotic work environment requires to be unpacked to be operational, it is not considered compact, and arguably falls under the same constraint as the manufacturing of timber framed modules for the DFAB house [Adel et al. 2018, Thoma et al. 2018] - i.e. robotic assembly requires a large working envelope. Contrastingly, this project aims to minimise deployment time by keeping the robotic work environment in one envelope, consequently maintaining system compactness.

While this thesis research investigates processes for on-site robotic timber fabrication, there exist solutions from practice not mentioned by Wagner et al. 2020. However, they sit outside the current work field of timber manufacturing but are worth noting since they bring an industrial perspective, compared to the three projects from academia discussed previously.

Some practice projects have focused on developing solutions for the robotic assembly of bricks through systems such as SAM [SAM] and the Hadrian-X system [Hadrian-X]. Other market-ready on-site robotic solutions are the 3DCP gantry system Cobod [Cobod] and the drywall cutting machine from Kobots [Kobot]. Differently, from previously mentioned solutions that focused on solving complex fabrication tasks, these systems aim to solve simpler tasks in construction - assembling straight brick walls [SAM] or performing cuts in drywall panels [Kobot]. Additionally, some systems present quick and easy deployment times while being in a compact work environment and thus are highly transportable [Kobot]. These types of tasks benefit from high repeatability within construction work, which can offset the cost of renting or purchasing such a system.

Therefore, this section has provided evidence that on-site or near-site robotic solutions can be made compact and portable by adopting a 'fabricator' approach, wherein the robotic work environment is contained within a fixed unit to minimise the deployment time. Additionally, for the proposed Factory-on-the-Fly (FotF) system to be widely embraced in the construction industry, Chapter 3 will focus on identifying a repeatable construction task that can be addressed effectively.

Fig 2.13
The brick-laying robot SAM on the construction site working in conjunction with brick layers, 2017, © Scott Peters, the image of the SAM system.

Fig 2.14
The Kobot system being used on the construction site to cut drywall panels, 2022 © Kobots.

Chapter 2 Summary

This chapter began by presenting how it is believed that robotic systems could be intuitively instructed, by presenting physical drawings as the basis for fabrication actions. The following section outlined a technical framework to enable robotic instructions to be conveyed through physical drawings. Two additional projects were discussed, which utilise a semi-digital drawing process to instruct robotic information. However, it is noted that these approaches have limitations compared to simply drawing information with a physical pen.

Furthermore, the chapter provided an overview of the two distinct approaches that have emerged in robotic fabrication since architectural academia began focusing on integrating robotics into construction in the early 2000s. It included case studies from both academic and industry research, highlighting the benefits and successful testing of these approaches on large-scale demonstrators. The research conducted in this study concludes that the ’fabricator’ approach is better aligned with the research objectives, specifically trajectory I.

Additionally, the chapter identified a divergence in the approach to robotic solutions for construction sites between academia and practice. Academia tends to focus on solving unique and morphologically complex tasks, while industry practice has developed systems to tackle simpler tasks with high repetition. The research project recognises that its efforts in developing a Factory-on-the-Fly (FotF) system will primarily follow the practice-oriented approach.

Fig 3.1
The developed construction system on the construction site, 2020, Odense, Denmark.

Chapter 3
Research Trajectory I

Chapter 3 Overview

Previous chapters have highlighted the market potential of on-site robotic fabrication in the timber housing sector, with the capacity to fabricate over 5000 houses annually (discussed in Chapters 1 and 2. In order to address this potential, the project has been grounded in the extensive background of off-site and on-site robotic timber fabrication, emphasising the role of hardware elements in enabling specific fabrication actions within the robotic work environment (Chapter 2). The insights gained from this chapter have guided the research trajectory of the project, addressing relevant research questions.

This chapter begins by outlining the application of the Research through Design (RtD) method to structure the research process, which resulted in the development of three built demonstrators. Subsequent sections delve into how the knowledge derived from each demonstrator has explored principles within the experiential framework, focusing on understanding the potential benefits of incorporating robotically manufactured elements in carpentry practices. Finally, a section highlights how hardware principles from the robotic work environment in each built demonstrator have been isolated and recombined to establish the foundation for a new Factory-on-the-Fly (FotF) system.

3.1 Introduction

Research trajectory I aims to design and propose a novel timber Factory-on-the-Fly (FotF) system specifically for Odico. This is achieved through a series of built demonstrators that test principles facilitated by robotic fabrication, potentially impacting the construction industry positively. As a result of this process, both research questions; '*Can onsite robotic systems contribute positively to the manual carpentry processes?' (RQ 1.1)* and '*How can on-site robotic fabrication systems be designed to influence the construction industry?' (RQ 1.2)* can be addressed.

Following the RtD process from (1.6.1), the research derives testable principles from topics of innovation described in the Reinventing Construction: A Route to Higher Productivity rapport from 2017 [McKinsey 2017]. The report put forth seven potential topics that could enhance productivity in the construction industry. Among them, four were found to be pertinent to the objectives of research trajectory I, as stated below:

- *Rethink design:* This topic could refer to many elements of a design, but this research, focuses on how it would be possible to rethink how we construct and assemble buildings through alternatively designed and fabricated structures.
- *Improve onsite execution:* Improving on-site execution is one of the basic premises for this research. However, in rethinking design, it will be possible to improve on-site execution through an increased construction pace.
- *Infuse technology and innovation:* The project infuses technology within the construction industry through developed robotic systems and instruction methods.
- *Reskill workers:* Enabling construction workers to use the developed systems will require reskilling workers, but it would be a short process due to the effort in minimising the technical barrier of using robotic fabrication systems.

Among these four topics, the first two can be examined within the scope of the PhD, while the remaining topics extend beyond the PhD's scope as they depend on the finished version of a transportable Factory-on-the-Fly (FotF) system. Therefore, the principles to be tested through built demonstrators are derived from topics 1 and 2 in the 2017 McKinsey report [McKinsey 2017]. Therefore, the research outlines a series of principles that is testable through built demonstrators:

- **P1** - Leveraging robotic fabrication to manufacture elements that simplify assembly can increase the construction pace.
- **P2** - Robotic fabrication strategies can minimise construction errors and construction costs while increasing the construction pace.
- **P3** - Through a digitally managed pipeline, resultant waste can be minimised.

Three built demonstrators has been developed by testing the identified principles, with each demonstrator examining one or multiple principles. The findings from each demonstrator are documented and utilised to determine whether a principle should be retested in subsequent built experiments. This iterative process has gained significant insights, including observations on the variations in fabricating different timber types (such as off-the-shelf timber versus unknotted glulam) and the impact on fabrication and assembly speed when testing the proposed principles.

This process enabled to present 'what' should be fabricated as part of research trajectory I (section 4.2). 'How' developed elements will be fabricated is identified through careful documentation of the robotic work environment and envelope of each demonstrator, based on the evaluation criteria related to how "compact" and/or "transportable" the solution could be.

Testing Principles across Three Built Projects

The target for each demonstrator has been to test P1 by leveraging timber joinery as assembly guidance for on-site construction work. Through the different demonstrators, this process has been refined by analysing fabrication and assembly time to identify a fast fabricating and assembling construction method. Testing P1 through the three demonstrators has developed a dataset (digital models of the structures) to test P3, where various computational techniques have been tested to optimise the cutting sequence of elements have been tested. The demonstrators covered a range of different sizes and complexities and were all fabricated at Odico and constructed at different locations in Odense, Denmark.

75 Unique Robotically Cut Timber Elements (Bicycle Shed, 2019 Odense)

This project was produced for a private client. Project specifications included an oval plan, outwards leaning walls, and the roof angled around two local axes. After the structure had been designed, it was fabricated over a week with an ABB IRB 6400 synched to a rotary table. The project was done in standard C24 lumber with either 145 or 195 widths, depending on the element. The structure was assembled in two days by one person.

99 CNC Timber Elements Consisting of 20 Different Types (Greenery, 2020 Odense)

This project continued the previous work carried out for the same client, who had previously commissioned the shed. The client expressed their desire to construct a greenery using the half-timbered construction system in this follow-up project. The elements required for this construction were fabricated at Odico using a 5-axis CNC machine, which took approximately two weeks to complete. The elements were specifically made from unknotted, finger-jointed glulam that had a high level of form stability. Once fabricated, the elements were then transported to the site for further installation.

175 Timber Elements (Olaf Ryes Gade, 2020 Odense)

This collaborative project between Odico and Brav Engineering [BRAV ApS] aimed to develop an innovative timber framing method, learning from the construction and assembly principles established in the greenery project. Thus, the objective was to create a timber framing method that was faster to fabricate and assemble. These advancements in the method drew the attention of developer Dennis Kassentoft Nielsen [Dennis Kassentoft Nielsen] and the carpentry company CS Byggefirma [CS Byggefirma ApS], who expressed their interest in utilising the developed method for a real project—an Odense-based two-story building spanning 50 m2. The project timeline was set at two weeks, with an initial prototype phase allowing carpenters to familiarise themselves with the system and make any necessary adjustments before the project arrived on-site. After the completion of the prototype, there remained one week to fabricate and assemble the building's structure at the construction site. The project utilised C24 off-the-shelf construction lumber, which measured 195mm in width. The fabrication of the elements took place over four days on a robotic system, followed by the delivery and assembly of the elements at the construction site, a task completed within one day by two carpenters.

The shed delivered a basic knowledge of robotically fabricated timber joinery that later informed the detailing of the greenery project.

The shed presented findings about how to process off-the-shelf timber material robotically.

The greenery informed documented a point of departure for conveying positional and assembly information in timber construction that informed the Olaf Ryes Gade project.

Fig 3.2
This diagram highlights how the three demonstrators have influenced each other with knowledge about material use and robotic fabrication strategies.

3.2 Benefits of Robotic Technologies for Carpentry Practices

This section reports on the joint findings from the two papers. *'Timber Framing 2.0'*, and *'Computationally enabled material management: Learning from three robotically fabricated demonstrators'*. The section unfolds through summaries of the papers, which are preceded and followed by bridging text. Lastly, the section concludes with an initial answer to research question 1.1: *'Can onsite robotic systems contribute positively to the manual carpentry processes?'*.

In response, using digital fabrication technologies to assist the carpentry field is not new, as exemplified by using these technologies to manufacture timber-framed modules in off-site factories [Popovic and Winroth 2016]. These modules are done in efficient production runs. Still, after the modules have been sent to the construction site, deviations may occur between the planned and built, which requires the modules to be modified [Balaguer & Abderrahim 2008]. Hence, it is possible that on-site factories like the FotF could transfer the efficiency benefits of off-site construction to the construction site itself. As previously highlighted in research [Rauch et al., 2015], this potential suggests that leveraging as-built information could enable just-in-time manufacturing that aligns with project requirements. However, to replicate the efficiency of off-site facilities, the on-site system would need to produce fully assembled timber modules, aligning with the 'assembler' approach. Nevertheless, this approach presents challenges in terms of compactness and transportability, primarily due to the size of robotic work envelopes required for assembling large modules. Therefore, the research focuses on developing a fabrication strategy that produces elements that humans can quickly assemble to minimise time spent on the construction site.

Summary:
'Timber Framing 2.0' pages 10 - 24 in book II.

This has been explored through the Olaf Ryes Gade project, an industrial collaboration among Brav Engineering [Brav], Odico and CS byggefirma [cs byggefirma] (fig 3.3-3.6). The project aimed to increase the assembly pace on the construction site by decreasing the time spent on assembling and manufacturing a timber structure. This was explored across five weeks, which resulted in three prototypes and the final timber structure assembled on-site. An interlinked fabrication process enabled such an agile process, where design, structure and fabrication models were one and the same.

