Impact of Robotic Fabrication on the Creative Problem-Solving abilities in Design Education

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The growing influence of digital manufacturing technologies is transforming design educational — requires new teaching strategies and at the same time offers opportunities for innovation, interdisciplinary exchange, and practice-oriented problem solving. The integration of robotic manufacturing into design education promotes critical thinking, enhances problem-solving skills and increases interdisciplinary interactions. Based on a systematic literature review, this paper examines the current teaching methods in dealing with robot applications in education and identifies the main challenges. It is shown that the existing approaches are often linked to student teaching, are based on subjective assessment and rarely use scientific evaluation methods. The lack of low-threshold access was also identified as a deficit. In response to this, this paper proposes a pedagogical framework that provides an early, creative and accessible introduction to robotic manufacturing. By combining structured learning formats with scientific evaluation tools, the framework aims to strengthen innovation in design education in the context of digital transformation. The first test phase is currently underway and aims to analysing key parameters of the learning environment to build a foundation for deeper insights into the factors that influence the learning process. As part of future research, particular attention will be given to fostering intrinsic motivation and ensuring effective knowledge transfer. To this end, key factors that support learners sustained and meaningful engagement with robotic manufacturing will be identified and investigated.

Keywords: robotic fabrication, design education, problem-solving competence, critical thinking, Educational Framework,

INTRODUCTION

The rise of digital technologies has given us a new way of thinking about design that seamlessly integrates construction processes, manufacturing methods and material properties into the language of form and geometry. (Stojaković and Tepavčević 2023). To keep up with this rapid development of technological innovations, the integration of technological change in teaching is essential.

This research paper analyses the influence of robotic fabrication on the creative problem-solving skills of people of all ages, children, students and adults, with various educational or professional background. The aim of this research is to investigate how the integration of robotic manufacturing into education can promote intrinsic motivation and curiosity towards new technologies, with the wider aim of reinvigorating the currently stagnant innovation process in the construction industry through the development of creative problem-solving skills.

Increasingly complex construction processes and global challenges such as resource scarcity and climate change make it necessary to rethink the teaching of robotic manufacturing. It is important not only to teach technical skills, it must also be understood as an integrative teaching format that promotes creativity, sustainability and interdisciplinary collaboration. The use of robotic technologies in an educational context creates the basis for enabling future and existing specialists to develop holistic, resource-saving and innovative construction methods. Robotic manufacturing is thus becoming a key component of a transformative, future-oriented building culture. (Jenny et al. 2022)

Another key component is strengthening the links between science and society to promote innovation and acceleration transfer. The scientific and academic community can act as an active motor of change and drive sustainable transformation processes at the interface between research and society. (Kastner and Langenberg 2023)

There is also a deficit in the existing range of courses on robotic fabrication. A study demonstrates that relevant courses are predominantly held at Postgraduate level, as they usually require in-depth prior knowledge and special safety precautions. However, this restricts early access to this pioneering technology and inhibits the potential to promote intrinsic motivation and creative problem-solving skills at an early stage.(Öztürk Kösenciğ, Güneş and Özbayraktar, 2024)

This literature review that forms the basis of the presented research looks at the teaching of robotic fabrication in the realm of construction education and examines the current state of the respective research which is concerned with the integration of robotic technologies into teaching. Different methodological approaches are used to uncover how robotic manufacturing technologies can stimulate and strengthen engagement, intrinsic motivation and problem-solving skills.

The purpose of the literature review and the establishment of the state of the art of educational methods in regards to robotic teaching it to develop a teaching framework that not only considers the academic perspective but is also transferable to the non-academic sector. We aspire help to design innovative and evidenced based teaching methods to inform workshops which are offered as part of a vocational educational program and provide the public with access to future technologies in the field of robotic fabrication.

METHOD

In this paper, a systematic literature review was conducted to investigate the impact of robotic fabrication in education on the advancement of critical thinking and to demonstrate the relevance of robotic technology education in relation to construction. The research followed the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page et al. 2021). The PRISMA method involves three key steps:

1. Search: Identifying all potentially relevant studies through a comprehensive search in academic databases using defined keywords.
2. Screening: Reviewing titles and abstracts to exclude irrelevant studies or those that do not meet the inclusion criteria.
3. Included Papers: Selecting studies that meet the criteria for full analysis and inclusion in the final review based on relevance to the research question.

Search procedure

A comprehensive literature review is conducted to identify and systematically analyse relevant scientific papers. The goal is to structure the search efficiently and filter relevant publications precisely.

