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# Challenges and potential for human–robot collaboration in timber prefabrication

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ABSTRACT

Recent advancements in robotics and human–machine interfaces enable new collaborative procedures that combine the strengths of machines and humans. Compared to existing automation technologies in the timber prefabrication industry, human–robot collaboration (HRC) offers new possibilities for increased flexibility and productivity. This paper aims to map out the challenges and opportunities for HRC within the context of timber prefabrication by constructing a conceptual framework. The framework is based on three pillars: (1) existing HRC theories and frameworks, (2) a literature review of HRC research in robotic timber fabrication, and (3) perspectives of human labour in the timber construction industry. The relevant topics among these three areas are triangulated to construct a conceptual framework that bridges the system-, design-, and human-centred considerations. The framework serves as an organising device to support future explorations and research on human–robot collaboration in robotic timber construction.

## 1. Introduction

Off-site prefabrication is known for many productivity and safety benefits over conventional construction [1,2]. Compared to steel and concrete, timber is a lightweight, sustainable material that offers further potential to reduce the carbon footprint of the construction industry. Despite a mature factory equipment market for high-level-of-automation timber prefabrication, many challenges exist around fully autonomous work processes with timber.

First and foremost, automated prefabrication entails a trade-off between process efficiency and design flexibility. Architects now heed the monotony of post-war prefabricated housing and work towards higher diversity and spatial quality in contemporary prefabricated buildings. Preservation of design freedom and project-based construction cultures are important to ensure context-specific buildings that can meet the demands for flexible floor planning and achieve a long lifespan (up to 150 years) [3]. The high production variety in these cases brings higher variability in tasks and part geometries, which poses a challenge for standard automation.

Second, embedding autonomous systems in human workplaces poses social and economic challenges. Economically, conventional automation requires high upfront costs and rigid changes to the production environment, which may hinder their adoption in the timber construction market where small and medium enterprises dominate. Socially, issues of ghost labour [4] or ironies of automation [5] are known to arise unless human participation is carefully considered in the design of semi-automated systems. A human-centred approach to address these issues is of high strategic importance for Industry 5.0 [6] and a more holistic consideration of social, economic, and environmental sustainability in production processes (SDG 8/9/12) [7].

Last but not least, although engineered timber is increasingly widespread, low-cost and less-processed forms of timber are still prevalent in construction today. Their inherent variability, e.g., knots in the grain and deformation when exposed to the environment, introduces inconsistencies that could lead to tolerance and quality issues.

All three challenges above make human-machine collaboration a highly relevant strategy to leverage the flexibility, dexterity, and expertise of human workers in conjunction with the efficiency of automated machines. In the human–robot interaction (HRI) community, the concepts of collaboration and cooperation are differentiated based on the temporal and spatial proximity of humans and robots. For this paper, the authors define human–robot collaboration (HRC) as the combination of human and robotic labour in shared space towards a common fabrication goal.

This research sets out to identify the gaps in current research on HRC in the timber construction context and develop a framework to

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guide future work in this area. The central aim is to uncover: **what is the design space for human–robot collaboration in timber prefabrication, and how is this design space embedded in its unique application environment?** To answer this question, two challenges need to be addressed.

In early research on construction automation, Everett noted that the key difference between automation and robotisation is that the former considers the synthesis of "machine and (hu)man" and the latter focuses on the technical procedures [8]. Human factors in automation is an extensive topic in aeronautical and manufacturing industries, for which many frameworks have been proposed to guide the design of human-machine systems [9–13]. Integrating these frameworks in the timber prefabrication context requires understanding how they relate to the unique processes and humans involved.

Meanwhile, many recent studies in the AEC community have explored novel permutations of human-machine teams in robotic construction. These cover a wide range of material systems such as masonry, steel, and plastering [14–16] as well as interaction modalities such as augmented reality, haptics, and brain waves [17–19]. However, there is no systematisation to ascertain the applicability of a specific approach to timber prefabrication at large or facilitate comparisons between the different approaches in this particular context. Therefore, the first challenge is a lack of method to organise and contextualise existing contributions from different domains such that future work can build upon and draw from them.

There is also a methodological challenge related to how different types of contributions (theoretical and experimental) and different perspectives (technical and human-oriented) can be integrated within an overarching framework. Existing methodologies for mapping HRC opportunities do not fully address this need for integration. Structured literature reviews provide a holistic view by summarising the key topics and research gaps based on a large collection of existing work [20,21]. This is, however, limited in capturing the multiple viewpoints inherent to each domain (e.g., robotics, human factors, architecture and design) and revealing the complexity and interrelations of various factors. A multiple case study approach generalises from a series of experiments and provides new tools and inspirations to aid future explorations [18]. Case studies unravel the connections between application setting factors and the HRC setup, but the findings are inherently limited to a subset of the HRC design space.

To address these challenges, this research adopts an integrative approach to construct a conceptual framework for HRC in timber prefabrication. This approach is based on the principle of triangulation in qualitative research [22] and the broader co-design methodology for interdisciplinary design and engineering [23]. Informed by existing theories of human-automation collaboration, a hybrid research procedure is designed to collect, analyse, and triangulate data, as shown in Fig. 1. In this process, the timber prefabrication environment is considered on the one hand through the design perspective, driven by the tight integration between design and construction for prefabricated buildings, and on the other through the human perspective, driven by the need to understand practical conditions of human labour in timber construction. The guiding research questions (RQ) are:

- RQ1: What are the HRC parameters adopted in existing robotic timber construction, and what are the unexplored areas?
- RQ2: What are the design parameters in robotic timber construction systems that impact fabrication, and in turn are connected to these HRC parameters?
- RQ3: How can the current conditions of human work in timber prefabrication environments be integrated to inform the choice of these HRC parameters?
- RQ4: How can the interrelations of these parameters be exploited to facilitate co-design and interdisciplinary enquiries?

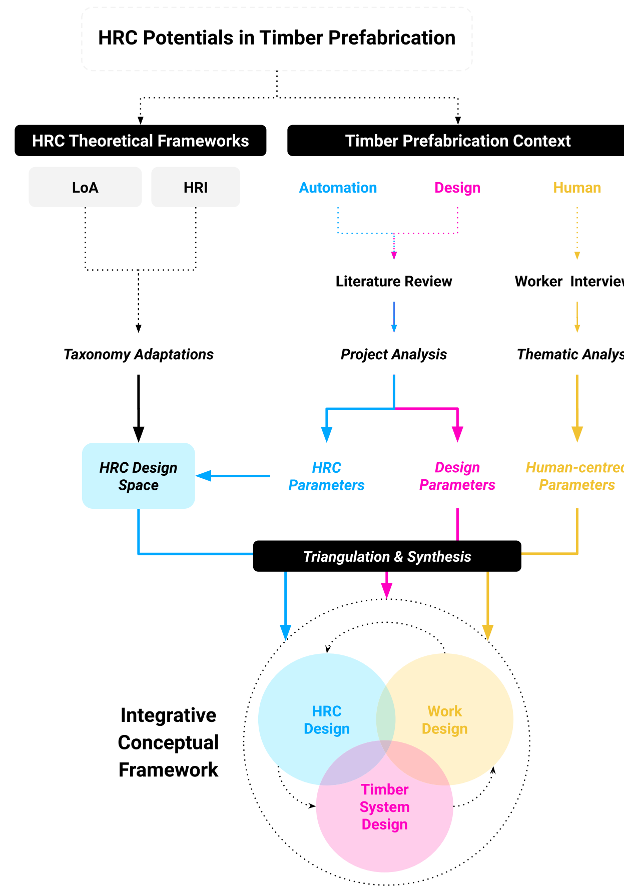


**Fig. 1.** Research design.

## 2. Research context

Two key considerations underlying the framework are (1) the application context of timber prefabrication and (2) the theoretical context of human-machine collaboration. These foundations are presented below to provide an overview of the research context and highlight related work in these areas.

### 2.1. Timber prefabrication and construction

Timber prefabrication can be considered in terms of automation, design, and human factors.

#### 2.1.1. Automation: Current state and challenges

Industrial automation for timber prefabrication has a mature ecosystem of solution providers offering equipment at various integration levels, from a single task such as joinery making to an entire assembly line [24]. Available machinery covers most production steps, such as formatting elements [25], automated stud framing [26], multi-function bridges to attach and cut openings in sheathing and panels [27], and automated material handling [28] etc.

In contrast to semi-enclosed, automated processing machines, industrial robots offer a more flexible approach to automating work steps. Robots can execute complex manipulation, assembly and milling operations through different tools and also pose less rigid spatial constraints compared with stationary assembly lines. This type of automation equipment has been implemented in several companies (e.g., Gropyus, IntelligentCity) and custom building systems developed in academic research projects [29–31]. In the context of this research, the mapping of HRC design space focuses on the use of these more flexible robotic methods.