Through a prototypical process, the project found a simple method to convey positional information - a simple notch, which is fast to fabricate compared to other more complex timber joinery types [Stehling et al, Takabayashi et al. 2018]. Once the fabrication and design had been finalised through the third prototype (fig 3.6), where carpenters came to Odico and carried out the test assembly, it was agreed with the client to fabricate the final structure. One robot and operator made this over four regular work days (8 hours per day) by one robot and

Fig 3.3
A detail of the floor separating details within the Olaf Ryes Gade project.

operator, and when the elements arrived on the construction site, they were assembled in one regular working day by two carpenters, thus totalling 16 hours.

Through this process, it was discovered that assigning the task of generating positional information to robotic fabrication reduced the risk of errors compared to relying on hand-drawn markings. Additionally, using positional

Fig 3.4
The Olaf Ryes Gade project after the structure was erected in one day in 2020, Odense, Denmark.

Fig 3.6
A) Carpenters mitigate the torsion of timber elements with a large wrench during the assembly of the third prototype. B) the third prototype that tested all the details to implement within the Olaf Ryesgade project.

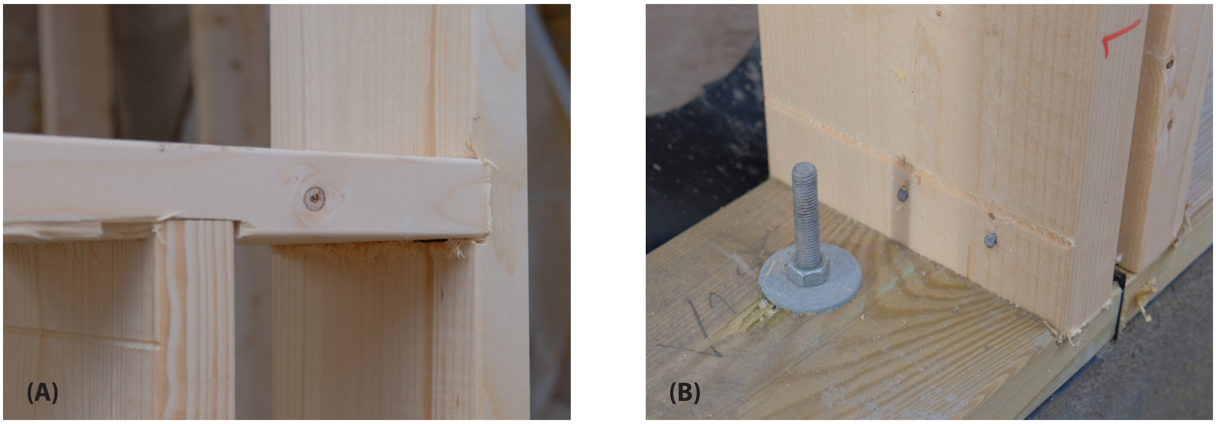


Fig 3.5
Besides the floor separating detail in fig 3.3, the project developed two other details to aid in assembly. A) Details of the notches made for the Olaf Ryes Gade project, which acted as positional information. B) a little grove that was cut for carpenters to rest their nail gun on.

information enabled a rapid pace of erecting the timber structure, indicating that robotically detailed timber elements are significantly quicker assembled by human hand than robotic systems [Helmreich et al. 2022]. This demonstrates that carpentry can benefit from robotically detailed elements whereby few workers can assemble a timber structure quickly. Thus, this is seen as a positive response to P1; 'Leveraging robotic fabrication to manufacture elements that simplify assembly can increase the construction pace'.

Manufacturing elements for construction with digital fabrication technologies have been happening for over thirty years [Mitchell 2001]. As the use of the technology matured in the early 2000s, the use of digital fabrication technologies has been described as having little cost difference between fabricating unique pieces or copies of an element [Mitchell 2001, Kolerevic 2003]. This is true in regard to machining time if the cuttable path is similar in length. However, this doesn't factor in the potential additional use of material due to poor nesting layouts.

Summary :
'Computationally enabled material management: Learning from three robotically fabricated demonstrators'
pages 26 - 43 in Book II.

From this line of enquiry, it has been possible to present research in response to SDG 12 [UN] and P3, 'Through a digitally managed pipeline, resultant waste can be minimised' through research that has explored computational tools to understand the material consequences of certain design choices. The basis for this analysis is the three timber demonstrators made through the thesis. Thus, the analysis has been limited to linear timber elements. The research tested three different computational techniques to test the consequences of cutting sequences on the material use of a given stock. Two of these methods documented that an alternative cutting sequence could ensure more than ninety percent use of a given stock (fig 3. 8).
Furthermore, the elements made from the stock were analysed to see how much material was removed to produce a finished element. Here it

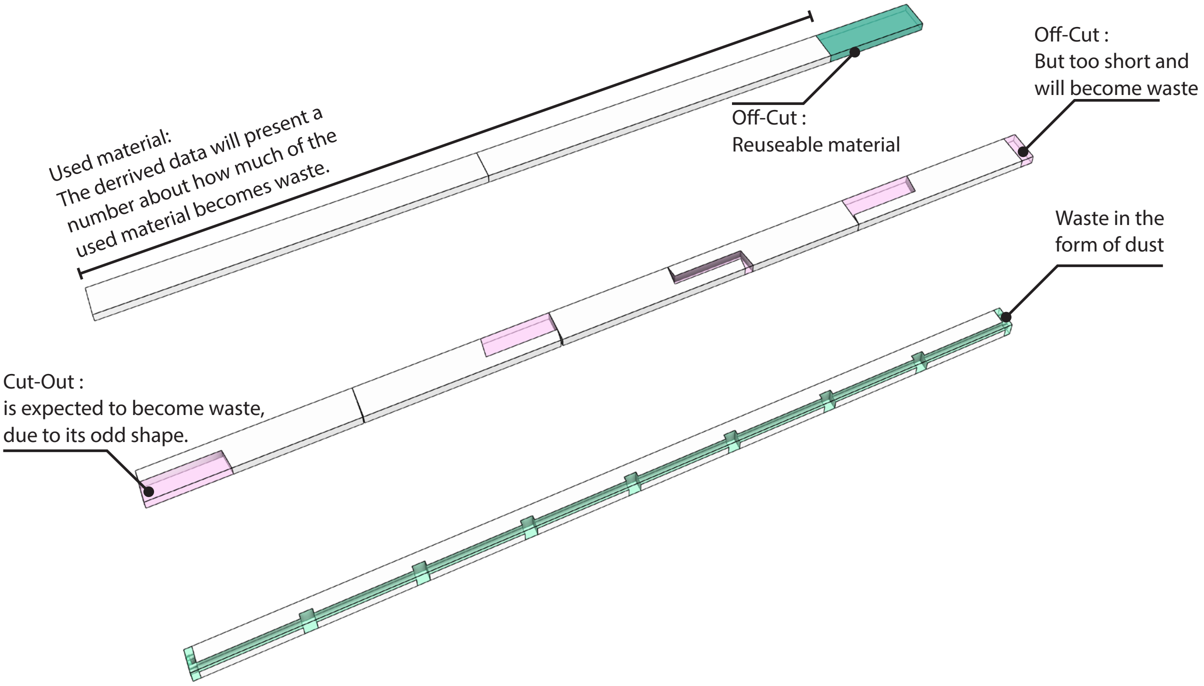


Fig 3.7
This diagram shows how paper 3 defined waste, namely through off-cuts, that can potentially be reused, cut-out that is waste, and lastly, waste in the shape of dust.

was found that some joinery strategies removed upwards of fifteen-twenty percent of material before an element was finished, whereas others removed as little as two percent. This was highly interesting since it gives an indication of waste produced and machining time for a given element type and thus the potential cost of a given element. Through this process, it was possible to propose a definition of 'waste', where terms such as 'cut-off', 'cut-out', and waste are used to describe what was left after a fabrication run (fig 3.7).

Although research question 1.1 remains an open question with multiple alternative answers that may arise in the future, this research highlights that robotic fabrication has the potential to accelerate the construction process. This is achieved through the use of robotically detailed off-the-shelf timber, which enables quick assembly. While further research is needed to determine the exact extent of this acceleration, initial findings and the growing adoption of the construction system [Carpen] suggest a positive increase in construction pace. Increasing the construction pace has positive side effects, such as minimising the risk of having the structure infected by mould, since it can be sealed quicker. Furthermore, the research has identified a technical framework and method utilising more than 90 percent of timber stock through alternative cutting sequences. Future work can further increase this number if a design optimisation is carried out through a cyclical design optimisation to improve the material yield of a given stock material.

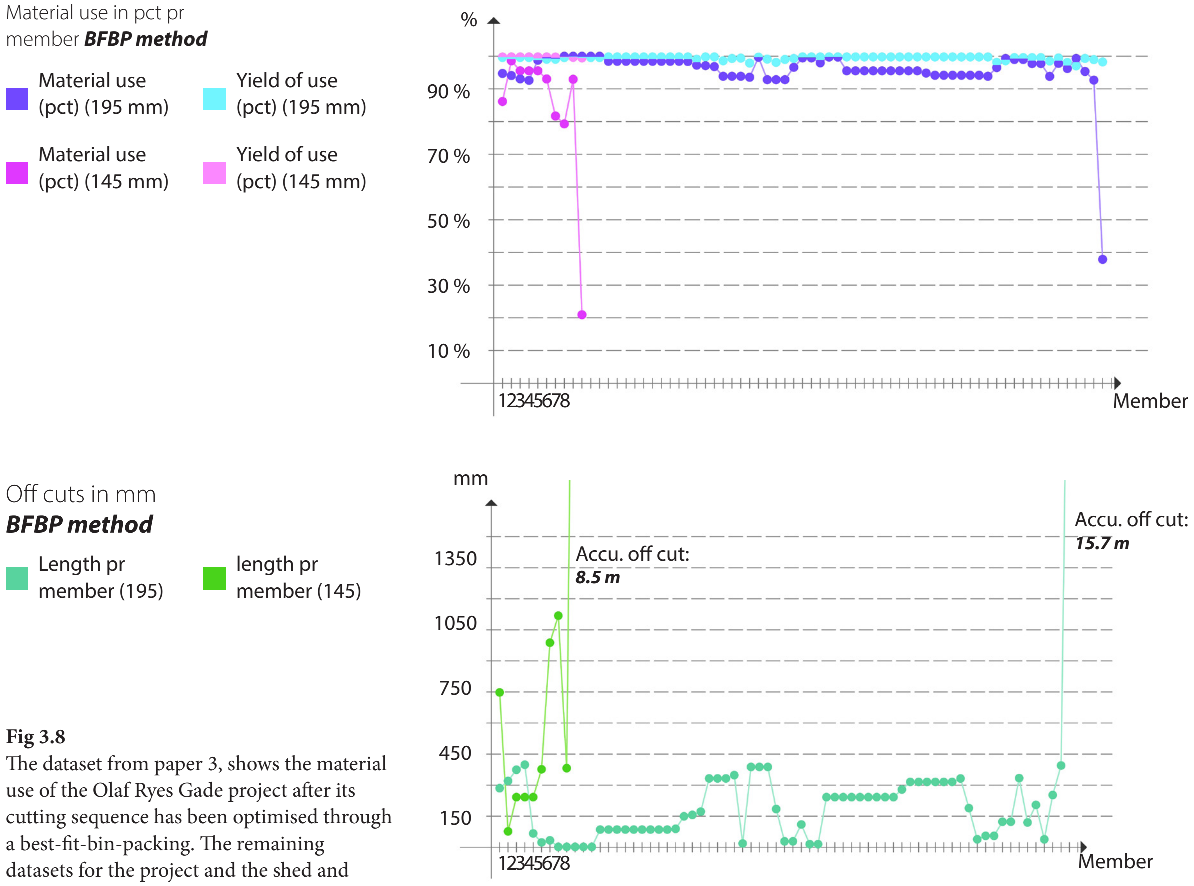


Fig 3.8
The dataset from paper 3, shows the material use of the Olaf Ryes Gade project after its cutting sequence has been optimised through a best-fit-bin-packing. The remaining datasets for the project and the shed and greenery are in paper 3.