The following scientific databases are used for data collection:

- Scopus (Elsevier)
- Google Scholar

Both platforms are well-known for their comprehensive coverage of interdisciplinary research fields and provide a wide range of relevant studies and publications.

Table 1 Number of publications from the search

Database	Results
Google Scholar	560
Scopus	15

A list of targeted keywords is created to ensure the search is methodical and reproducible. Four key terms are defined for the literature search: "robotic fabrication", "educational", "design education'", and "teaching". These terms are combined in specific search queries to cover different thematic areas.

The four central keywords are taken from the research question and are intended to place a clear focus on robotic fabrication in education and limit the sector to design education.

The research is limited to the period from 2022 to 2025 in order to focus specifically on current developments in the field of digitalization and robotic manufacturing in the construction industry. This temporal limitation allows to map the most recent dynamic progress of the technology and to precisely identify existing research gaps with regard to its integration into educational processes.

The search queries that were applied across both databases were constructed by combining the key terms in specific ways to capture all relevant publications and ensure comprehensive coverage of the research topic.

The keywords are used in the search as follows: "Robotic fabrication" AND 'educational' OR 'design education' OR 'teaching'. The topic of robotic fabrication is specifically combined with terms from the field of education in order to only consider sources that are related to knowledge transfer and teaching.

The retrieved publications are systematically analysed to ensure they align with the study's research objectives and provided valuable insights into the integration of robotic fabrication in construction education.

The result of the keyword search is presented in Table 1, which lists the number of publications found according to the relevant keyword combinations

Screening: Identification of relevant papers

The analysis of the literature research demonstrates the significant scientific relevance of robot-assisted manufacturing. However, research within the educational sector, particularly in the context of the construction industry, remains limited. For the purposes of this study, only those studies directly related to the construction sector were selected, while studies focused on other areas of the manufacturing industry were excluded.

The initial search with the defined keywords resulted in a total of 575 hits in the selected databases. After removing duplicates, 559 publications remained to be included in the screening process. As part of the title screening, all articles that focused exclusively on material technology aspects, form finding, software development or related technologies such as AI, VR or AR were excluded - provided there was no recognizable reference to an educational concept. As a result, 510 contributions were classified as not relevant. The remaining 49 publications were analysed in full text and included in the further evaluation.

After analysing the 49 publications reviewed in full text, 33 papers were excluded from the systematic literature search. These articles did not fulfil the central inclusion criterion, namely the focus on a pedagogical approach in connection with a new or existing teaching method in the context of robotic manufacturing. Instead, these articles focused predominantly on purely application-related topics, historical developments or the analysis of technical processes without an educational perspective. As such, they did not contribute to answering the research question in terms of a pedagogical approach and were not considered in the further analysis. The result of the applied procedure is depicted in Figure 1

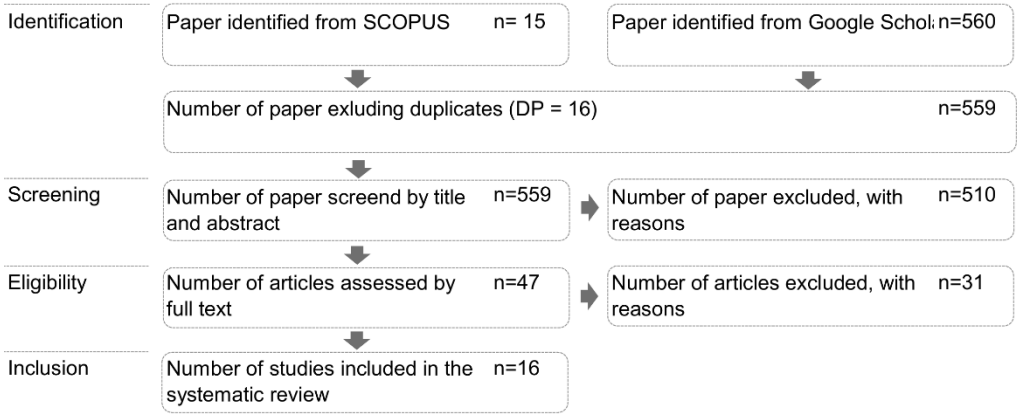

Figure 1 Schema of the PRISMA results

DATA EXTRACTION AND ANALYSIS

The analysis of the systematic literature search was carried out using a criteria-based analysis method. Pre-defined evaluation criteria were used to systematically compare and evaluate the teaching methods used in the studies. The focus lies on the approach, the teaching method and the systematic evaluation. The target group is also recorded.

The literature research shows that the teaching of robotic fabrication methods is becoming increasingly important in the construction industry. Three of the papers included are from 2022, four from 2023, six from 2024 and three from the current year 2025, which deal with the teaching of robotic manufacturing methods.