Although both industrial robots and automated production lines have been used in large prefabrication enterprises for decades (e.g., BoKlok), the majority of work steps are still done manually in small and medium-sized enterprises[1] (SME) [32]. In 2020, the German construction sector saw SMEs contributing 76% of the total turnover and 88% of total employment [33]. The cash flow requirements to invest in automated assembly lines may not be tenable for smaller enterprises that already have to deal with low margins and high upfront costs common to construction projects. These challenges surrounding automation adoption have been a topic of much research [34–36]. For instance, Orlowski proposed an assessment methodology to evaluate the benefits of adopting automation in timber panel prefabrication, noting that the investment break-even period requires longer-term cost evaluations [34].

### 2.1.2. Design: System and prefabrication typologies

Light-frame wood and mass timber are two primary building systems for wood construction. Light-frame construction, such as platform or balloon framing, is popular in low-rise, single- or multi-family homes. They are more cost-competitive than mass timber for these typologies [37] but also limited in multi-storey construction unless they are hybridised with concrete or mass timber. Mass timber systems use engineered wood such as cross-laminated timber (CLT), which has better structural performance and fire protection and thus enables multi-storey buildings more suitable for inner city developments. Svatoš-Ražnjevi et al. classified 350 multi-storey timber buildings and noted the following structural systems: 1D frame structures (52%), 2D bearing walls (32%), 3D volumetric modules (7%), and a combination or hybrid of the above (13%) [38]. Custom building systems for long-span spatial structures such as segmented shells [29] and roofs [30] constitute a unique category, which draws from integrative research in computational design and manufacturing and continues to push the boundaries of novel timber architecture.

Due to its lightweight and workability, timber is especially suited for prefabrication among which two dominant methods are element prefabrication and volume prefabrication. Element prefabrication constitutes the majority of prefabricated timber elements and consists of a combination of 1D (columns, girders) and 2D (walls, floors, roofs) assemblies. These elements are then shipped to the construction site in a kit of parts. Volume prefabrication poses more limitations around spatial configurations but drastically improves on-site efficiency. It also requires higher supply chain integration as complete modules with furnishing and building services are installed by the same contractor [39]. From a prefabrication perspective, the design space of components built off-site can be broadly categorised as either 1D, 2D, or 3D, sometimes with integration of multiple trades such as Mechanical, Electrical and Plumbing services.

### 2.1.3. Human: Skilled craft in timber construction

In timber construction, the main craft trade is carpentry, which in Germany is further split into the main construction trade (Zimmerer, translated as Carpenter) and finishing trade (Tischler, translated as Joiner) [40]. Results of the 2019 census show that 94.2% of craft workers are employed in companies with less than 19 active employees (Fig. 2a). Small carpentry enterprises have a highly competitive share in cumulative enterprise turnover in the main construction trade. However, large enterprises are more dominant in the finishing trade (Fig. 2b). The economic significance of these smaller firms calls for more flexible and cost-competitive automation solutions that address their specific needs.

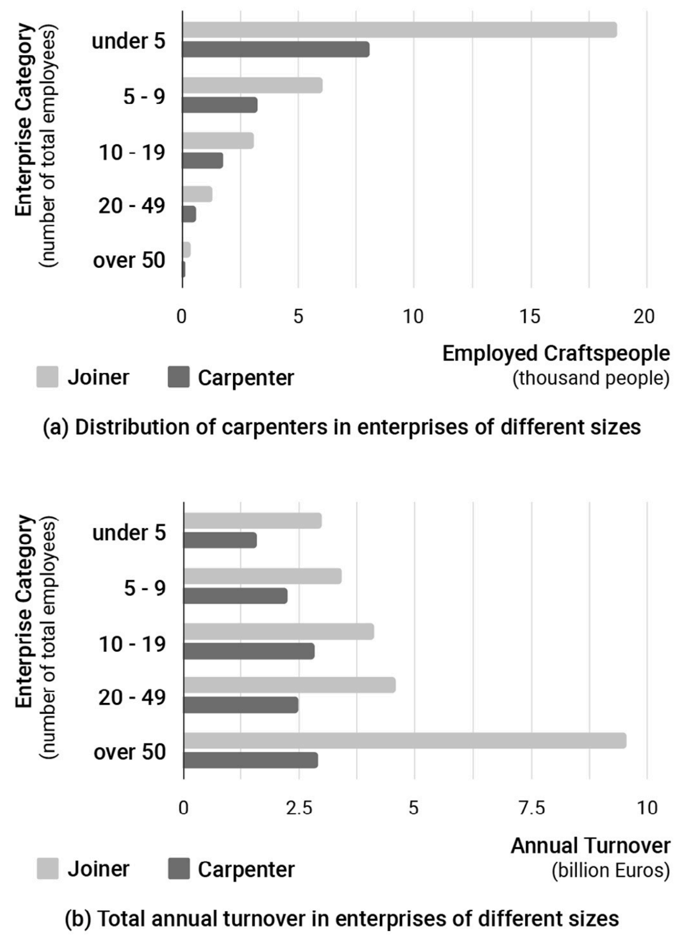


**Fig. 2.** German timber craft worker employment and enterprise turnover in 2019 (data extracted from [40]). Joiner is translated from "Tischler(in)" and carpenters from "Zimmerer(in)" in the original documents.

The worker composition in these timber construction firms is diverse due to the vocational training system. Becoming a carpenter in Germany is based on a dual training system over three years, culminating in a journeyman's examination. The second and third years require trainees to split their time between a construction company for several days a week and the vocational school [41]. Additional training for CAD/CNC systems, wood processing, or restorations can be pursued based on the individual's interests. Experienced carpenters could work towards becoming master craftsmen by taking an examination at the chamber of crafts in the individual state. Craft workers at these different levels – apprentices, journeymen, and masters – as well as those with different specialisations, contribute to various parts of timber construction processes.

In their study on automation in construction versus manufacturing, Everett and Slocum noted that "craft workers contribute to process design … they do not just execute the work, they also help decide *what to do, how to do it, when to do it, and where to do it*" [42]. A more accurate understanding of the human participants in timber prefabrication is critical for designing human-centred systems. Because such understandings are scarce in current robotic fabrication research, this paper triangulated interview data with these craft workers to identify their unique skill profiles and perspectives.

[1] SMEs are enterprises that employ less than 250 people or have an annual turnover of fewer than 50M euros, European Commission.

### 2.2. Theoretical frameworks for human–machine collaboration

Many theoretical frameworks have been proposed to guide the design of effective human-machine collaboration. This section presents an overview of these frameworks, which serve as the basis for conceptualising the HRC design space.

#### 2.2.1. Function allocation

Early work on answering the questions "what to automate" and "to what extent" traces back to avionics and traffic control. The Fitt's List approach is an extensively cited method based on allocating tasks to humans and machines based on what best matches their capabilities [43]. This approach has a profound influence on automation system design but also faced much criticism — "The credibility of Fitts List foundered on a simple paradox: If a task could be described exactly (i.e. in mathematical terms), then a machine should perform it; if not, it could only be tackled using the *ill-defined flexibility* of a human being" [44]. The slippery and context-specific promise of "flexibility" often leads to leftover allocations and a slew of human factor issues such as the "out-of-the-loop performance problem" [45]. This flexibility is also fallible, as underscored by cognitive psychology research [46].

Function Allocation (FA) is a fundamental design concern for human-centred automation [47]. Nevertheless, its practicality for design processes has been questioned given the ambiguities in its formulation in existing work, as various schemes, methods, or concepts [48]. Quantitative FA approaches based on signal detection theories and Bayesian analysis for correct and timely alarms to operators [49], task load models, and cognitive modelling [50] have been widely researched, and more recent approaches based on skill or complexity levels applied in many HRC studies [51]. There are also qualitative design guidelines for different stages of work [11] and both micro-ergonomics (task-oriented) and macro-ergonomics (systems-oriented) perspectives [12]. For the purpose of this research however, the authors embrace FA as a design philosophy rather than a specific methodological framework — the allocation principles are extracted from existing research projects, as appropriate categories "emerge from the data" [52].

#### 2.2.2. Level of automation taxonomies

The degree to which machines and humans participate in a process is measured by the level of automation (LoA). LoA is a system-level metric that delineates the degree of autonomy in a given work process by addressing human–machine roles in the system as a whole. Since the first widely-cited LoA taxonomy proposed by Sheridan and Verplank in 1978 [53], dozens of similar taxonomies have been proposed by researchers from various disciplines [13,54]. Vagia et al. conducted a review of these taxonomies over four decades and concluded that there is no "optimal" scale but rather each scale should be driven by system-specific user and application scenarios [55].

LoA provides a useful framework to guide automation design by considering humans and machines as a whole. For instance, Parasuraman et al. proposed an iterative process framework to design automation systems based on a 10-point LoA scale applied to four stages of information processing and actions [11]. LoA is also widely used in identifying automation possibilities in existing work processes, for instance, to study precast concrete production [56] and aerospace fibre composite manufacturing [57]. In timber prefabrication, a study by Popovic et al. analysed the LoA in the Swedish house-building sector by targeting an off-site exterior wall assembly process [36]. The authors applied the LoA taxonomy in addition to value stream mapping and hierarchical task analysis to shed light on the degree of automation in the house-building industry. In addition, dynamic levels of automation, or adaptive automation, were noted by many as a critical strategy for flexible manufacturing systems [13].