3.3 Developing a New FotF

This section reports on the paper *’Design Method for Transportable Robot Units (TRU): Using Experience to identify new work environments for TRUs’*, which has been submitted to the journals; Automation in Construction and Advances in Manufacturing, and is awaiting peer review. This section summarises the paper flanked by an intro and response to research question 1.2; *’How can on-site robotic fabrication systems be designed to influence the construction industry?’ (RQ 1.2)*

The aim of developing a transportable robotic environment for fabricating linear timber elements has been to manufacture elements supporting the carpentry industry. Based on the previous section, such elements would be detailed similarly to the Olaf Ryes Gade project, whereby the focus of this section becomes to identify the necessary hardware requirements to fabricate such elements.

Summary:
’Design Method for Transportable Robot Units (TRU): Using Experience to identify new work environments for TRUs’ pagers 46 - 65 in book II

The knowledge basis for this development is the robotic work environments that enabled fabricating the three built demonstrators, combined with knowledge from section 2.3. Both the Olaf Ryes Gade project and shed manufactured elements based on findings from section 2.3 - namely, elements were fixed on a rotary table with either manual or pneumatic clamps (fig). Applying the rotary table’s freedom enables the processing of long timber elements at either end from a stationary robot position. However, it meant elements had to be precut by hand because full-length members would collide with the robotic work environment (walls and/or robot) when the rotary axis turns. Furthermore, some of the elements rotated by the rotary table were 2.9 meter-long timber members, which gives a large robotic work envelope which isn’t highly transportable. Thus the paper identified an alternative approach where a linear axis was developed to move timber forward, whereby the robot can process elements from a fixed position. This enabled to process full-length timber members in a compact work environment since the timber element didn’t require a rotation.

Timber members positioned on the linear axis are, similarly to the Shed setup, clamped with pneumatic clamps during machining. Unlike previous robotic work environments, this new FotF system incorporated an automatic label machine [X1Jet] as part of the linear axis, which prints labels on elements during manufacturing. Furthermore, a new feature of this new system is elements are manufactured through a semi to fully autonomous manufacturing process, where elements are loaded/unloaded by the robot using a pneumatic gripper. The wood is picked from a finite stack of lumber, which, when empty, will have the robot prompt the operator to change the stack. These minor innovations led to a proposal for a new transportable robotic timber unit, where every piece of hardware could be fitted into a trailer that can be pulled by a regular car

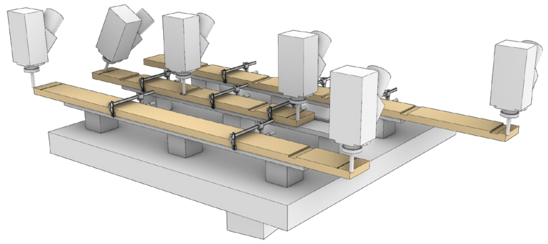


Fig 3.9
Principle work environment used for the initial version of the Olaf Ryes Gade project that partly informed how the new FotF system should be.

or van - making the system highly transportable (fig 3.10, A).

This initial digital study became the basis for an application with the Innovation Fund, where Odico received funding to fully develop the system while testing it on commercial projects (fig 3.11). The system was built in Odico's facility, where it performs alpha tests before commencing commercial production in the summer of 2023 (fig 3.10, B & 3.12) [carpen].

Importantly, this paper has described how a specific use case has informed the design of a new FotF system. Within this research, the use case has the potential to mitigate a latent manufacturing potential of timber structures for upwards of 5000 timber houses per year in Denmark, based on the current lumber production of Denmark [Danish Wood]. Manufacturing this amount of housing would mean the system could assist in fabricating roughly 20-30 percent of yearly constructed houses, which equates to 12-18

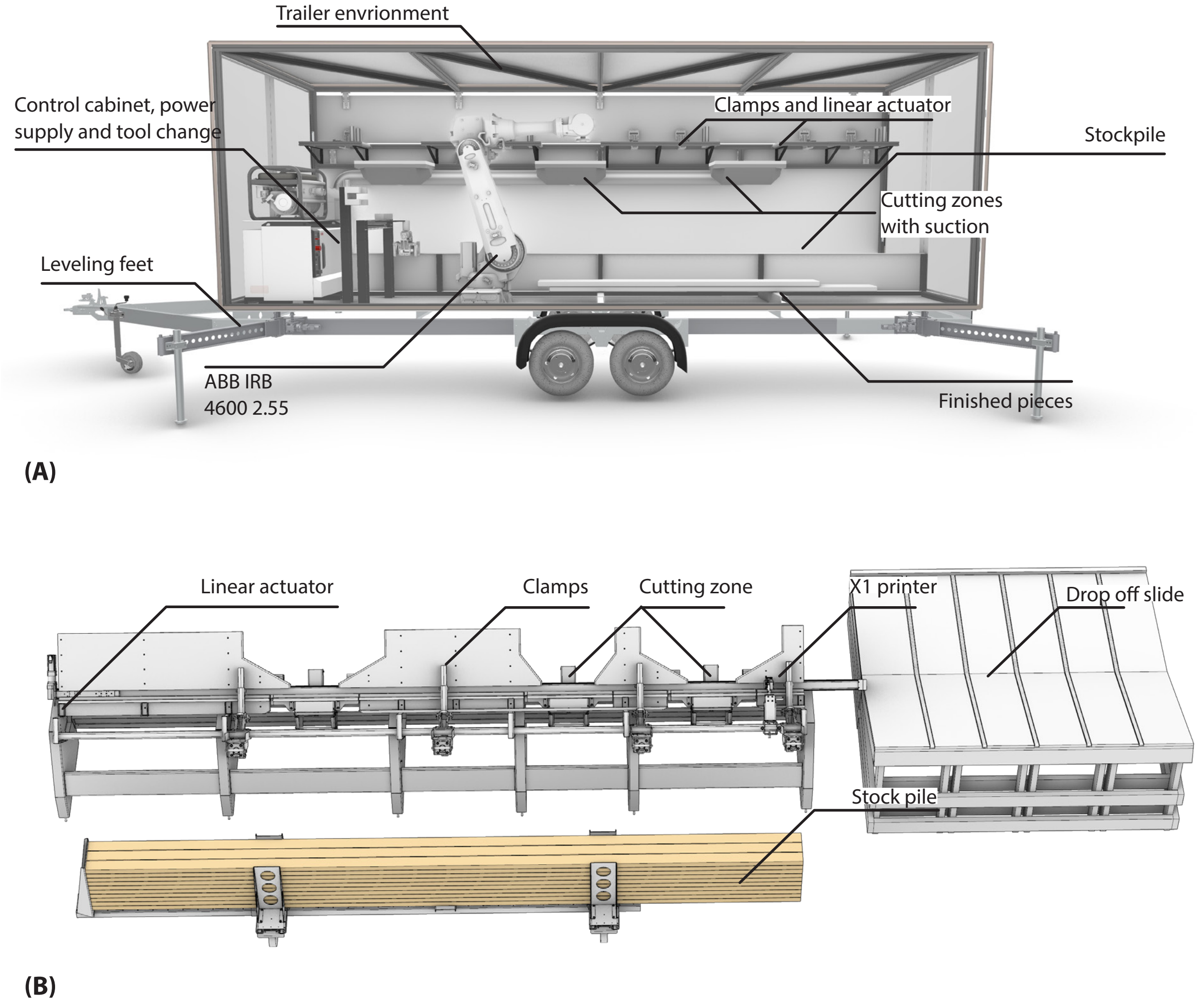


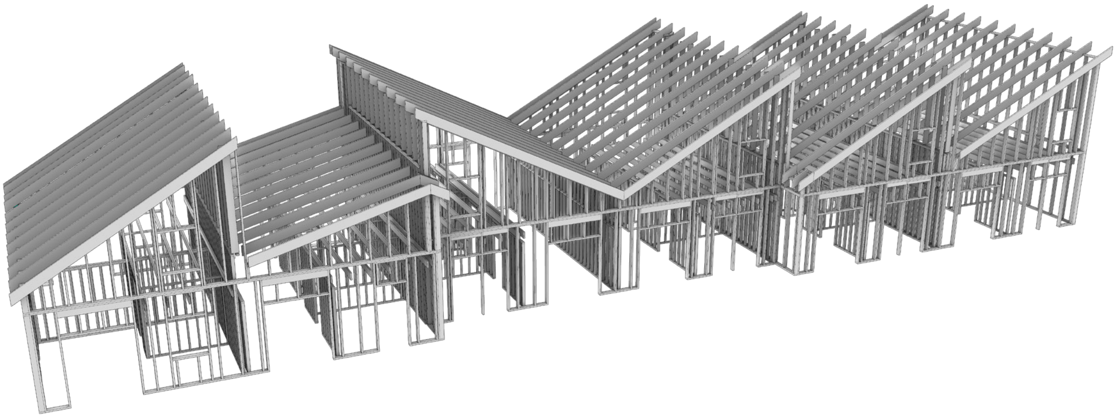
Fig 3.10
A) The version of the FotF system, that was used to secure funding to establish the physical version in fig 3.12. B) A digital overview of the elements within the off-site robotic work environment currently in alpha testing at Odico's facilities.

percent of total built square metres per year in Denmark [Danish Statistics]. This approach contrasts current practices in academia, where on- or near-site robotic systems have been aimed to solve construction tasks for a single project [Wagner et al. 2020]. Thus, this new FotF system represents an on-site manufacturing process within the AEC industry, where a robot fabricates elements at scale, which can significantly increase construction productivity. Furthermore, the system differs from the previously described manufacturing paradigm of the car industry, where robotic systems produce a singular product indefinitely; this system will be able to fabricate elements that manage the variability of making houses for unique construction sites.

Therefore, in response to research question 1.2, the research has demonstrated how to design a FotF system that can benefit the construction industry by manufacturing elements at scale. The basis for such a system has been three built demonstrators, which explored what would be the right approach to fabricate timber elements that could enter into current carpentry construction practices. Furthermore, to meet the promise of Rauch et al. 2015, it will be required that entire ecosystems of on-site robotic units are developed. The term ecosystem refers to multiple transportable robotic fabrication units - each solving unique fabrication tasks at scale. This approach contrasts with how both Rauch et al. 2015 and Wagner et al. 2020 describe on- or near-site robotic systems as reconfigurable between construction tasks, which is possible

but is assumed to establish periods of downtime during a construction process where systems are reconfigured.

Fig 3.11
The timber structure of a new project that will be manufactured during the summer of 2023. The structure consists of a series of row houses to be made by the FotF system in fig .12. The ambition is to manufacture the elements for 10 such units.