The evaluation shows that the teaching method learning-by-doing is the most frequently used teaching method with three applications. This is followed by methods where students translate their theoretical knowledge into designs/prototypes, such as project-based learning (PrBL) and studio experiments.

Of the papers analysed, four describe the use of prototyping, a method widely used in architectural teaching to link design concepts to physical outcomes. Seven works focus on predefined tasks that are further developed independently by the participants. In three of these cases, a hot wire cutter was explicitly used, which indicates a recurring, practical application in the context of robotic manufacturing.

Only five studies use scientifically based methods to record and evaluate learning outcomes.

In addition, the results of many of the teaching formats, except for two studies, were conducted with students, which limits their transferability to other target groups.

Table 2 illustrates teaching methods, application areas, methods of evaluation of the learning success as well as the target audience within the relevant papers.

Table 2: Summary of Recent Research on Teaching Methods and Evaluation in Design Education

Paper	Application	Teaching methods	Evaluation	Participants
Jenny et al. 2022	prototypes	learning-by-doing	Analysis of the results	Students
Oktan and Vural 2022	prototypes	Flipped-classroom	Portfolio Evaluation	Students
Mayor Luque, Dubor and Marengo, 2022	Drawing (2D) / Hotwire-Cutter		Analysis of the results	
Hunt 2023	milling / Hotwire-Cutter		Analysis of the results	Students
Hansen 2023	Roboter controlled by hand via distance sensor			Students
Pedersen and Reinhardt 2025	Drawing fabrication (DF)		Incoming/ outgoing questions	mixed Group
(Yazar et al. 2023)	Hotwire-Cutter	studio experiment	Analysis of the results	Students
Stuart-Smith 2023	Application with the material ceramic		Interview / Survey / analysis of the career path	Students
Di Marco and Lombardi 2024	prototypes	Flipped-classroom		
Sophocleous and Georgiou 2024		Project-based learning (PrBL)	Analysis of the results	
Avinç 2024	prototypes	learning-by-doing	Analysis of the results	Students
Olukanni et al. 2024				
Küçük 2025	Experiments with materials			Students
Antunes et al. 2024	Application	learning-by-doing	Analysis of the results	mixed group
Miller and Tan 2024	online course		Survey	mixed group
Abdel Rijal 2025	Application			Students

DISCUSSIONS

The evaluation of the selected papers suggests that initial teaching approaches for integrating robotic applications into design education have the potential to promote critical thinking and a solution-oriented approach. However, only five papers measure the actual difference in these skills with pre-workshop and post-workshop interviews or structured observations. Furthermore, the measure tools together with the answers are not published.

Central to the success of these approaches is the way in which robotic fabrication is embedded in the teaching context. In this regards the materiality used in the educational framework and the fabrication method respectively are instrumental in shift the learning focus either on the material and its behaviour or towards the control and understanding of the robotic processes. It appears that the learning with complex materiality or designs is deviating the learning away from the robotic understanding. The role attributed to the robot in the learning process and the question of whether the innovation potential of future-oriented technologies can be recognized by the students and pedagogically used effectively at an early stage is rather obscure.

Analysis of Papers

The analysis of the selected papers aims to identify key challenges in the teaching of robotic manufacturing technologies in the context of the construction industry. In addition, the existing research gaps are identified and potential starting points for further research are pointed out, which can be derived from the results. Table 3 illustrates the pedagogical method identified as effective on the students' problem solving and robotic skills. It can be deduced from the analysis that using the learning-by-doing method, but also under guidance and with an introduction, is a promising method in the field of future technologies. For example, students learned how robot arms work better by independently designing new processes. Furthermore, their own research makes it possible to include the rapid development of technologies. It is also clear that the learning units must be simple and well-structured so as not to overwhelm the students. The accessibility and visibility of the courses on the new technologies of the future must come to the fore in the studios. Intrinsic motivation can also be increased by aiming for publications in the field of research. There seems to be a correlation between the level of acquired research skills, and the willingness to learn new skills.

Table 3 Educational methods

Paper	Effectiveness
Jenny et al. 2022	Joint development of research topics - research as a form of architectural practice.
Jenny et al. 2022	Constructivist methods create a connection between the real and digital worlds.
Oktan and Vural 2022	Strengthening the interplay of material and design and production as a joint composition that can be implemented with robotic fabrication.
Hunt 2023	Targeted focusing on individual parameters by specifying a created robot path.
Hansen 2023	Low-threshold access
Pedersen and Reinhardt 2025	Combination of a theoretical introduction and a learning-by-doing task.
Yazar et al. 2023	Strengthen intrinsic motivation in research by creating incentives, such as conference papers
Di Marco and Lombardi 2024	Research skills increase the success of project-based learning methods

Table 4**Error! Reference source not found.** highlights the challenges in current teaching methods and reveals existing gaps. It provides a basis for developing a research framework. Systematic evaluation is essential to assess effectiveness. A balanced mix of hands-on experience and instruction supports learning success, while task difficulty must align with participants' skill levels to prevent overload and resistance to the technology.