#### 2.2.3. Human-robot interaction taxonomies

In the early 2000s, many concerns about human-machine collaboration within automation design evolved towards human–robot interaction (HRI). Compared to the LoA taxonomies used in industrial and automation engineering, HRI taxonomies capture more dimensions of the interaction dynamic, such as team traits and composition as well as environmental and social factors. These HRI taxonomies draw from adjacent fields of computer-supported cooperative work and multi-agent robotics [58]. Onnasch and Roesler reviewed HRI taxonomies and proposed to consider factors in three clusters: interaction context, robot, and team classification [59]. It is also important to note that many HRI taxonomies are adapted and extended for specific applications e.g., health care [60].

In the AEC context, several HRC taxonomies have been proposed to define directions for future research. Liang et al. proposed a 5-level taxonomy for collaborative human–robot work in construction teams, building upon the Levels of Robot Autonomy taxonomy by Beer et al. [20,61]. The authors highlighted two promising future directions: robot learning from demonstration and human-multi-robot collaboration. Here, HRI variables such as human acceptance, trust, and social effectiveness are considered as a function of robot autonomy. In other words, the HRI design is mainly driven by the capability of robots. This "robot-centred" approach can also be seen in many similar HRI taxonomies [62]. An alternative approach is based on the consideration of human work characteristics, for which Hopko et al. provide a general model to accomplish this [63]. Han et al. reviewed the research in Collective Robotic Construction (CRC) and Human-Robot Interaction (HRI) and defined an intersectional research area — Collective Human-Robot Construction (CHRC) [21]. Although the authors did not define a taxonomy, they provided two axes to map existing research: autonomy–collaboration, and design–fabrication. This approach provides a more nuanced and interdisciplinary lens to view collaboration between humans and machines as well as the interrelations between design and fabrication.

### 2.3. Point of departure

Following the summary of existing theoretical frameworks in 2.2, this research contributes an analysis of the HRC design space, which draws from one HRI taxonomy in particular. This multi-dimensional taxonomy, proposed by Rodrigues et al. in 2023, is one of the latest HRI taxonomies tailored to the AEC context and has improved upon many existing models [64]. However, a few modifications are needed to convert such a taxonomy towards a design space, i.e., moving from classifications that "identify and structure characteristics and dimensions" to describe phenomena [65] towards focusing on "design artefacts" anchored in a particular problem space [66].

First, a clear delineation is needed to differentiate independent design variables that define a design alternative versus a-priori or evaluation parameters which are pre-defined given the goals of the application or are subsequently measured in empirical studies. Second, categorical values defined for general construction processes need to be refined to more accurately capture the parameters for timber prefabrication. This includes categories that may be too broad (e.g., task types like excavation, demolition, and underwater construction) or too narrow (e.g., considering mobile robots as a single morphology that encapsulates both industrial robots on a mobile base, and small, single-task machines). Last but not least, additional parameters that are of interest to prefabrication applications may need to be added.

A conceptual framework represents an "epistemological paradigm in looking at a given research problem" [67]. Given the multitude of factors involved in designing for HRC in timber prefabrication, concepts and perspectives from various sources need to be synthesised to construct such a framework. The research methodology behind this process is described in section 3, and the results of the analysis in Section 4. Section 5 presents the conceptual framework and illustrates its application as well as the revealed challenges and potential of HRC, followed by a discussion on limitations and future work in Section 6.

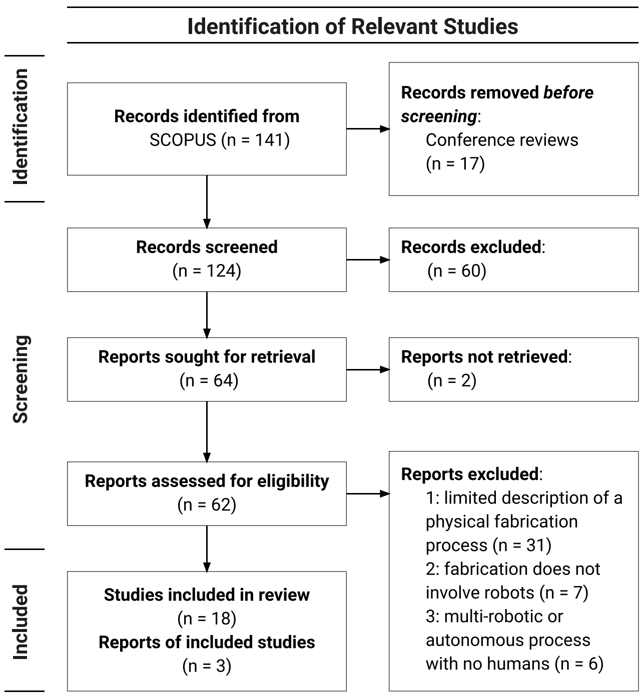


**Fig. 3.** Literature review procedure for relevant human–robot collaboration research in timber construction.
*Source:* The diagram is adapted from the PRISMA flowchart [68].

## 3. Methodology

The overall research design is illustrated in Fig. 1 and this section details the methods of data collection and analysis.

### 3.1. Triangulation

The concept of triangulation underlies the "integrative" nature of the core research question [23]. Denzin proposed four types of triangulation which can be used to enhance the validity and reliability of findings [22]. The application of triangulation in this research is described as follows.

*Theoretical Triangulation*: The HRC design space mapping is based on an existing classification [64], while other frameworks, such as LoA and function allocation philosophies, are also applied. This triangulation reduces the bias of applying a single theoretical model, such as a robot-centred classification of autonomy, towards conceptualising more holistic systems.

*Methodological Triangulation*: Using literature review as a sole methodology to outline the design needs of HRC systems is insufficient given the lack of reporting on human perspectives. To reveal human-oriented aspects and bolster the ecological validity for applications in real-world scenarios, interviews with trained carpenters were conducted to construct human-centred aspects of the framework.

*Data Triangulation*: The research contextualises HRC design as an embedded problem within its application environment. This requires triangulating both design data related to timber assemblies and human reports on the skill profiles and experiences in the industry. Though this is different from the classical time/space/people definition of data triangulation, the framework sets out to establish connections between these three areas.

### 3.2. Literature review

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) workflow is a guideline to improve the transparency and rigour of literature reviews and has been widely adopted by researchers in various fields including construction automation [68–71]. Based on a title, abstract, and keyword search in the SCOPUS database (Fig. 3), the review used the search terms: (timber/wood) AND (robotic/automated) AND (assembly/fabrication/construction) AND (collaborative/collaboration/human). Among the 141 results, 62 papers were assessed to identify relevant studies that demonstrate human–robot collaborative workflows for timber construction.

Three main exclusion criteria used in this process were (1) papers that did not contain sufficient descriptions of physical fabrication [72–74]; (2) papers that proposed multi-robotic collaboration or purely autonomous work cells with no data on human involvement [75–77]; (3) papers that described fabrication processes using either human labour entirely, e.g., with augmented reality [78], or other digital fabrication technologies such as CNC or gantry machines for 3D printing [79,80]. 18 papers were selected based on their inclusion of physical timber construction and HRC processes. Where multiple selected papers described the same study or project, they were reviewed and consolidated as one data point [81–83]. Where a selected paper did not contain enough fabrication details, a search was conducted for associated papers, which were then reviewed and consolidated as one data point [3,84]. In total, 16 projects ranging from 2017 to 2023 were analysed in detail.

In the first part of the analysis, HRC systems data were extracted from the studies to formulate the design space, using the HRI taxonomy from Rodrigues et al. as a blueprint [64]. The second part of the analysis was based on the same surveyed projects from which timber system design parameters were organised into three categories — typology, connections, and scale. The correlations of these parameters with the HRC design space were mapped using contingency tables but due to the small sample size, no quantitative correlation ($p$-value) is provided.

### 3.3. Worker interviews

The interviews were conducted with workers over three levels of experience — Apprentice (less than 2 years), Journeyman (2–12 years), and Master (12+ years). The interviews included two participants per group i.e. N = 6 overall. A popular measure of universal occupation characteristics is the Work Design Questionnaire (WDQ), which proposes four groups of questions: task, knowledge, social characteristics and work context [85]. Informed by the WDQ categories, this research applied an interview format in search of more open-ended findings. The interview questions covered three main topics: task-skill characteristics (task and knowledge aspects), experiences (overall satisfaction and social aspects), and work environments (work context).