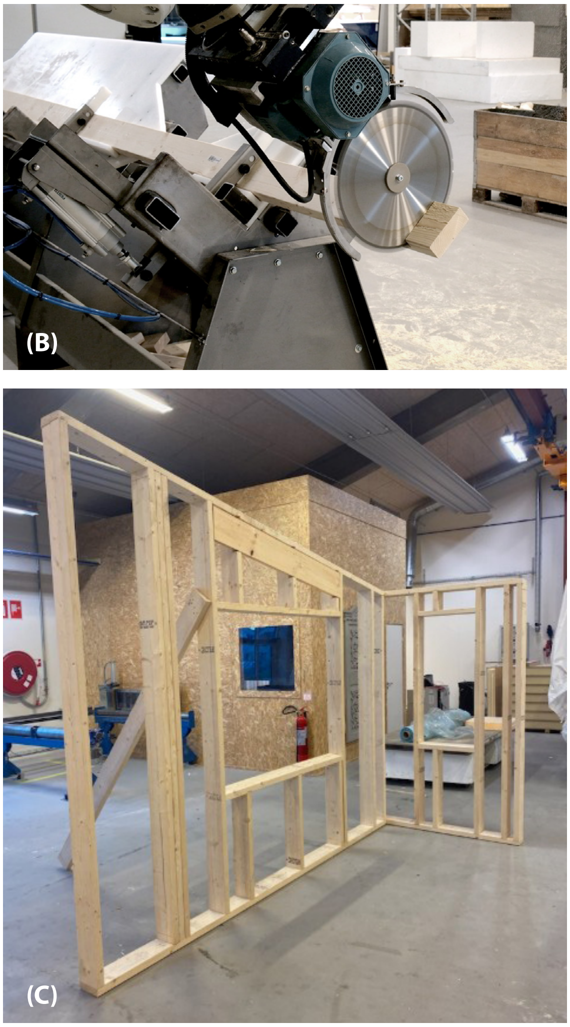


Fig 3.12
A) An overview image of the developed FotF system, with its linear axis positioned in front of it. B) The robot trimming elements for the prototype C), which was manufactured to test the different details of the construction system.

Chapter 3 Summary

Chapter 3 presented the approach taken by research trajectory I to address research questions 1.1 and 1.2:

'Can onsite robotic systems contribute positively to the manual carpentry processes?' (RQ 1.1)

'How can on-site robotic fabrication systems be designed to influence the construction industry?' (RQ 1.2)

Through this process, a novel construction system has been developed, which is perceived to benefit the carpentry profession by increasing the pace of construction for 1-2 story timber housing. Additionally, the research has outlined an approach to address Sustainable Development Goal 12*: Responsible Consumption and Production,* by leveraging computational processes enabled through robotic fabrication. This approach aims to achieve a yield above 90 percent from a given stock and minimise waste while documenting if off-cuts can become part of a new process.

Furthermore, the chapter has described how the findings obtained from three the robotic work environments from three built demonstrators have informed the proposal of a new FotF system, that is currently undergoing off-site alpha testing at Odico's facility.

Fig 4.1
A series of panels made with the developed instruction method, during the two-week user study in February 2023, Aarhus.

Chapter 4

Research Trajectory II

Chapter 4 Overview

Previous chapters have presented the thesis background of state-of-the-art projects and approaches in the context of robotic timber fabrication (Chapter 2) and discussed limitations and challenges for intuitive work processes for carpentry that delay the adoption of industrial robotic arms in manufacturing for use on construction sites. The thesis has continued to discuss developing and exploring a transportable robotic unit for efficient manufacturing of timber elements for 1-2 story timber housing (Chapter 3). Based on knowledge from section 2.1, this chapter responds to research trajectory II, by presenting an intuitive robotic instruction method that, through hand-drawn markings, can instruct fabrication action to an industrial robotic arm. The functionalities of this instruction method are choreographed through a control device.

The development and subsequent testing of the instruction method are described through three sections, where section 4.1 describes how the research has been structured through the action research framework. Section 4.2 describes the development process of the instruction method reported in three peer-reviewed papers. Section 4.3 reports on the first user studies of the method through a paper that is under review.

4.1 Structuring the Research

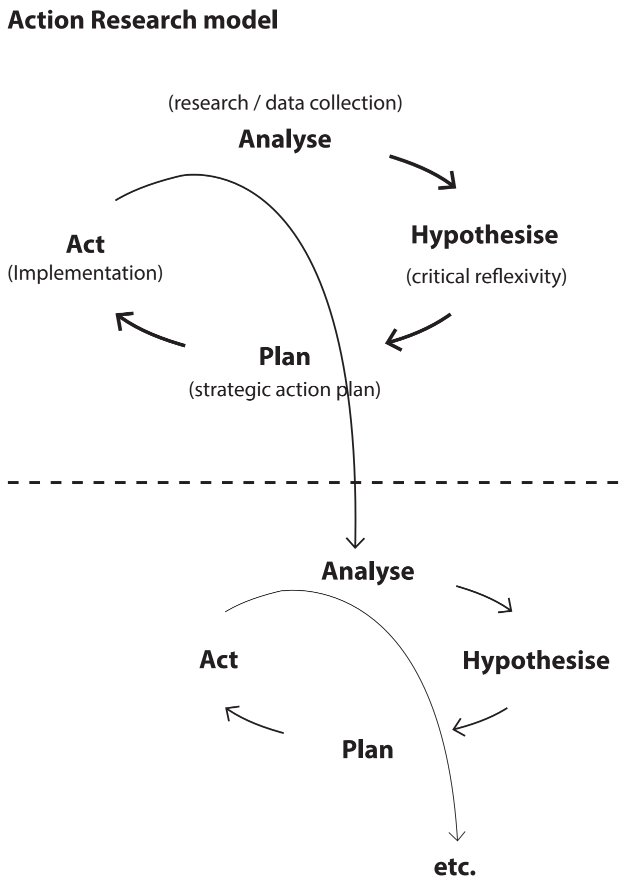
The research described in this chapter explores research trajectory II, where work has been structured through the action research framework described in section 1.6.2. Elements of the research trajectory were addressed in section 2.1 and section 1.8, namely how the carpentry user group have informed how robotic fabrication should be instructed - through physical drawings. Thus, this chapter aims to describe how this has been enabled through published papers in book II.

The aims of each step of the action research framework are detailed in fig 4.2. Following these steps will augment the existing FotF software system with a new instruction method that can enable robotic non-specialists to instruct a robotic fabrication system. Each cycle is detailed in the subsequent sections 4.2 and 4.3, which correspond to research questions:

’How can robots be instructed by users with limited knowledge about robotics? What are the critical aspects and methods that enable such a system to function? (RQ 2.1)’

‘Can instructing robotic information through physical drawings, allow robotic non-specialists, to instruct ad-hoc robotic fabrication information? (RQ 2.2)’ .

Fig 4.2
This diagram depicts how the action research framework has been used to structure the research in research trajectory II.



Cycle I	
Analysis	How do on-site construction workers receive construction instructions? Analysis indicates that today it is through CAD-printouts, whereas drawings used to be made on-site.
Hypothesis	Robotic arms can be instructable through physical drawings, if robots can ‘see’ and ‘understand’ the drawn
Plan	Planing the implementation- led to patent application EP4165483A1 which is currently pending.
Act	The Patent was used as a development plan for the different functionalities of the technology, and was excecuted by the researcher.
Cycle II	
Analysis	When the developed is observe to be robost, it should be tested against a user group.
Hypothesis	Instructing robotics through physical drawings will allow robotic non-specialists to instruct an industrial robot arm with ad-hoc fabrication information
Plan	Plan the user studies and how they are evaluated
Act	Carry out the user studies, and gather data.

4.2 Research Cycle I

This section reports on findings from three peer-reviewed papers; 1) '*Augmented Drawn Construction Symbols: A Method for Ad Hoc Robotic Fabrication*'; 2) '*Hand-Drawn Digital Fabrication: Calibrating a Visual Communication Method for Robotic on-Site Fabrication*'; and 3) '*Robotic Drawing Communication Protocol: A Framework for Building a Semantic Drawn Language for Robotic Fabrication*'. Each paper develops parts from patent diagrams (fig 4.4) included in book II [Pedersen et al. 2021]. The subsequent section unfolds through a text body, a paper summary, and a text body, and so forth, to establish connections between the papers. This approach successfully addresses research question 2.1: '*How can robots be instructed by users with limited knowledge about robotics? What are the critical aspects and methods that enable such a system to function?*'

Following the action research framework, the initial step involved analysing how robotics should be instructed to ensure intuitiveness for on-site construction processes. This analysis is detailed in section 2.1, where on-site construction practices indicate that physical drawings serve as a simple instruction method to facilitate ad-hoc fabrication actions. The analysis served as the basis for the hypothesis to test; '*Robotic arms can be instructable through physical drawings, if robots can 'see' and 'understand' the drawn*'. Section 2.2, presented the technical basis for allowing a robot to 'see' and 'understand' a drawing.

Following the identification of the technical framework, it was possible to conduct a feasibility study, which documented that the system could detect and develop information to allow a robot to see and retrace a physical line (fig 4.3). After conducting the preliminary feasibility study, Odico pursued a patent for the instruction technique. As a part of the application, multiple diagrams were created to illustrate the range of functionalities to be incorporated into the instruction method. These patent diagrams encompassed various potential use cases, and were a guiding framework for developing the instruction methods during the initial research cycle.

The patent diagrams outlined three core functions to be developed (see fig 4.4), which include the proof of concept, the new method, and the drawing classification. Each of these functions required to be developed before the system could be moved into the second research cycle and be used with a user group. The development process of each functionality was documented through progress reports in the form of three peer-reviewed research papers.