Table 4 Challenges and gaps

Paper	Challenges and Gaps
Hansen 2023	The continuation to a pre-programmed code, where the course participants can edit individual parameters, is described as the next step.
Pedersen and Reinhardt 2025	Future research could investigate image processing for the detection of unknown materials in circular economy.
Yazar et al. 2023	Working with small modules in the robot code language.
Avinç 2024	Workshop was only conducted once. It is recommended to conduct a longitudinal study to collect further data from workshops and to measure the learning success.
Olukanni et al. 2024	General robotic skills were taught. Continuation is to be carried out in specific applications in certain cases.
Küçük 2025	It is recommended to investigate and optimize studio teaching and impact to effectively include future technologies.
Miller and Tan 2024	To prevent course participants from becoming overwhelmed, it is recommended that only a smooth learning curve is created.

FRAMEWORK

Based on the analysed studies and identified research gaps, a practice-oriented framework for future teaching formats with robotic fabrication can be developed. The aim is to promote technological skills, creative problem solving and critical thinking.

Basic principles

- Low-threshold entry options: Use of pre-programmed robotic paths to reduce barriers of inhibition and provide an initial sense of success.
- Learning-by-doing or design build: Practical application as a central learning tool to promote intrinsic motivation and problem-solving skills
- Flipped classroom approaches: More space for exchange, practice and reflection, through self-directed learning of the basics
- Promotion of interdisciplinarity: design, materials, programming and sustainability come together.

Workshop structure

- Introduction and safety: Basic understanding of robotics, initial interactions.
- Understanding and analysing: Explanation of programming using pre-designed path, joint interpretation and discussions about movement processes

- Creative application: own manipulation of robot paths. Designing prototypes with creative freedom
- Reflection and evaluation: Joint evaluation of the results. Scientifically based evaluation questionnaire to record learning effects, motivation and understanding.

CONCLUSION AND OUTLOOK

Conclusion

Robotic manufacturing promotes interdisciplinary collaboration and strengthens communication skills, as it requires the integration of various design and production parameters from the outset. Aspects such as manufacturing methodology, material behaviour and the reversibility of components - especially in the context of sustainability - must be considered holistically right from the initial design idea. This integrated approach requires close cooperation between disciplines such as programming, design, engineering and materials science. The necessary coordination between these areas promotes joint problem solving and a common language. This makes interdisciplinary dialog an essential part of the learning and innovation process.

To emphasize the potential and possibilities of robotic manufacturing in education, it is essential to introduce the technology early in the design process so that it can be understood as a creative extension of the design toolkit and does not lead to overwhelming later in the process. The research shows that robotic technology is predominantly integrated at advanced educational levels. This delayed implementation is mainly due to the complexity of the technologies involved and the lack of accessible, low-threshold entry points. Therefore, there is a significant gap in pedagogical research to develop didactic concepts that simplify access and enable intuitive, hands-on use of robotic tools from the very beginning.

In summary, the following research gaps have been identified:

- Lack of empirical evaluation and unclear long-term effect
- Limited accessibility to robotic technology
- Lack of structured teaching models that enable early integration of robot-assisted manufacturing into design training and low-threshold access

Outlook

The research gaps identified in this thesis form the basis for the development of a new learning concept that integrates robotic manufacturing into design education in a low-threshold and pedagogically effective way. The first approach will be a pre-programmed robot path that is explored and creatively manipulated together. This will allow participants without extensive prior knowledge of programming to immerse themselves in the logic and application of the technology at an early stage.

The first application of this series of experiments will take place as part of a workshop using light painting. This method offers a clear and safe introduction to the three-dimensional movement of the robot. Key aspects such as programming, spatial imagination and aesthetic experience are addressed while potentially deviating aspects like materiality are omitted. The combination of intuitive access and creative freedom promotes both technical understanding and creative exploration of technology.

The workshop is accompanied by a scientifically structured evaluation that serves to analyse the pedagogical framework. The aim is to investigate the impact of the method used. The results will inform the further development of the concept and, in the long term, contribute to the development of sustainable and inclusive teaching formats for robotic fabrication in teaching.

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