The thematic analysis method was used to extract common themes from the interview transcripts. This method is commonly used for identifying patterns or themes within data and offers more flexibility compared to methods that stem from specific theoretical or epistemological approaches e.g., grounded theory and discourse analysis [86]. The analysis involves six steps (1) familiarisation with data, (2) initial codes, (3) search for themes (4) review themes (5) name themes and (6) producing report [86]. The report on these themes is presented in section 4.3 and provides human-centred considerations for HRC system design.

## 4. Results

The following sections present the results of the data collection and analysis. The HRC design space is first formulated, followed by its connections to timber system design factors and human-centred viewpoints.

### 4.1. Design space of human-robot collaboration in timber fabrication

Supported by the surveyed data (2017–2023), each variable in the design space is defined and existing contributions are summarised to reveal gaps in current research. Additionally, a new level of automation (LoA) scale is established for timber fabrication to facilitate comparison and evaluation of different automation setups. Task-oriented LoA provides an actor-neutral means to describe autonomy levels, where the term "actor" refers to the entity, either human or robot, which executes the production task [87].

#### 4.1.1. A-priori parameters

A-priori parameters are grouped because they represent requirements that precede HRC process design in prefabrication applications. This includes task types, training/learning, and environmental factors.

*Task Types*: In the existing classification [64], the following task types apply to the fabrication of timber structures: *Positioning (Pick and Place), Assembling (Connectors), Cutting/Milling, Coating/Gluing, Marking, Recycling/Disassembling, Transportation/Lifting Material Handling, Bending/Shaping, Finishing, Installation (Services, Facades), Monitoring*. Task types explicitly addressed in the surveyed studies are summarised in Fig. 5a. There are several common yet unexplored tasks for collaborative execution, such as transportation, finishing and service installations.

*Training/Learning*: Though most projects apply HRC in the operation phase, some systems are designed for training and learning. This includes both human training (developing skills for humans) and robot learning (such as reinforcement learning (RL) and learning from demonstration (LfD)) [64]. Both LfD and RL were demonstrated in a study using robotic screwing [88].

*Setting*: The surveyed studies cover laboratory (controlled environment), off-site (environment with some natural influences such as errand human interaction and noise), and on-site (job sites or in-situ construction environments) (Fig. 5b). In procedures proposed for on-site deployment, semi-controlled environments (e.g., exhibition sites) were adopted instead of real construction job-sites [89,90].

*Robot Location*: All of the reviewed processes are located indoors. This is inherent to the concept of prefabrication — to reduce the amount of construction work carried out in exposure to weather.

#### 4.1.2. Planning parameters

Given the temporal separation between the planning and fabrication phases, the original task factors are split into planning and evaluation parameters.

*Task Planning*: Planning involves the breakdown and allocation of a task between team members and can be classified as offline, online, and hybrid [91]. Task planning is a distinct process from motion planning, which will be discussed later in *robot skill*. Hybrid or online planning methods involve a representation of the physical environment in the digital fabrication model. This cyber–physical feedback enables more high-level robotic skills such as environment awareness and adaptability. Most surveyed studies make use of some degree of online planning, whether to adapt to task failure, robot base changes, or accepting human input [89,90,92,93]. Since prefabrication involves predetermined outcomes, some degree of offline planning is often needed, resulting in hybrid methods (Fig. 5d).

*Allocation Principle*: Though not captured in the source taxonomy, this variable is proposed as a unique and separate concern from *task planning*; it describes the value proposition behind deciding whether a human or a robot should execute the task. A classification is proposed based on the observed cases: (1) *leftover allocation*: human does what the automation is not equipped for, (2) *error correction and takeover*: human fixes unexpected errors or takes over when automation cannot ensure correct or timely execution (both actors are theoretically equipped for the same task), and (3) *knowledge and creativity*: human teaches the system or exercises creative control (Fig. 5e).

#### 4.1.3. Robot parameters

Four robot-oriented parameters describe design choices related to the robotic system used in the timber prefabrication task.

*Robot Type*: The original classification of robot type is split into *type* and *morphology*. The robot type (stationary, mobile, wearable) describes the spatial relationship between the machine and the human. Robot arms mounted on AGVs or gantries are considered mobile as they are capable of re-configuring their global position in space. The majority of surveyed robots are stationary (Fig. 5g).

*Robot Morphology*: Morphology describes the form factor of the robot (articulated arm, humanoid, zoomorphic, exoskeleton, swarm). All robots in the surveyed research are articulated arms, with a mix of industrial and collaborative robots (Fig. 5f). Although several multi-machine fabrication studies present workflows where small mobile robots work with timber [75,76], these works did not address human interactions. Further investigation into interactions with these smaller, often single-task robots for timber construction is an interesting area for future research.

*Safety Mechanism*: Over half of the studies use collaborative robots with low payloads, which employ hardware-based safety mechanisms by design. With industrial robots, safety is ensured through control-based mechanisms such as limiting velocity and separation monitoring. Industrial robots mounted on mobile bases have additional degrees of freedom and must deal with higher planning complexity to ensure safety. Prediction-based, motion-planning-based, and psychological factors-based methods were not found in the surveyed studies.

Rodrigues et al. originally proposed seven categories for robot traits, which include *situation awareness, anticipation, adaptation, decision-making, motion planning, mobility, and manipulation* [64]. By splitting these seven traits according to the distinction between physical and cognitive automation ("mechanisation" and "computerisation") [13], the authors propose a refinement of this category as *Robot Skill*.

*Robot Skill*: The proposed skill categories are detailed in Table 1. In timber prefabrication, the manipulation category can more specifically address contact-rich, payload-specific, and tool-specific manipulation skills. Mobility skill includes 1DoF [99], 2DoF [90] and 3DoF [96] movements. When the movements are executed manually by an operator [92] the robot is considered to not have mobility skills. Higher-level cognitive skills (anticipation, adaptation, and decision-making) depend on some form of situational awareness, which is further delineated as goal, task, and team awareness. The presence of these skills is extracted from descriptions of computational workflows in the papers. The implementation of these skills often exists in a separate computational environment with bi-directional communication with robotic control (most use Grasshopper[2] in the surveyed studies), although direct integration with robot control is also possible [88,103]. These skills are also summarised in Fig. 5h. Out of all the skill categories, anticipation, team awareness and goal awareness are not documented; these are important prerequisites to enable more seamless human–robot collaborations.

#### 4.1.4. Human parameters

Three parameters capture the selection of human-oriented parameters in the HRC design.

*Human Skill*: The inclusion of human skills as a design parameter allows a clear decision process for function allocation (Table 1). Even though skills such as motion planning, anticipation, and adaptation come naturally to humans, mobility and payload-specific manipulation may be limited to some, e.g., those with injuries or musculoskeletal diseases. The table highlights human skills that were prioritised during task allocation, instead of all skills that the human may possess or exhibit. The most commonly prioritised physical skills are contact-rich manipulation (e.g., for fine adjustment and assembling

[2] Grasshopper is a scripting software embedded in the Rhino 3D modelling environment, developed by Robert McNeel & Associates.

**Table 1**
Physical and cognitive skills are formulated based on the *Robot Traits* category in the construction HRI taxonomy [64]. Projects that **explicitly** describe a process which applies the particular skill in its HRC setup are referenced and a count of each skill is summarised.

| Human and robot skills | | | | | | | |
|---|---|---|---|---|---|---|---|
| Skill group | Sub-group | Robot skills | | | Human skills | | |
| | | Description | Count | References | Description | Count | References |
| Manipulation | Contact-rich | Force–torque sensing | **5** | [88–90,94,95] | Dexterity | **8** | [88–90,92,94–97] |
| | Tool-specific | Cutting, milling | **7** | [3,89,90,96–99] | | | |
| | | Screwing | **4** | [88,94,95,99] | Screwing | **7** | [81,92–94,96,97,100] |
| | | Nailing | **2** | [3,100] | Nailing | **2** | [81,101] |
| | | Gluing | **1** | [3] | Gluing | **1** | [81] |
| | Payload-specific | Heavy payload | **7** | [3,81,96–100] | | | |
| Mobility | 3 DoF | Full spatial motion | **1** | [96] | Material transfer and supply | **6** | [3,81,90,93,97,99] |
| | 2 DoF | In-plane motion | **1** | [90] | | | |
| | 1 DoF | Linear motion | **1** | [99] | | | |
| Situation awareness | Environment | Material and spatial sensing | **7** | [88–90,92,94,95,102] | | | |
| | Team | Understanding of teammates | | | Error correction and task takeover | **4** | [81,94,95,100] |
| | Goal | Understanding of high-level goals | | | | | |
| Decision-making | | Robot makes design choices | **2** | [92,102] | Human makes design choices | **3** | [92,98,102] |
| Motion planning | | Online motion planning during tasks | **4** | [89,90,92,93] | | | |
| Adaptation | | Robot adapts its current task | **2** | [90,102] | | | |
| Anticipation | | Robot anticipates a future state | | | | | |

complex connectors) and material handling (e.g., replenishing material supply, loading/unloading materials) (Fig. 5j). Humans are also allocated certain cognitive tasks that combine the use of situation awareness and decision-making, such as error corrections and takeovers. In design-oriented cases, humans are tasked with making creative decisions.