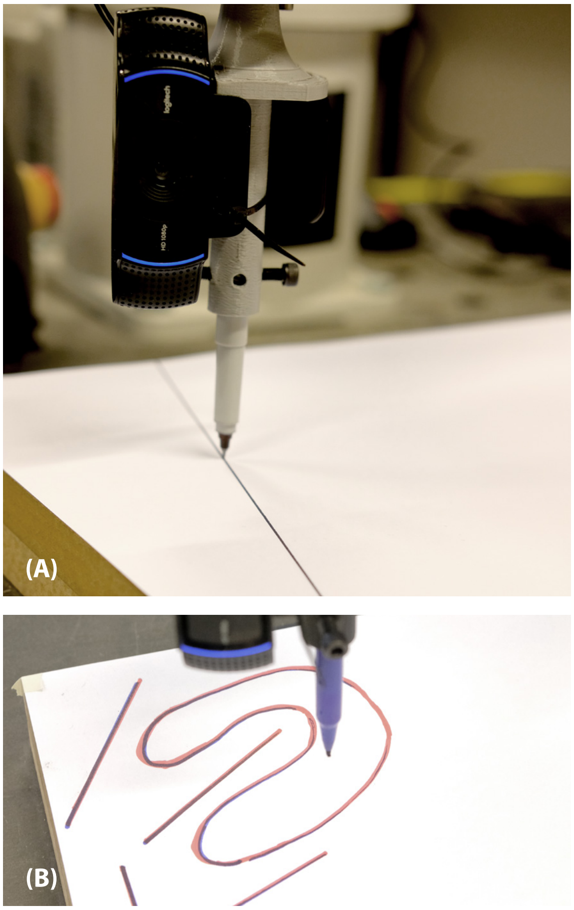
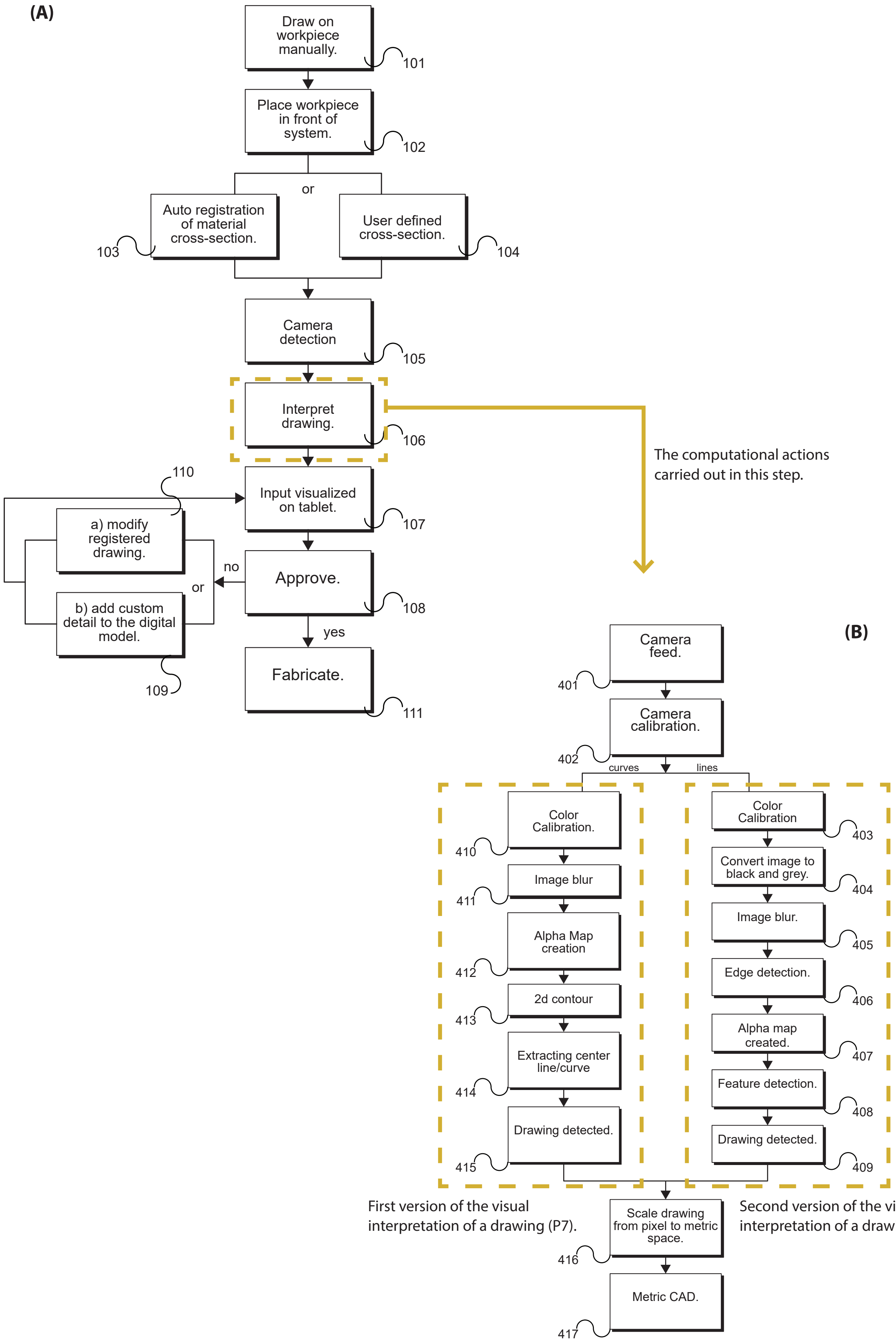


Fig 4.3
A) An initial image from the feasibility study, where a line was drawn in black, and retraced by the robot based on information gathered from a camera. B) Later research performed a similar test at a later stage, but with a red (human) and blue (robot) marker.



The computational actions carried out in this step.

First version of the visual interpretation of a drawing (P7).

Second version of the visual interpretation of a drawing (P6).

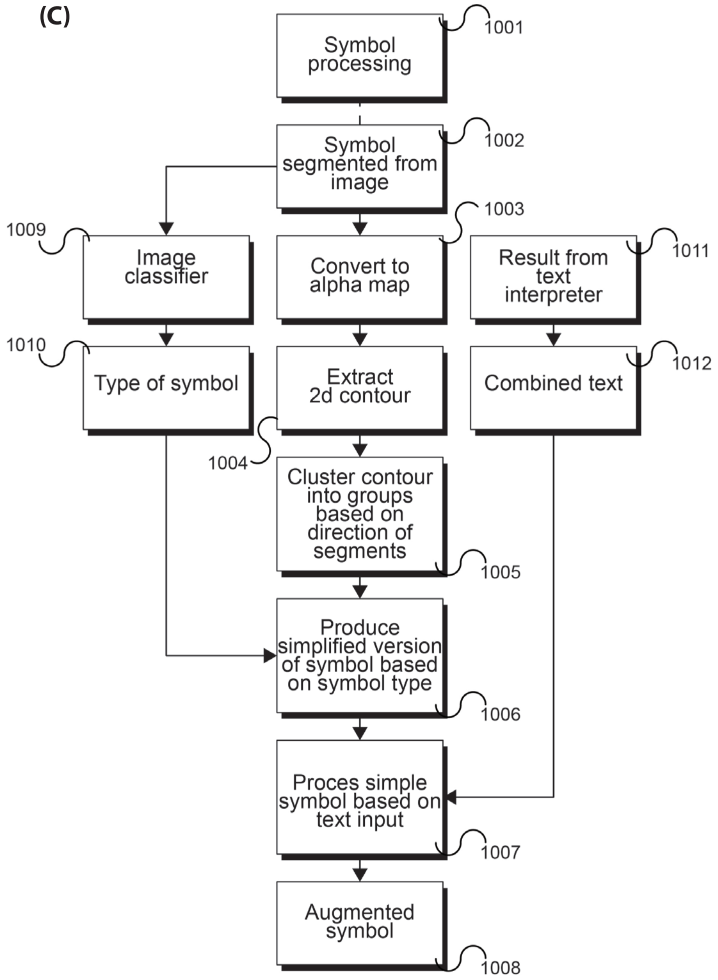


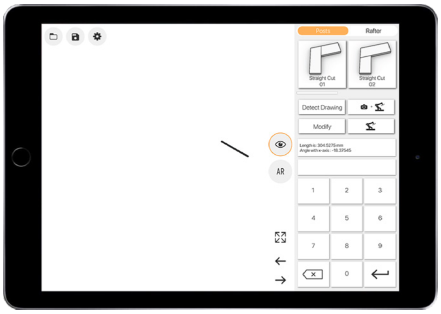
Fig 4.4
The different patent diagrams used to structure the research within research trajectory II. A) describes the principle workflow followed by the 'Proof of Concept' detailed in paper 7. B) is an unwrapping of the 'interpret drawing' box in patent diagram A), it details the continued development of the digitisation of hand drawings, thus, the 'new method' is detailed in paper 6. Lastly, C) details the logical flow behind the image classification process.

Summary:
'Augmented Drawn Construction Symbols: A Method for Ad Hoc Robotic Fabrication'
Pages 86 - 103 in book II.

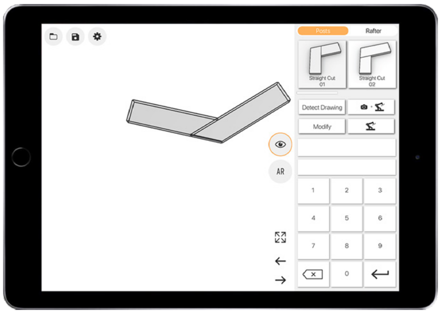
The identified proof of concept from the patent diagram is reported in this paper, which developed an initial version of the instruction method, which enabled to instruct robotic actions through the following steps; 1) a workpiece is positioned in front of the robot with a drawing on it; 2) from the control device (tablet), the robot is navigated to a detection pose; 3) the system is prompted to detect a drawing; 4) the drawing is visualised on the control device, where it can be assigned fabrication actions; 5) the fabrication actions are sent to the robot for fabrication. This process was enabled through an augmentation of a WIP version of the FotF software framework, which included new software functionalities, a parametric library to augment the drawn with geometric and fabrication actions, and augmented reality (AR) functionalities to overlay the physical situation with developed information (fig). The basis for these new functionalities was a visual system that could identify and digitise drawn lines, whereby the drawn conveyed real-world scale and position, which was used to position and scale information from the parametric library. The developed fabrication or geometric information from this process can be overlaid with the physical fabrication situation through the developed AR pipeline (fig). Testing this process resulted in small fabrication tests aimed at making timber joints.


Operator making a Drawing


Robot at detection pose

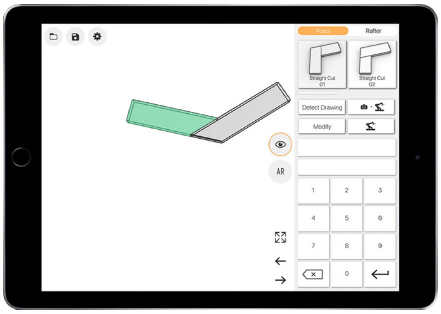


Drawing detected



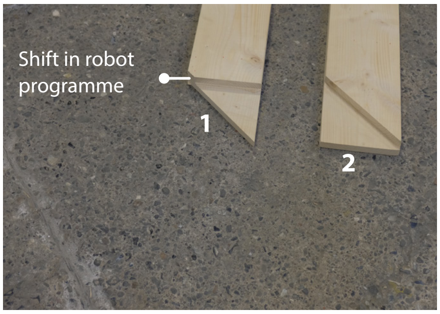
Augmenting marking with 3d information


Operator inspecting the AR representation of the 3d model



Select a piece to cut and press fabricate

Fabrication in progress



Result from first test cuts

Fig 4.5
The step-by-step process of instructing a robot through drawing.

Fig 4.6
An image of the AR pipeline used for the first paper where the object (box) should be positioned on top of a timber physical block based on the floral marker. But as the image highlights, the white block deviates too much from its physical twin.

Following the paper's publication, further research explored the AR functionalities and its precision was found limited and was abandoned for future research (fig 4.6). This conclusion was made in 2019 based on regular tablet devices. However, innovations in AI functionalities and technical improvements of tablet devices may increase the precision of such functions today. While this part of the research trajectory was put on hold, it can be further expanded in the future to revise and increase functionalities. However, the significance of this first development effort is the ability to use a simple physical representation (line) to inform the position and size of more complex computation information or fabrication sequences, which makes the possibilities of the method believed to be nearly endless.

Summary:
'Hand-Drawn Digital Fabrication: Calibrating a Visual Communication Method for Robotic on-Site Fabrication'
Pages 104 - 124 in book II.

Building upon the findings of the initial study, which underscored the potential of the instruction method, the vision framework was reevaluated to introduce a novel approach for analysing information derived from the vision system. This revision's main focus was enhancing how computer vision algorithms isolate a drawing within an image. In the first instance of the vision system, feature detection algorithms were used to find linear or circular segments that had to be combined. Instead, the new approach used simple functions to isolate a given colour within an image, which made it a requirement to know the digital colour of a marker in an image for a given lighting situation. Changing to this method enabled isolating any drawing type; 1) Line, 2) Open Curve, and 3) Closed Curve, after which its outline could be extracted from. However, to make an outline relevant for robotic fabrication, its centre line representation is required to be extracted from the outline, which was best handled through individualised approaches to each drawing type since generalised approaches require removing digital noise.