*Information Support*: This factor is included as "decision support for operators" in other HRI taxonomies [58]. Compared to the input or feedback interfaces in the *communication* category, information related to the task as well as the HRC system is required for effective human participation. The authors argue that this should be included as an independent parameter because existing research suggests that operator support interfaces impact many factors in HRI such as task performance, situation awareness, and interaction efficiency [104,105]. Four categories of information support are suggested: (1) *static documentation*, e.g., plans and instructions which are fixed throughout fabrication, (2) *dynamic documentation*, e.g., digital models and interactive manuals which could change and adapt, (3) *communication*, e.g., information acquired during run-time, like asking another teammate, or (4) *implicit*, where people hold the process knowledge in their minds, such as existing knowledge, or briefing before fabrication.

*Human Role*: This factor has five original categories: *operator, supervisor, cooperator, collaborator, and bystander* [59,64]. The operator role applies to humans that directly control the action of the robot e.g., haptic teleoperation. This was not found in the projects unless a human manually guiding a cobot is considered. In robotic fabrication, the role of a supervisor is most common, whether directly in the robot cell or in front of the computer screen. When humans share tasks explicitly in the production process, they act as a collaborator (dependent actions) or a cooperator (independent actions). Most studies make use of humans as cooperators (Fig. 5i). The bystander role was not specifically addressed, which should perhaps not be the case given the presence of errand humans in production environments and potential issues related to situation awareness and safety.

#### 4.1.5. Context parameters

Shared attributes between humans and robots are split into Context and Interface parameters, depending on whether they relate to the physical production setup or the communication and interface design. In prefabrication, the former is often determined by production needs.

*T/S Proximity*: Most studies using industrial robots apply sequential collaboration in the same workspace (synchronous and colocated) (Fig. 5k). In some cases, humans were reported to correct errors where multiple co-bots are executing tasks, which suggests an asynchronous and colocated collaboration with the other robot [94,95]. In the non-colocated category, Kramberger et al. presented a Learning from Demonstration process where human teaching occurs in a separate cell prior to the main robotic execution [88]. One observation from process descriptions is that humans might assist in robotic procedures like remedying material errors or replenishing material supply during robotic execution [97,99]. This would constitute asynchronous cooperation, which, if left unconsidered, could lead to issues in estimating the mental workload demands and safety conditions.

*Team Composition*: In the majority of studies, one robot works alongside multiple humans (Fig. 5l). In multi-robotic procedures, each robot sometimes executes a different task type [3,96,99]. Explicitly multi-human, multi-robot teams were not found in the surveyed studies and could be an interesting setting to study more heterogeneous tasks and interactions. However, the interaction might become overly complex without a basis of understanding first the system behaviour with a limited number of actors. Real-world off-site environments often involve other workers as bystander participants. Explicitly considering their interactions with the robotic process is important to ensure situational awareness and safety but there is no available data to support further elaboration on these cases.

#### 4.1.6. Interface parameters

The means by which humans communicate to and receive feedback from the robots are the input and feedback interfaces, originally defined with three categories in each case: physical, non-physical, and multi-modal [64].

*Feedback Interface*: Physical feedback from the robot (tactile and kinaesthetic) was not found in the surveyed studies. Non-physical feedback using sound or vision can be integrated through external devices or be directly observed through the natural environment. In most projects, it is not explicitly stated whether the humans receive feedback from computer screens, or from observing the robot task in the real world. In three of the surveyed projects, AR was implemented for robotic feedback [92,93,100].

*Input Interface*: Conventional input interfaces for robots are physical. This can be further divided into control device (e.g., pendant, controller, or external buttons), computer (e.g., keyboard and mouse), or directly on the robot (e.g., haptic teaching mode). Non-physical input, such as gesture, speech, and brainwaves, are also possible, and two studies used an AR device for robot input commands [93,100]. Unfortunately, information on the input interface is uneven across the projects. Based on experience, the most likely choice would be a robot controller or computer, which are both physical mediums (Fig. 5m).

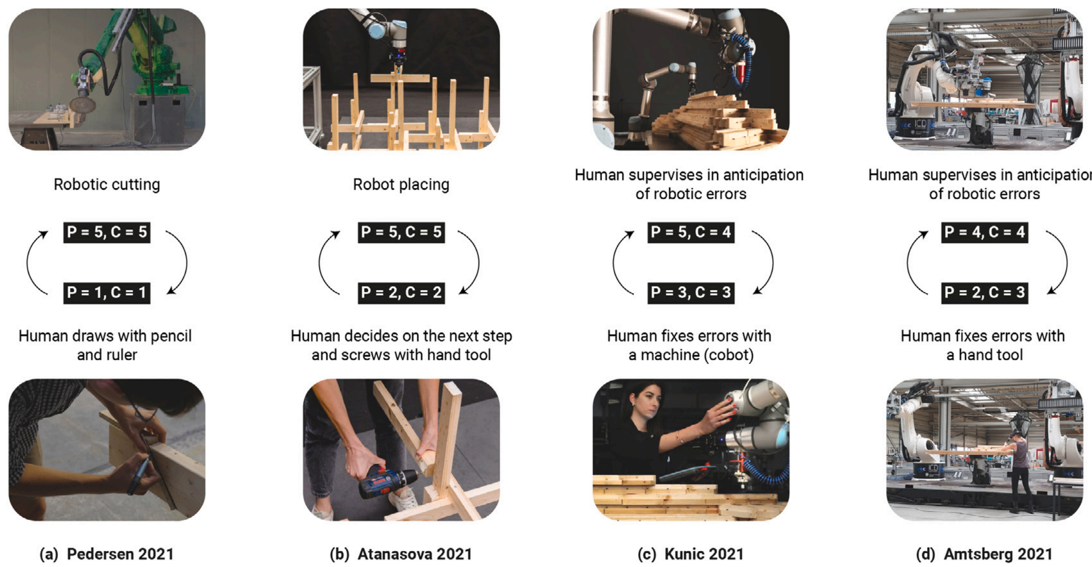


**Fig. 4.** Illustration of the cognitive and physical LoA using four surveyed studies [92,95,98,100]. During automatic robotic operations (P = 5) or robot control in manual mode (P = 4), cognitive automation levels are normally high (C = 5). However, if the machine procedure has a higher margin of error and humans are expected to fix them as they occur, then the human workload is higher (C = 4). During human interventions, the cognitive automation level varies depending on the setup from the designer, where full creative authority (C = 1), creative decision within system constraints (C = 2), and simple error corrections with main parameters determined by the system (C = 3) can be observed (credit: (a) Aarhus School of Architecture and Odico Construction Robotics (b) Augmented Fabrication Lab, Technical University of Munich (c) CREATE, University of Southern Denmark, (d) ICD, University of Stuttgart).

**Table 2**
Refined cognitive and physical level of automation scale in surveyed HRC projects.

| | | |
|---|---|---|
| Cognitive LoA scale | | |
| C = 1 | Creative improvisation | Human controls the entire process and develops their own course of action |
| C = 2 | Action selection | Human decides what to do but some aspects are constrained by the system |
| C = 3 | Intervention | Human participates in the process with minimal creative choice e.g., fix errors |
| C = 4 | Supervision | Human supervises the process while anticipating potential errors |
| C = 5 | Autonomy | Human is not involved |
| Physical LoA scale | | |
| P = 1 | Manual | Human applies all the power. e.g., lifting beams, wielding a hammer |
| P = 2 | Hand-held power tool | Human carries the machine and apply some power. e.g., screwdriver, nail gun |
| P = 3 | Static machine | Main power comes from the machine e.g., table saw, manually moving a cobot |
| P = 4 | Programmable machine | Human physically controls through an HMI. e.g., CNC, robot in manual mode |
| P = 5 | Autonomous robot | Human only needs to switch on the machine. e.g., autonomous robots |

*4.1.7. Evaluation parameters*

The evaluation category captures the dependent variables that are used to evaluate the task execution. The introduction of an actor-neutral, task-oriented level of automation scale is presented, which documents the physical and cognitive autonomy levels of the overall process. In contrast to robot-oriented measures of autonomy, the abilities to sense, plan and act are subsumed within the aforementioned *robot skills* category.

*Level of Automation*: Based on the reported tasks in the surveyed studies, a five-point LoA scale for physical (P) and cognitive (C) processes is proposed. Compared to various LoA scales in existing work [13,53,55], this scale is tailored to the conditions found in existing robotic timber construction projects (Table 2). As LoA parameters are often dynamic within a given procedure, the shifts in LoA are illustrated in Fig. 4 using four projects from the survey [92,95,98,100].

Within this new scale, a few illustrative cases can be identified and aligned with certain ideals[3] in construction:

- Lights-out Automation (C = 5, P = 5): The machine is entirely responsible for the production process.
- Craft-based Construction (C = 1, P = 1): Craftsperson builds everything and has full control.
- Intelligent Assistant (C = 1, P = 5): Craftsperson decides what to do while all physical work is carried out by an autonomous robot capable of correcting its own mistakes.
- Dystopian Machine (C = 5, P = 1): The human obeys an autonomous system that gives out instructions and does all the manual work.

The main motivation for proposing a new LoA scale from the survey is that it establishes a set of common conditions for (semi-)automated timber prefabrication. This facilitates the comparison of autonomy levels of the fabrication task in different HRC setups and may be used to provide guidelines for human factors issues that are likely to arise at a given level [10].

*Human Factors*: These are called Human Traits in the original taxonomy, which include trust, ergonomics, mental workload, and situation awareness. Reports on these issues were scarce in the papers which hinders further understanding of human factors in existing setups.

*Team Trait*: This factor addresses the qualities of the HRC team such as team and shared situation awareness, shared mental models, fluency and interaction efficiency [64]. These criteria were also not present in the surveyed studies.

[3] The authors do not explicitly advocate for any of these “ideals”.

While Human Factors and Team Traits are common concerns in HRI research, these are rarely documented in HRC fabrication studies. Task performance, such as speed and accuracy should also be in this category, but as this is unevenly reported in the surveyed studies, it is omitted from the discussions. Finally, based on the refined parameters above and some structural changes to the original taxonomy, a map of the HRC design space along with the surveyed data is shown in Fig. 5.

### 4.2. Integrating timber system design

The second analysis is concerned with identifying the design parameters of timber assemblies and identifying their relationships with the HRC design space. The data here is therefore based on the same set of projects.

#### 4.2.1. Connections

Assembly operations involve both material manipulation tasks such as pick-and-placing, and fixation tasks such as nailing, screwing, or inserting nut-and-bolt assemblies.

*Joint Types*: Joint types relate both to the machining effort and their assembly tolerance. *Single-laps* are the most common because they do not require geometric features from milling and there are fewer tolerance requirements (Table 3 (a)). *Peg-in-hole* or *cross-lap* assembly requires more contact-rich manipulation, as the structural integrity relies on tight fitting joints. In the surveyed studies, these are either assembled manually or machine learning methods are applied.

*Fasteners*: Connection methods are often considered based on ease of fabrication, structural strength, and reversibility. *Nails* are the easiest to apply and can be easily automated, however, the materials cannot be separated without damage afterwards. *Screws* are the most commonly used connector in the surveyed projects, among which half are executed manually (Table 4 (a)). Both nailing and screwing connections are sensitive to knots in the timber, which could cause an automated procedure to fail. *Bolts* provide larger holding strength than screws but it requires either the pre-embedding of the nut in the material [94,95] or requires human assembly as the insertion requires both hands [96]. Both projects that employed *glue* were categorised as *Hybrid* because glue was used in addition to screws and nails. Although it is possible to use glue alone, fasteners are helpful in combination to eliminate unwanted movements during transport and pressing.

#### 4.2.2. Typology

Typology parameters capture the geometric characteristics and complexity of the assembled structure. In relation to the main prefabrication typologies outlined in Section 2.1.2, most elements in the surveyed projects produce some form of three-dimensional components.

*Global Typology*: This refers to the typology of the prefabricated element instead of the final construction assembly. The geometric complexity of the global typology is directly linked to the planning complexity during prefabrication. *2.5D clusters* are the most common where timber elements are assembled in one direction through stacking; it is more tolerant of potential accumulations of material errors (Table 3 (b)). A cluster assembled from multiple directions constitutes a *3D cluster*, but it slightly differs from *truss* and *timber frame* typologies because the elements have larger areas of overlap with each other.

*Local Typology*: The local typology directly influences tool-specific and payload-specific manipulation skills. The majority of elements are linear, among which short timber *slats* are the most common; these elements require lower payload and relatively simple grippers. Longer *beams* are seen in the construction of three-dimensional structures [96–98]. Circular *rods* [89], thin *sheets*, and *lamellas* [99,102] are used in facade-like elements (Table 4 (b)). A *hybrid* of plates and slats often involves multiple robotic tools [3,99]. It is important to note that, due to the experimental nature of HRC in digital fabrication research, some of these typologies may be selected due to space or material constraints, rather than their applicability in specific building typologies. Plate and column/beam typologies are more common in conventional construction.

#### 4.2.3. Scale

There are three types of constructions in the surveyed studies: *projects*, which are finished and installed on site (N = 6); *prototypes*, which are smaller-scale demonstrators resulting in components or built objects (N = 9); and *demos*, which showcase the fabrication process with little mention of final physical results (N = 1). The majority of research falls in the prototype category, and the availability of scale-related data is uneven for prototypes and demos.

*Element Quantity*: The element quantity can be considered per prefabricated component, or throughout the whole structure. The latter is used in this analysis as it more accurately reflects the scaling factor of the entire HRC process. Three studies used more than 1000 elements, where the production efficiency is conceivably of much greater concern than studies demonstrating novel workflows using less than 50 elements. The majority of the studies use between 300 to 1000 individual wood elements (Table 3 (c)). Three studies did not provide information on material quantity.

#### 4.2.4. Correlation with the HRC design space

The relationships between the design and HRC parameters are mapped using contingency tables, as shown in Tables 3 and 4. Due to the small data set (N = 16) and non-binary categorical values, no *p*-value was computed. However, a qualitative discussion of the findings is given to interpret the relationship between the design parameters and HRC configurations. Two HRC design parameters with high occurrence throughout the samples and more variability are selected: *robotic skill* (contact-rich manipulation) and *allocation principle*.

The contact-rich manipulation skill is enabled by force–torque sensors available on cobots. Studies using contact-rich skills cover most joint types and element typologies, but studies with traditional pick-and-place skills are mostly limited to single lap joints and 2.5D cluster constructions (Table 3 (a, b)). This points to the possibility that this robotic skill can enable a greater geometric range of prefabricated elements. However, this type of manipulation has only been explored in small-scale studies, both in terms of payload as well as dimensions. In one project, reinforcement learning results reached up to a 93% success rate [88], and in 7% of cases, human interventions were needed. This calls for a consideration of human factors in these situations and more robust contact-rich methods that could be applied to projects at a larger scale (Table 3 (c)).

Physical skills by humans are often used for correcting errors from robotic procedures. In smaller projects, humans contribute through creative input and occasionally correcting errors. In larger projects, humans mostly take up the leftover tasks (things that robots cannot do) (Table 4 (c)). Screwing connection is a common candidate for left-over allocations due to the higher tolerance requirements and risk of material damage (Table 4 (a)). Slat is the most common element typology and is used with many different types of allocation principles (Table 4 (b)). In a conventional design-to-fabrication workflow, the design environment contains geometric and building data, while the fabrication environment contains information for human or robotic execution. Some studies reverse the unidirectional data link such that the system enables creative input from humans in the fabrication environment, where both physical and AR input methods have been demonstrated [92,98,102]. Although these processes show some novel possibilities when element quantity is low (1–300), the applicability is challenging at larger scales. More complex typologies are often used in these studies, although it would be interesting to see how such creative skills can be applied in conventional construction systems and make use of the unique cognitive skill sets of craftspeople, rather than designers.

#### 4.2.5. Limitations

This analysis is far from a thorough map of the myriad design criteria of timber building systems, but rather a set of available criteria which allows an integrative consideration of the HRC system parameters in conjunction with the design space of timber structures. For