The new technique underwent testing in an experiment where different types of drawings were converted into fabrication information based on user inputs specifying the preferred centre-line approach. This approach resulted in the utilisation of the system to create a 1:2 built demonstrator. In addition to introducing valuable functions to the instruction method and validating the effectiveness of the new technique, it highlighted the potential to enhance the freedom and possibilities offered by small robotic systems. This was demonstrated by employing an ABB 120 robot [ABB 120] that could manipulate elements beyond its documented reach by

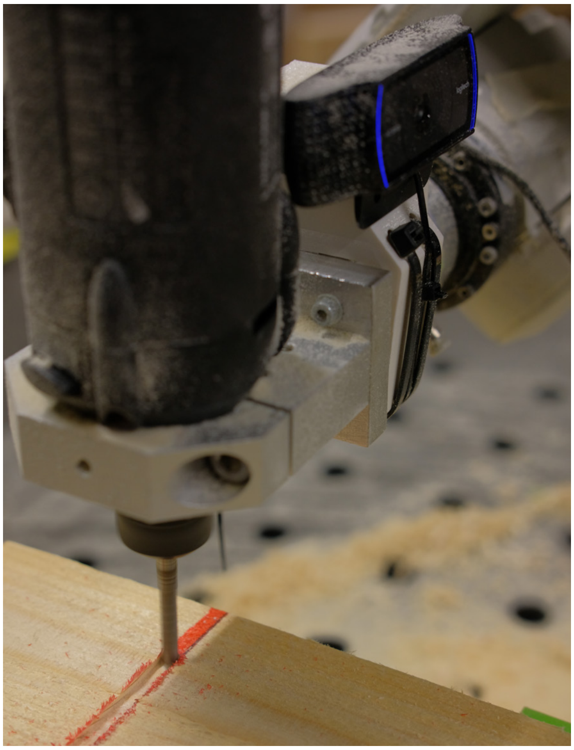


Fig 4.7
An image showing a robotic end effector milling along a drawn line, based on inputs from the webcam next to the spindle.

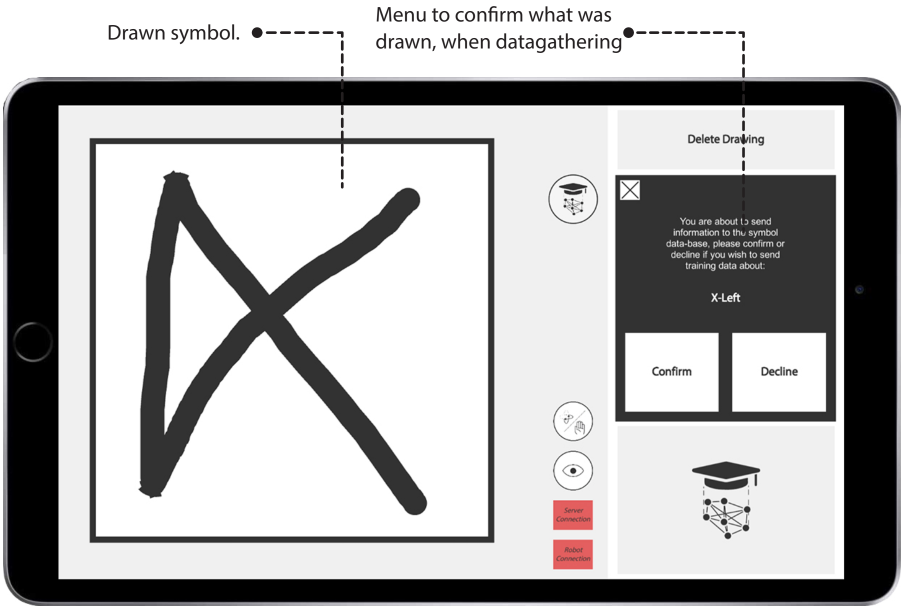
Fig 4.8
A demonstrator made by the researcher, where everything was milled with the developed instruction method.

repositioning the workpieces to enable the robot's visual perception of the drawings.

While the recent system modifications have enhanced the potential usability of the instruction method, they have also raised the need for the system to comprehend the drawings, as the system relies on customised centerline strategies. Therefore, the research began to explore Machine Learning techniques outlined by An et al. 2020 to classify drawings into given types, whereby the system would understand what it has seen. This can prevent users from having to specify which centre-line strategy to follow. At the same time, it could enable the robot to derive implicit fabrication information from a drawn symbol - similar to how carpenters communicate fabrication or assembly information to one another.

Summary:
'Robotic Drawing Communication Protocol:
A Framework for Building a Semantic
Drawn Language for Robotic Fabrication'
Pages 126 - 141 in book II.

This paper outlines the process of using machine learning techniques to classify detected drawings into certain drawing types. The paper reports on developing a process whereby digital drawings can be made on a control device (fig 4.9) and used as training data to classify physically drawn elements. This can enable an operator to quickly develop data for new symbols or drawing types to be embedded within the classification system, because compared to using physical data, it


Drawn symbol.

Menu to confirm what was drawn, when datagathering

You are about to send information to the symbol data-base, please confirm or decline if you wish to send training data about:

X-Left

Fig 4.9
Making the robot understand - a digital training pipeline positioned in the software app, where you can draw symbols, label them, and save them on a server for future training.

	actual: OpenCurve	actual: Line	actual: Line	actual: OpenCurve	actual: ClosedCurve
RND Forrest on Digital Data	OpenCurve (96.7 %)	Line (98.6%)	Line (98.9%)	OpenCurve (96.2 %)	OpenCurve (58.7 %)
RND Forrest on Physical Data	OpenCurve (95.3 %)	Line (80.6%)	Line (98.3%)	OpenCurve (96.3 %)	ClosedCurve (95.6 %)
RND Forrest on combined Data	OpenCurve (98.7 %)	Line (95.6%)	Line (99.3%)	OpenCurve (98.0 %)	ClosedCurve (94.3 %)
SVM on Digital Data	OpenCurve (94.6 %)	Line (99.6%)	Line (96.8%)	OpenCurve (95.4 %)	ClosedCurve (98.2 %)
SVM on Physical Data	Closed Curve (75.1 %)	Line (99.1%)	Line (96.6%)	OpenCurve (82.1 %)	OpenCurve (60.6 %)
SVM on combined Data	Open Curve (62.4 %)	Line (99.9%)	Line (97.0%)	OpenCurve (74.6 %)	ClosedCurve (99.46 %)

	actual: OpenCurve	actual: Line
RND Forrest on Digital Data	OpenCurve (95.9 %)	Line (96.9%)
RND Forrest on Physical Data	OpenCurve (96.3 %)	Line (98.0%)
RND Forrest on combined Data	OpenCurve (98.4 %)	Line (99.4%)
SVM on Digital Data	OpenCurve (94.5 %)	Line (96.1%)
SVM on Physical Data	OpenCurve (93.2 %)	Line (92.7%)
SVM on combined Data	OpenCurve (98.6 %)	Line (96.6%)

Table 4.1
Classification results that highlight which classification method produced the best results in a study where digitally drawn data was used to classify physical data.

would not need to be digitised. The research found that digitally drawn data could classify physical drawings with a 90-98 percent (table 2.1) classification score, where poor data explained misclassifications.

This section has described the development process of a system whereby robotic fabrication information can be instructed through physical drawings in an attempt to lower the knowledge barrier of using robotic fabrication. Importantly, for such a system to work are computer science techniques, Machine Learning, computer vision and network communication. Through the first research cycle, the researcher has documented that the system functions through a built demonstrator, which is the conclusion of the first research cycle. Thus, the research into intuitive instruction methods moves on to the second cycle of the research framework.

4.3 Research Cycle II

The results obtained from the first research cycle indicate that the system was fit for testing through user studies, marking the initiation of the second research cycle. This cycle aims to assess user acceptance and adoption of the developed instruction method, which will be evaluated through questionnaires administered during the user studies. Consequently, the role of the researcher transitioned from active participation to that of an observer, enabling others to test the developed instruction method. These studies were intended to commence in early 2020 but were significantly delayed due to the Covid-19 pandemic, where most of the world was locked down during 2020 and 2021. Thus, the user studies were pushed towards the tail end of the PhD - in February 2023, where it was possible to organise two separate user studies with participants from the Aarhus School of Architecture. This could have been better since the target user group has been defined as carpenters. Still, through the questionnaires, it was possible to evaluate whether participants would be considered robotic specialists. Thus, the following section develops knowledge in response to research question 2.2: '*Can instructing robotic information through physical drawings, allow robotic non-specialists, to instruct ad-hoc robotic fabrication information? (RQ 2.2)*'

The hypothesis developed for the second research cycle is an inversion of the research question 2.2; '*Instructing robotics through physical drawings will allow robotic non-specialists to instruct an industrial robot arm with ad-hoc fabrication information*'.

Summary:
'The robots see red: Instructing industrial robots with on-object drawings.'
Pages 144 - 161 in book II.

Testing of this hypothesis is reported in this paper, where a group of robotic non-specialists were allowed to test the functions of the developed instruction method. The tests were evaluated through questionnaires that aimed to understand if using the system altered participants' perception of using robotic fabrication. Consequently, the project designed two questionnaires, with one administered prior to system usage to establish a baseline, while the second questionnaire evaluated the impact of the instruction method based on the responses. The user studies followed the following plan:

- Administer the questionnaires either through paper printouts or verbally during a semi-instructed interview.
- Introduce the instruction method along with its fundamental functions to the participants.
- Enable participants to utilise the system.
- Administer the follow-up questionnaire to gather data regarding the participants' experiences after using the robotic instruction method.

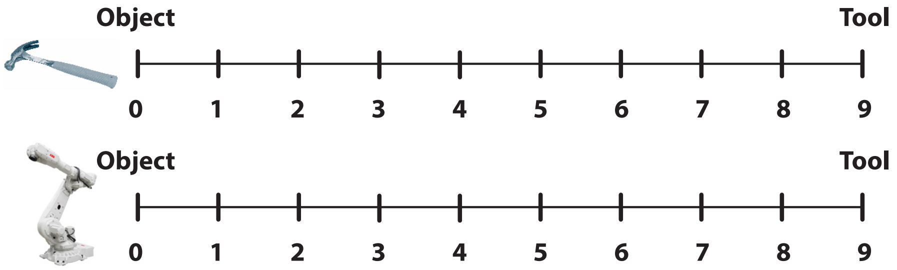


Fig 4.10
The spectrum for participants to fill out before and after exposure to the instruction method.

An important part of this questionnaire was for participants to state their personal position about a robot as a tool in comparison to a hammer, which served as a baseline for how intuitive robots were. Once participants had used the system, they would be presented with a second questionnaire to evaluate if using the system had altered their position.

As part of the user studies, participants were asked to instruct milling actions on wooden elements, where a drawing was used to inform complex surface morphologies. Through this process, it was observed that the longer participants were exposed to the systems, the more comfortable and exploratory they became. This led to some participants beginning to use the system in unforeseen ways, which indicates that the users understood the system and made creative leaps to extend its use.

During this process, the research paper documented the diverse outcomes achievable with the instruction method while also highlighting the challenges associated with developing questionnaires. It was observed that participants' interpretations of the questions could lead to inexplicable answers, making the questionnaire design a complex task.

In summary, this section can conclude based on the two user studies that documented how robotic non-specialists were able to instruct robotic information through the developed method and accompanying software. As mentioned earlier, the user group consisted primarily of architectural students rather than carpenters. This demographic proved beneficial as it uncovered creative applications of the instruction method that may have remained undiscovered if carpenters were the sole users of the system. Furthermore, the studies aimed to determine if instructing robotics using the developed method would lead participants to perceive the robot as a tool. The research revealed a notable improvement in participants' perception of the robot as a tool both before and after the studies were conducted.

Fig 4.11
A) Robotic programming through drawing, where B) is the milled version; the parameters that control the depth and smoothness, are specified in the software.

Fig 4.12
A structure made by a group of students during the two-week user study. The top is robotically made, and the wooden structure is made by hand.

Fig 4.13
During the two-week user study, participants began using the instruction method through an alternative approach. Instead of using a red marker to draw the instruction, they began using red paper instead of a red marker, where they blocked out the red with objects. The blocked area would be avoided during the machining process. This image shows a test where the participant blocked the red paper with a twig.

Chapter 4 Summary

This chapter has documented how an intuitive instruction method can be developed based on extrapolated knowledge from on-site construction processes. Developing the instruction process sits within the first cycle of an action research framework, which documents how a patent application could structure research into enabling a robot to both 'see' and 'understand' a drawing. The development of such a process unfolded through three papers summarised in section 4.2. Following the development process, the project carried out two user studies to test if robotic non-specialists could use the method to instruct ad-hoc robotic actions for various fabrication tasks. This study was detailed in a paper that awaits peer-review, where the findings from the user studies were positive and presented an exciting aspect; participants of the studies, began to present new ways of using the system, which is considered a creative leap that will be a subject for future research.

Chapter 5
Discussion

Chapter 5 Overview

The PhD project has been conducted at the intersection between academia and practice to propose a new timber FotF system for the industry partner, which can assist the carpentry profession in manufacturing timber structures for 1-2 storey housing. Additionally, and essential to the project, a new robotic instruction method has been developed to augment the current FotF software framework with ad-hoc fabrication possibilities. The new instruction method has aimed to enable robotic non-specialists to instruct robotic fabrication actions.

The project has developed through a design-led research approach where two individual research trajectories have produced built demonstrators to acquire knowledge. Research trajectory I has documented how fabrication principles from three built demonstrators could be successfully used to mature and propose a new FotF system to manufacture 1-2 storey housing. Research trajectory II has developed a patent-pending robotic instruction method where on-object drawings can enable robotic non-specialists to instruct complex fabrication actions such as timber joints or complex surface morphologies. Furthermore, through this research journey, topics have emerged which is relevant to discuss within this thesis:

1. ***On/near site robotic fabrication?***
   The project has successfully devised a new solution within the FotF (Factory-on-the-Fly) framework. However, assessing the relevance of using robotics on the construction site is crucial. Section 5.1 of the project outlines a standpoint by examining the historical application of robotic technologies and proposing potential reorientations for future implementation.

2. ***Physical or digital instruction?***
   Through the research, it has been possible to develop a new patent (pending) for a robotic instruction method that breaks the current file-to-factory paradigm. Therefore, this section discusses how such a method can enable creative use compared to conventional file-to-factory workflows.

3. ***Resilient robotics?***
   The research was directed into two individual research streams, which have led to a resilient framework for on-site robotic fabrication. This notion of 'resilience' is discussed through the perceived benefits of combining the results from each research trajectory

5.1 On/Near Site robotic fabrication?

The research project has investigated the use of robotics on the construction site, especially considering the successful utilisation of such technologies in off-site facilities. This question holds relevance and is believed to revolve around the distinction between known and unknown construction environments and tasks. In response to such a question, it is hard not to answer with ’it depends’ because it is found to be a matter of complexity and having identified the correct use-case for the system.

If the aim of using robotic or CNC technologies is to fabricate complex architectural forms, such as Kilden Performing Arts Centre in Kristiansand, Norway from 2012 [Kilden, Stehling et al. 2017] or the new Swatch HeadQuarters in Biel, Switzerland from 2019 [Swatch, Stehling et al. 2020], it would be nearly impossible to use on- or near-site robotic solutions. Due to the intricate and diverse nature of such construction projects, which encompass numerous unique elements within different bounding volumes, it is challenging to devise a universal solution capable of effectively addressing such fabrication tasks. The complexity of these projects makes it difficult to create a transportable, one-size-fits-all solution. Consequently, it is more advantageous to approach such fabrication tasks by developing bespoke fabrication setups that can be easily customised and adapted to future assignments.
Thus, it could be argued that the transportable ‘TIM’ framework could be employed in such a fabrication process since it has proven to fabricate elements for a similar project type, namely the Buga pavilion [Wagner et al. 2020]. However, it should be noted that the system was designed to be integrated into an off-site facility, as explained in section 2.3, and its portability was found limited due to documented deployment time. As a result, the ‘TIM’ framework is perceived similarly to off-site construction facilities, where the reconfiguration of robotic work environments is necessary between different fabrication tasks. This reconfiguration process entails redevelopment time and specialised knowledge, which incurs additional costs that are included in the overall fabrication expenses of such projects. While this holds true for unique projects, in cases where a fabrication task can be repeated, the number of projects executed can offset the development or reconfiguration costs. Consequently, the utilisation of such a system becomes more cost-effective. This parallels the manufacturing process of cars, where a reduction in the cost of both cars and robotics was achieved through mass production and repetition.

It is important to emphasise that this does not imply a need for the field of architecture to transition towards a manufacturing pipeline akin to the car industry, where every car or house is a duplicate of one another. Nor does it imply a complete shift towards modular construction. On the contrary, the focus should be on directing the use of robotic technologies towards fabricating adaptable ’systems’ capable of managing the inherent variability found in construction projects, or at least a significant portion of them. The objective is to leverage robotics to accommodate the unique requirements and complexities of architectural construction while achieving a higher degree of efficiency and flexibility. The term ’system’ is used in reference to construction processes, such as timber framing, which have been used to fabricate infinitely varied houses through an on-site carpentry process. This research believes that for a transportable robotic unit to gain relevance within a construction process, it should be able to assist such construction tasks, hence why the development of the FotF has been aimed at fabricating the developed construction system from the paper; ’*Timber Framing 2.0*’ pages 10 - 24 in book II.

Hence, the adoption and relevance of robotic fabrication on construction sites depend more on the 'product' being fabricated than the robotic system itself. Consequently, the level of adoption becomes a question of scale—how many individuals or entities would prefer to utilise the FotF system for manufacturing elements for timber houses compared to constructing unique, morphologically complex structures? It is worth noting that throughout the research, there has been a recognition of the latent potential to manufacture timber structures for over 5000 homes per year using Danish timber resources [Danish Wood]. Effectively this would equate to roughly 20-30 percent of built homes, which is 12-18 percent of the total floor area built in Denmark per year [Danish statistics]. This represents a significantly higher use rate than systems aimed at formally complex architectures, representing a seemingly minor percentage of built projects today. Arguably this fabrication action could be carried out in an off-site facility, thus continuing the current status quo. However, if the developed construction system continues to be adopted by developers [Carpen], they could see a financial incentive to acquire a system of their own. Here they could benefit from the system being designed to fit into a compact and transportable work environment, saving them the investment of dedicating an interior manufacturing area to facilitate the system.

Therefore, through the above arguments, the research believes that there is a potential to embed robotics on the construction site. When it will happen is a relative question, but one thing is for sure: for these systems to become relevant to onsite construction practices they need to fabricate construction elements at scale and not simply solve a unique project.

5.2 Instruction Method, Software or Robotics?

Through the past 15 years, robotic fabrication has primarily been used as an enabler for fabricating complex forms, whereas recent research has begun to explore robotic fabrication as enabling creativity [Jensen et al. 2020]. Jensen et al., present research into design and fabrication systems based on systems developed in the package McNeel Rhinoceros3d (rhino) [rhino] and Grasshopper3d (gh) [GH]. Here the design process is referred to as 'indeterministic', whereas robotic fabrication is deterministic [Jensen et al. 2020]. Interestingly, this research describes how robotics can be part of a conventional design process, progressing from exploring an indeterminate design space through a project to a deterministic file-to-factory robotic fabrication process (fig 5.1, A). Architects can employ this process without knowledge about robotic fabrication since they can ask for robotic assistance.

Alternatively, if an architect has knowledge about robotic systems and can instruct them with information, they can follow an iterative design process informed by robotic fabrication (fig 5.1, B). Here the indeterminacy of the design process can be broken by sequences of deterministic robotic fabrication, which subsequently can inform the design process and so forth [Jensen 2021].

Within the file-to-factory approach, the creative work is carried out through the design process, where the fabrication process simply follows a given instruction. Within the design process informed by robotic fabrication, the flexibility and success rely on the designer's ability to build or adapt a given design and fabrication system [Jensen 2021], such as a rhino and gh workflow, where plugins enable robotic instruction [Hal, KukaPRC, Taco]. Thus, to unlock the full creative potential of a robotically informed design process, a level of specialist knowledge is required from the designer because otherwise, they will be limited to the constraints of a developed design-to-fabrication system.

Overlaying this terminology on the work of research trajectory II positions the instruction method within a robotically informed design process. As section 4.3 demonstrated, this is due to architectural students and others being able to develop their designs seamlessly, moving between designing and fabricating cyclically. However, as the research documented, not the design system was adapted but the instruction method. This is because the design system employed by participants was a closed software that could not freely be modified. This makes the creative jump different from the research presented by Jensen 2021, which described how fabrication and design systems could develop together, but the instruction method remains the same.

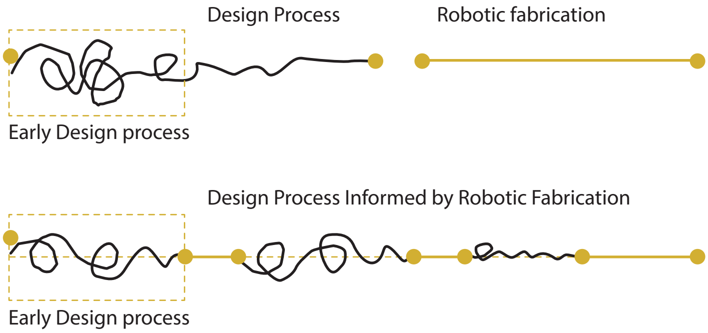


Fig 5.1
Reproduction of diagram from publication [Jensen et al. 2021].

This difference is important because the documented shift from instructing fabrication information through drawings to blocking out red paper gave participants new design opportunities. This is exemplified by how participants began approaching the system with tracings on top of landscape printouts to make terraced landscapes or using a printout of a red graphic to interpret sound waves (fig 5.2).

Not only did this alternative use illustrate the flexibility and robustness of the developed method, but it showed how the system opened for a creative process while using robotics, where little to no robotic and computational knowledge is required. This places the developed instruction method in uncharted territory as it shifts the concept of a design process influenced by robotic fabrication to an exploratory robotic fabrication process facilitated by a flexible instruction method.

This shift in how robotic technologies are instructed revolves around a programmatic shift from a digital to a physical condition being the start of robotic programming. This shift is of great importance as it moves robotic use towards a potential future where communication processes with digital media or machines begin to disappear. Licklider has described such a future in his article ‘Man-Computer Symbiosis’ [Licklider 1960]. Here he outlined how interactions or instruction of computer systems is of the utmost importance when discussing user adoption. He highlights how using computers should be as simple as talking to it or following a technical discussion:

> *’...Nowhere, to my knowledge, however, is there anything approaching the flexibility and convenience of the pencil and doodle pad or the chalk and blackboard used by men in technical discussion.’ [Licklider 1960]*

Licklider emphasised the notion of ’use’ because computers were challenging to use when writing his paper, since neither interfaces nor instruction methods had matured. Thus he focused on how technology could be useful for seemingly computer non-specialists, such as an elderly CEO. However, since the use of various types of technology has become commonplace, this research finds that as technology becomes more intuitive, it will become more usable and new types of creative use will emerge.