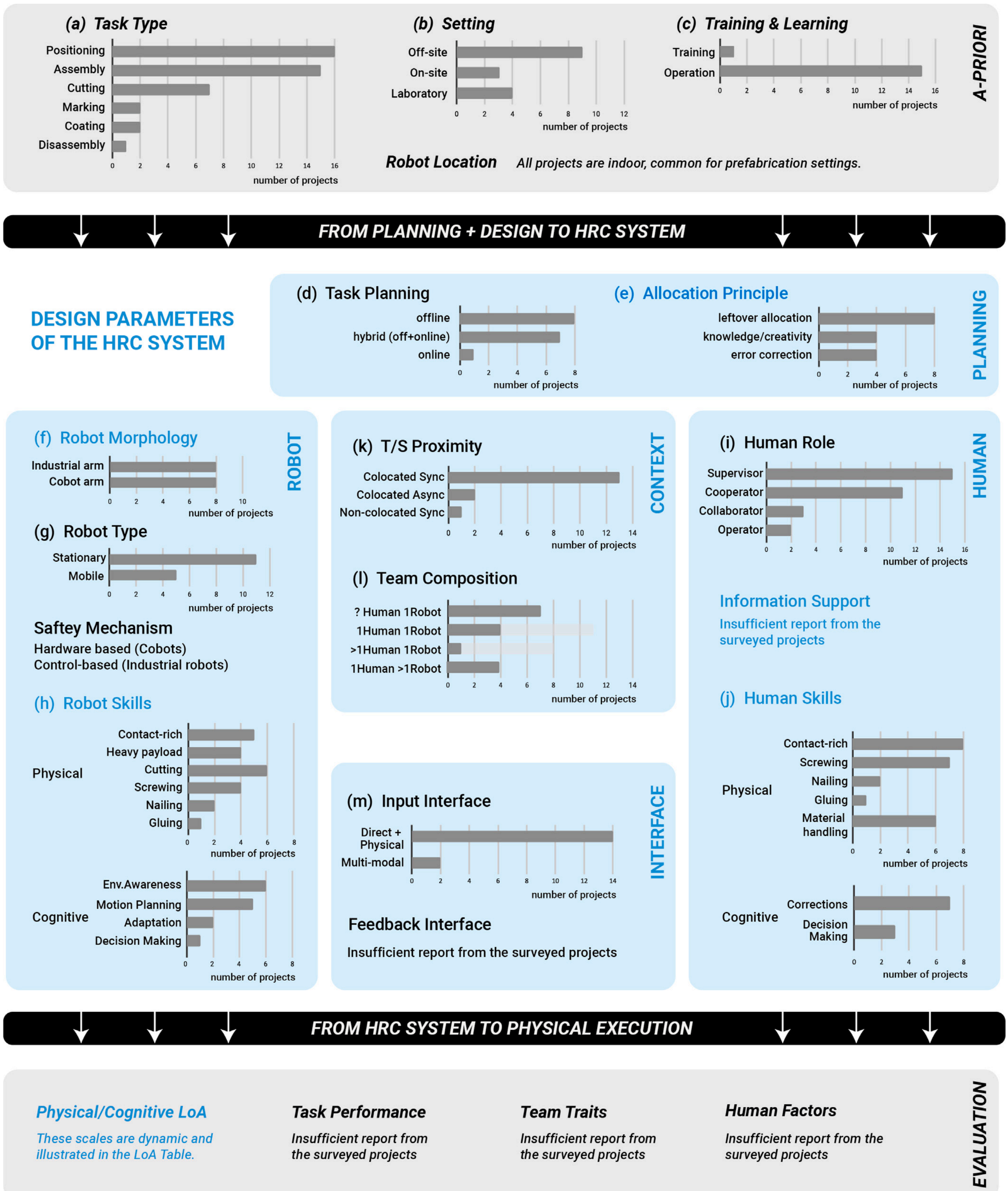


**Fig. 5.** A graphical summary of the HRC design space parameters containing data from the surveyed timber fabrication projects. The modified and newly proposed variables are highlighted with blue text. New variable groups are shown with either a blue (HRC design variable) or grey tint (a-priori and evaluation parameters). The temporal sequence connecting these new groups is denoted at two interfaces based on the typical boundary in a digital timber prefabrication process. The human-oriented parameters, namely Information Support, Human Role, Skills, and Human Factors, are used to inform the design of subsequent interviews.

**Table 3**
Contingency table between various design parameters and HRC parameter: *manipulation skill*.

(a) Joint type and manipulation skill

| Joint types | Robot manipulation skill | | | Total |
|---|---|---|---|---|
| | Contact-rich | Traditional pick + place | Not applicable | |
| Butt joint | 1 | 2 | | 3 |
| Cross/half lap | **2** | | 1 | 3 |
| Peg-in-hole | 1 | 1 | | 2 |
| Single lap | 1 | **7** | | 8 |
| **Total** | **5** | **10** | **1** | **16** |

(b) Component typology and manipulation skill

| Component typology | Robot manipulation skill | | | Total |
|---|---|---|---|---|
| | Contact-rich | Traditional pick + place | Not applicable | |
| 2.5D cluster | 1 | **5** | | 6 |
| 3D cluster | 1 | 1 | | 2 |
| Facade | 1 | 2 | | 3 |
| Spatial truss | **3** | 1 | | 3 |
| Timber frame | | 1 | 1 | 2 |
| **Total** | **5** | **10** | **1** | **16** |

(c) Component typology and manipulation skill

| Element quantity | Robot manipulation skill | | | Total |
|---|---|---|---|---|
| | Contact-rich | Traditional pick + place | Not applicable | |
| 1000+ | | 3 | | 3 |
| 300–1000 | **1** | 4 | | 5 |
| 50–300 | | 2 | | 2 |
| 1–50 | **2** | | 1 | 3 |
| Unknown | **2** | 1 | | 3 |
| **Total** | **5** | **10** | **1** | **16** |

**Table 4**
Contingency table between various design parameters and HRC parameter: *allocation principle*.

(a) Fastener type and allocation principle

| *Fastener type* | Allocation principle | | | Total |
|---|---|---|---|---|
| | Error correction | Knowledge + creativity | Leftover allocation | |
| Bolt | 2 | | 1 | 3 |
| Hybrid | 1 | | 2 | 3 |
| Nail | | 1 | 1 | 2 |
| None | 1 | 2 | | 3 |
| Screw | | 1 | **4** | 5 |
| **Total** | **4** | **4** | **8** | **16** |

(b) Element typology and allocation principle

| *Element typology* | Allocation principle | | | Total |
|---|---|---|---|---|
| | Error correction | Knowledge + creativity | Leftover allocation | |
| Slat | 3 | 2 | 4 | 9 |
| Beam | | 1 | 2 | 3 |
| Hybrid | | | 2 | 2 |
| Rod | 1 | | | 1 |
| Lamella | | 1 | | 1 |
| **Total** | **4** | **4** | **8** | **16** |

(c) Element quantity and allocation principle

| *Element quantity* | Allocation principle | | | Total |
|---|---|---|---|---|
| | Error correction | Knowledge + creativity | Leftover allocation | |
| 1000+ | 1 | | **2** | 3 |
| 300–1000 | 1 | | **4** | 5 |
| 50–300 | | **2** | | 2 |
| 1–50 | 1 | 1 | 1 | 3 |
| Unknown | 1 | 1 | 1 | 3 |
| **Total** | **4** | **4** | **8** | **16** |

**Table 5**
Interview sample.

| ID | Role | Experience (years) | Environment |
|---|---|---|---|
| H1 | Master | 47 | Offsite mostly |
| H2 | Master (Foreman) | 18 | Onsite mostly |
| H3 | Journeyman (Machinist) | 8 | Offsite |
| H4 | Journeyman | 7 | Offsite mostly |
| H5 | Apprentice | 2 | Offsite + Onsite |
| H6 | Apprentice | 2 | Offsite + Onsite |

instance, material selection is of great importance to both fabrication and design, but the majority of surveyed studies did not contain detailed information on the species or types of timber material. Other scale metrics such as square footage, or size of the elements are also important factors that could be included.

### 4.3. Integrating human-centred work design

The goal of the third analysis is to address the gap in understanding human profiles in timber prefabrication environments. Semi-structured interviews were carried out with carpenters at the skill level of apprentice, journeyman, and master in a German timber construction firm. The sample is shown in Table 5. Each session lasted around 45 min and the questions were structured around three topics: tasks, work environments, and experiences. The results were analysed through a thematic analysis approach using the interview transcripts [86]. The key themes are presented below and the number of occurrences by participant are noted in brackets.

#### 4.3.1. Roles

In responding to the *task* questions, the interviewees described common tasks at their jobs. An overview of these tasks, grouped by roles, is provided below.

*Master*: The main tasks for a master craftsperson are team coordination, assembly checking, and organisation. When the team comes across unclear plans, he/she would review the issues before the question moves upstream. In on-site scenarios, the master (foreman) has similar tasks but the coordination challenge also involves remote, non-colocated settings, e.g., logistical tasks like managing the delivery of materials.

*Journeyman*: The main tasks include element construction, material preparation, and transportation in preparation for on-site assembly. The additive assembly tasks are carried out manually based on plans and often in teams of two or more people. The subtractive processing steps are carried out by dedicated machine operators who nest and cut the pieces and also maintain the machine. Additionally, this worker coordinates the inflow and outflow of materials needed and tags the finished pieces so they can be identified later. On-site tasks include various assembly procedures from setting up sub-structures to assembling facades.

*Apprentice*: These early-career craftspeople carry out miscellaneous tasks both in the prefabrication and on-site assembly since they need to learn the processes in both environments. Their tasks also include various errands, which might make them most susceptible to tiresome, monotonous jobs.

#### 4.3.2. Task-skill characteristics

To integrate the task-related data with the human skill parameter, the coding process focused on key cognitive skills required to execute these tasks, summarised below.

*Communication and Teamwork* (N = 6): This is a skill mentioned in every role. It does not only occur among team members participating in the same construction task but also between locations (office and factory, factory and job site), for example when there are problematic plans or missing materials. Occasionally important information is not captured in the documentation and needs to be communicated on the go (H1). At the apprentice level, they rely on communication skills to adapt and learn from more experienced workers (H5, H6).