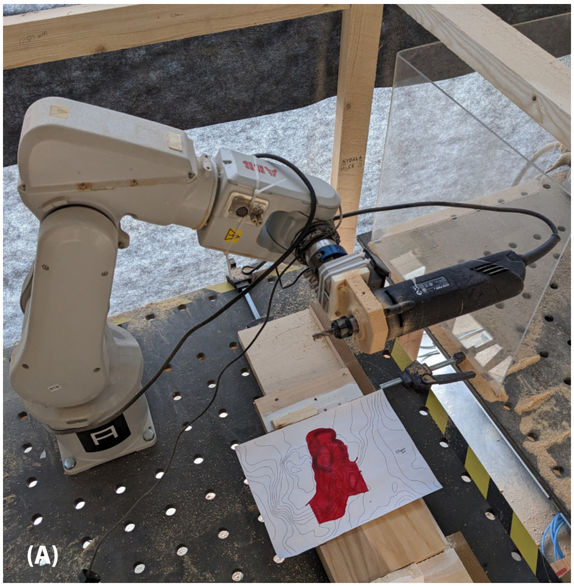


Fig 5.2
Images showcasing different methods whereby the instruction method has been modified. A) the operator has positioned a piece of white paper with a red drawing, on top of the workpiece. Before the robot begins to machine the workpiece the operator is prompted to remove the paper. B) Instead of a drawing on paper, the operator used a printout from a graphical software to position on top of a workpiece to instruct robotic action.

5.3 Resilient Robotics

The project has progressed through two separate trajectories, where research trajectory I has led to a proposal for a new FotF solution that has been designed to efficiently fabricate a construction system to make the structure for 1-2 story timber houses. Research trajectory II has developed a new instruction method to augment the existing FotF software framework [Neythalath 2021]. Whereby robotic non-specialists have been found able to instruct robotic fabrication actions through physical drawings or other creative alternatives (section 4.3). On the surface, these two trajectories seem to pull in opposite directions - efficient production vs creative exploration. Still, they do have the potential to complement one another to form a resilient robotic framework that can mitigate fabrication tasks across scales.

Currently, the world is facing both a housing crisis and a climate crisis. If simply focussing on the housing crisis, the AEC industry should construct upwards of 100.000 housing units per day to meet demands [World Economic Forum 2022]. To best do this without worsening the current climate crisis through increasing CO2 emissions through new builds, it would be wise to promote building reuse through retrofits that can be a more climate-neutral alternative to new builds [Wilson & Newburg 2015, Penn State]. However, this establishes a challenging spectrum, where one end requires efficient fabrication facilities to construct new homes quickly, and the other emphasises adaptability and flexibility in response to an unknown building mass.

This spectrum creates an ideal opportunity to implement the new FotF system. When viewed solely from the perspective of addressing the housing crisis, the system can fabricate the developed construction system efficiently, resulting in the rapid construction of timber structures for housing purposes. The feasibility of this approach stems from the fact that the foundations for houses today are well-documented and fall within a narrow tolerance range. This enables rapid physical measurements that can inform the fabrication process for new structures. While the complete efficiencies of the new system still need to be fully comprehended, they will be continuously documented during its first commercial application. In the upcoming summer of 2023, more than 60 houses will be semi-autonomously fabricated, providing valuable insights into the system's capabilities and potential advantages.

However, it is conceivable that the system was to mitigate both the housing and climate crisis. In that case, the challenge is slightly different because something digitally made is required to meet an unknown building condition. Therefore, the instruction method could be used to instruct fabrication information for custom elements to establish a known interface point, wherein timber elements from the system could be positioned. Thus, the system would establish a 'new build' situation within an old building that can rely on the fabrication and assembly efficiencies from the FotF system that produces elements from the construction system.

This approach to fabrication indicates that the efficient use of the FotF system will harbour the greatest use. However, the complementary use of the intuitive instruction method will make the framework resilient since it mitigates new and retrofit situations.

Chapter 5 Summary

Through this discussion, it has been possible to reflect upon the scope of the research, which has led to arguments for how to unlock the potential of digital fabrication technologies within the AEC industry. Namely, robotic use needs to shift from solely being used to handle morphologically complex forms and move towards challenging how we construct by developing simple augmentations of conventional construction practices. Such elements will arguably be quick to fabricate, and the small changes in the construction approach will be simpler to accept by an otherwise conservative construction sector.

Furthermore, the research found that developing an intuitive instruction method, which builds on a robust software framework, can be modified by presenting instruction information differently than expected. This finding was interesting because it was achieved through a user group of robotic non-specialists.

Lastly, despite the two research trajectories appearing to oppose one another, they have the potential to complement one another to form a resilient robotic fabrication framework. This framework could aid in mitigating the current climate and housing crisis by simplifying the retrofitting of old buildings.

Chapter 6
Conclusion

6.0 Conclusion

The research thesis has developed two separate research trajectories; where research trajectory I identified what elements a transportable robotic unit should fabricate while proposing how it could efficiently manufacture such components. The second trajectory determined how a robotic system could be intuitively instructed through an understanding of conventional processes of communicating construction information by the indented user group - carpenters. This led to the formation of a cyber-physical robotic system that can efficiently manufacture elements for timber houses while allowing to mitigate ad-hoc assignments that occur on construction sites.

The transportable robotic system was developed based on the knowledge extracted from several built demonstrators. Through this process, the project developed a new timber framing method, where the initial findings indicate that the construction method can reduce time spent on the construction site through an increased construction pace. In conjunction with this development, the project has presented a computational method to manage and evaluate the material use of linear timber elements, which highlighted that material yield of a given stock could be above 90 percent. The combination of these subjects - computational material management and the construction system - will be subjects for future research.

The instruction method followed a similar approach but was primarily developed through digital demonstrators that were tested through their ability to fabricate elements for physically built demonstrators. Developing this method has allowed us to invert current approaches to robotic fabrication, from deriving fabrication information from a digital model to information derived from physical on-object drawings. The method grew from a technical and historical analysis that highlighted if physical drawings could instruct robotic actions, it would minimise the technical barrier of using such technology.

The instruction method underwent testing in two user studies, demonstrating that individuals without specialised knowledge in robotics could effectively instruct fabrication actions to a robotic system using physical drawings. Furthermore, the studies revealed an even more intriguing outcome: as participants understood how the system could visually interpret the drawings, they began to devise new alternative methods for instructing robotic fabrication actions. This discovery suggests that the instruction method not only empowers users to be creative but also warrants further research into the system's capabilities and its potential to unlock robots as thinking tools for exploring design possibilities rather than mere production machines.

6.1 Future work

Throughout the thesis, subjects of future research have been identified which were outside the thesis due to the limited scope of the PhD and time available to conduct the research. Additionally, the Covid-19 pandemic pushed activities and made it challenging to conduct experiments promptly. Thus, the research presents multiple future research pathways in either trajectory.

Timber Fabrication,

The findings from the built demonstrators yielded predominantly positive results, particularly concerning the construction system developed for the Olaf Ryes Gade project. The project was observed to be relatively straightforward to assemble and exhibited fast fabrication times. However, further research is needed to determine the extent of these improvements compared to conventional carpentry processes. Similarly, in the investigation of material management through a computational fabrication pipeline, it is necessary to compare the findings to those of conventional carpentry processes to assess the potential benefits. The combination of these two research subjects presents a latent potential to be continuously explored using the developed FotF system.

Testing systems with craftspeople

In order to achieve this, a collaborative project is essential, with potential collaborators including carpentry schools. The primary objective of this project would be to educate future carpenters about the applications and possibilities of robotic fabrication. This would be accomplished through a construction process involving the creation of four demonstrators. The first three demonstrators would be identical, while the fourth would be unique and follow the approach established by the third demonstrator.

1. Carpentry demonstrator, this would be made conventionally, where physical drawings are given, and through a conventional carpentry process, the students would build the project. To carry out the construction task, they would use conventional carpentry tools. As part of this process, the time associated with cutting, positional marking, and assembly would be documented to be compared in subsequent studies.
2. Mixed carpentry and robotic demonstrator, the carpentry students are given the same set of drawings, but all pieces have been robotically precut with no markings or notches. Therefore, this study establishes a baseline for cutting time compared to the conventional carpentry process while gaining additional data points regarding the time spent marking positional information and assembling the structure. The assembly is carried out using carpentry tools.
3. Construction system demonstrator, here, carpentry students are given a different set of drawings that only convey labelling and diagrammatic assembly information. Alongside these drawings, participants will get all elements to assemble the structure, which has been robotically fabricated and labelled. This gives data regarding the assembly time of the construction system compared to conventional carpentry processes while giving fabrication data related to fabricating a fully detailed system compared to simply cutting elements to size. The assembly is carried out using carpentry tools.
4. Complex construction demonstrator, this demonstrator would be geometrically different to the built design of demonstrators 1 - 3, with the same element count. The demonstrator would be fabricated with the same details as the construction system used in demonstrator 3 and assembled

> following the same instructions. Thus, this demonstrator aims to map assembly and fabrication times concerning an increased complexity.

In addition to the highlighted fabrication and assembly data, the system would track material use and compare it to how carpenters estimated and procured material for the 1 st demonstrator.

Cyclical Design Optimisation

Continuing the previously described project, the research could further combine the construction system with the material management technique, where data from the material evaluation technique can inform a cyclical optimisation process. Future research could modify a given timber structure marginally to move closer to a 100 % material yield, or the structure would be modified to meet a specific amount of stock. This process would alleviate the handling of off-cuts and give an accurate bill-of-material. Through this process, it would be possible to explore the design space of material optimisation, which in the first instance, focuses on linear timber elements. Afterwards, it will move towards a similar process for sheets or other material types.

The robotic instruction method

Regarding future research directions, it is important to acknowledge several pathways that can further enhance the instruction method. Chapter 4 discussed the advancement of an instruction method enabling intuitive robotic action instructions through physical drawings supplemented by a corresponding user interface. This area of research has proven to be highly engaging and effective. Yet, due to project scope limitations and challenges posed by the Covid-19 pandemic, certain elements remain untested, while others require further testing. Consequently, further research into this method necessitates implementing multiple new user studies, allowing for the exploration and testing of previously untested elements of the process.

Robot language testing?

All the technical elements presented through the research were adopted successfully, but the full scope of the robotic language described in the paper, '*Robotic Drawing Communication Protocol: A Framework for Building a Semantic Drawn Language for Robotic Fabrication*', still needs to be tested due to the pandemic. Therefore, future research would revolve around testing the technical framework through user studies where participants would develop a drawn language and subsequent semantic protocol and decision tree for robotic action as described in the paper.

Creativity with robots through intuitive instruction

Through the two-week user study, the participants highlighted a new and creative way of using the developed method, which was beyond what had been initially expected. This revealed a trajectory of interest to pursue, namely, does this type of instruction method enable the use of robotic fabrication systems as a creative thinking tool instead of a productive machine? This study would centre around a continuous user study where creatives (students or practitioners) use the system extensively for a given design task to see if it enabled or disabled a creative process. Furthermore, it would be interesting to compare the user study to other professions such as carpenters or other crafts professions - to understand if craft workers would make the same leaps as the creatives might do? Performing this study would require establishing several user studies.

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