*Construction knowledge* (N = 5): This was aptly described by H1 as being able to "think your way into a building". It implies a type of knowledge with which craftspeople consider the end product and make decisions such as spotting problems, thinking ahead of the construction procedures, and adapting the tasks based on what is needed and available at the time. Because mistakes during prefabrication can propagate and become more time-consuming to correct later on, the master checks the dimensions and uses this knowledge to ensure smooth operations downstream.

*Coordination and Management* (N = 2): This skill is particularly relevant at the master level. These more experienced craftspeople coordinate a team to complete assembly and resolve potential issues when they arise (H1, H2). In on-site scenarios, team management is even more challenging because there are constantly new people joining and old workers leaving (H2).

#### 4.3.3. Job satisfaction

A prevalent notion in support of adopting robotics is that robots can fulfil Dull, Dirty, Dangerous (3D) tasks and liberate humans from such undesirable environments [106,107]. However, the types of tasks that make the profession interesting or fulfilling are rarely mentioned as something to be favoured. The workers were asked what they love the most about their jobs and three themes were repeatedly mentioned.

*Joy of building* (N = 4): "When you arrive there is only a foundation slab, and when we leave there is a house on top". The joy of building was repeatedly cited as a reason why the workers love their jobs. It was clear from the interviews that this process involved not only manual skills and tool knowledge but also more intricate mental processes that inform decision-making based on an understanding of how a building is constructed.

*Task Variety* (N = 2): One apprentice responded that he loves the variety of the job — "even if I have to screw the same girders for a week, it is tough, but at the end of the day there is always something new" (H5). A worker who previously worked as a sawyer said — "with sawing it is very monotonous but in milling, there is so much variety with the different projects and materials" (H3).

*Teamwork* (N = 2): Both apprentices said they love the teamwork. Since they are also required to acquire new knowledge from more experienced members of the team, they rely on high levels of communication and a supportive team environment for learning.

#### 4.3.4. Job issues

On the flip side, to the question "what are some tasks that you find unpleasant", repeating themes are:

*Contact with chemicals* (N = 3): Direct contact with materials such as glass fibre for insulation filling causes itching on the skin. Handling glue for Farmacell panels, which sticks on the skin and is hard to wash off, is another such example. In the case of machining, workers are exposed to some amount of hazardous dust despite the ventilation systems in place.

*Ergonomics* (N = 2): Two workers mentioned that large formwork elements are not the most comfortable job to do, because one has to kneel or bend down to work. Unlike smaller assemblies, assembly tables cannot be used to establish a comfortable working height. Adverse weather also leads to some unpleasant tasks, such as needing to stuff insulation or seal packages outside in high summer.

#### 4.3.5. Work environment

The work environment was examined to understand the spatial characteristics of the work tasks. This provides insights into some criteria to consider when designing production layouts for HRC processes. Two main themes are:

*Flexibility* (N = 5): In the off-site environment, workspaces are always flexibly allocated based on the production needs at a given time.

The constraint mostly comes from machinery, e.g., availability and payload of gantry cranes, or the need for large format equipment such as Hundegger machines (H2, H3, H4). Although there are dedicated storage areas, many workpieces are flexibly stored based on the need for pick-up or assembly. Additionally, two degrees of flexibility can be observed around each assembly "job" (i.e., a collection of tasks related to the construction of a single component):

- *Within Job*: While the assembly areas are set up over the duration of the assembly job, the sizes of the areas vary according to the building components e.g., a large roof structure for a sports hall may take up an entire hall, whereas smaller constructions are carried out over a few assembly tables. When materials need to be re-sorted before being used in assembly, the workspace around them is adapted to do so (H1, H3).
- *Between Job*: If many projects are underway at the same time, the arrangement of job areas is negotiated between various teams and may change during the work stages (H1, H5). A high degree of flexibility allows teams to adapt based on the needs of the production scenario.

*Mobility* (N = 2): Despite the effort to streamline the operations as much as possible and set up a "street" for assembly (H5), workers often need to move around to either retrieve tools and materials or communicate with each other to negotiate and solve problems.

#### 4.3.6. Correlation with HRC design space

Some qualitative observations can be made about the work characteristics of the interviewed carpenters and the HRC design parameters outlined previously. Design suggestions based on these human-centred constraints are given below.

*Allocation Principle*: The "joy of building" relies upon tacit knowledge and skills that underlie the mastery of building with wood. Given that robotic construction automates both physical and cognitive aspects of the construction task, there is the question of how craftspeople's control and decision-making agency can be preserved, especially with regard to the risks of de-skilling when using automated systems [45]. Or rather, how can HRC systems be designed to preserve the cultivation, enjoyment and furtherment of the craft itself?

*Team Composition*: Teamwork is a significant aspect of a carpenter's job, both as a pleasant aspect of the work and also out of necessity in the construction process. Despite the prevalence of dyadic human–robot collaboration research, it is perhaps important to consider how multiple human beings can naturally interact with each other and work together to retain this collective culture.

*Robot Skill*: Tasks such as installing soft insulation or glue application, which are unpleasant or hazardous to humans, are addressed in rather few of the HRC studies. Although industrial automation equipment can deal with these tasks, to the authors' knowledge they have not been addressed in open robotic setups. Disregarding these task types in the development of robotic skills risks that these aspects become "left-over" jobs for humans. This contradicts the promise of robotics to liberate humans from dull, dirty, and dangerous tasks [106,107].

*T/S Proximity*: The work environment traits highlight high degrees of mobility and flexibility. This brings back the consideration of bystanders in HRC processes. Other than the human, for whom the HRC process is explicitly designed, what of the other humans who share the same space? In relation to the need for non-dyadic HRC, how does T/S proximity evolve when multiple human beings are present?

*Communication Interfaces*: The mobility and flexibility requirement of the work environment makes mobile displays and interaction technologies highly relevant as the human-machine interface. Projection-based, mobile or head-mounted augmented reality presents interesting opportunities in this area.

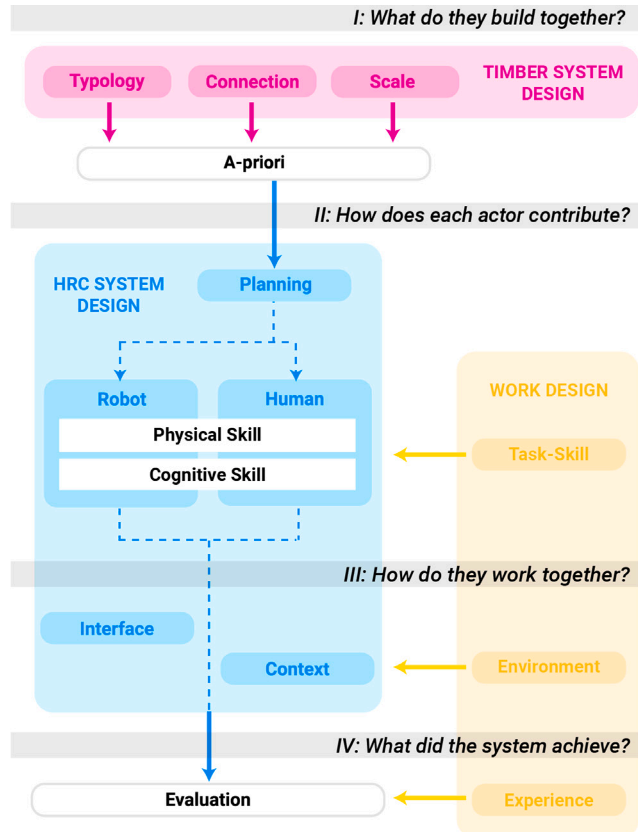


**Fig. 6.** Integrative conceptual framework for human–robot collaboration in timber prefabrication. The four guiding questions demarcate the design-, HRC system- and human-oriented parameters, denoted in pink, blue and yellow. Details on these parameters are provided in Tables 6 and 7.

## 5. Conceptual framework for HRC in timber prefabrication

By synthesising the results from the analysis, the authors propose a conceptual framework for human–robot collaboration in timber prefabrication (Fig. 6). The parameter groups depicted in the figure are annotated in detail with categories and guiding questions, as shown in Tables 6 and 7. The covered concepts are grouped under four main questions: *"I: What do they build together", "II: How does each actor contribute", "III: How do they work together"*, and *"IV: What did the system achieve"*. In the following sections, three proposed applications of the framework are first described, followed by an outline of HRC research scenarios where the framework can be used. Lastly, a summary of gaps in current research and potential directions for future work are presented.

### 5.1. Proposed application

The framework serves as an organising device to describe, guide, and generate hypotheses for future work in this area. As an illustration, it is applied to one of the surveyed projects — the BUGA Wood Pavilion [3,29,108].

#### 5.1.1. Description and organisation

First and foremost, the conceptual framework provides an integrative lens to describe the solution space of HRC in timber prefabrication. It adapts HRI taxonomies towards a design space definition and provides tailored parameters to describe the relevant processes and tasks. It also facilitates a more holistic understanding by connecting variables across different domains, representing perspectives from system,

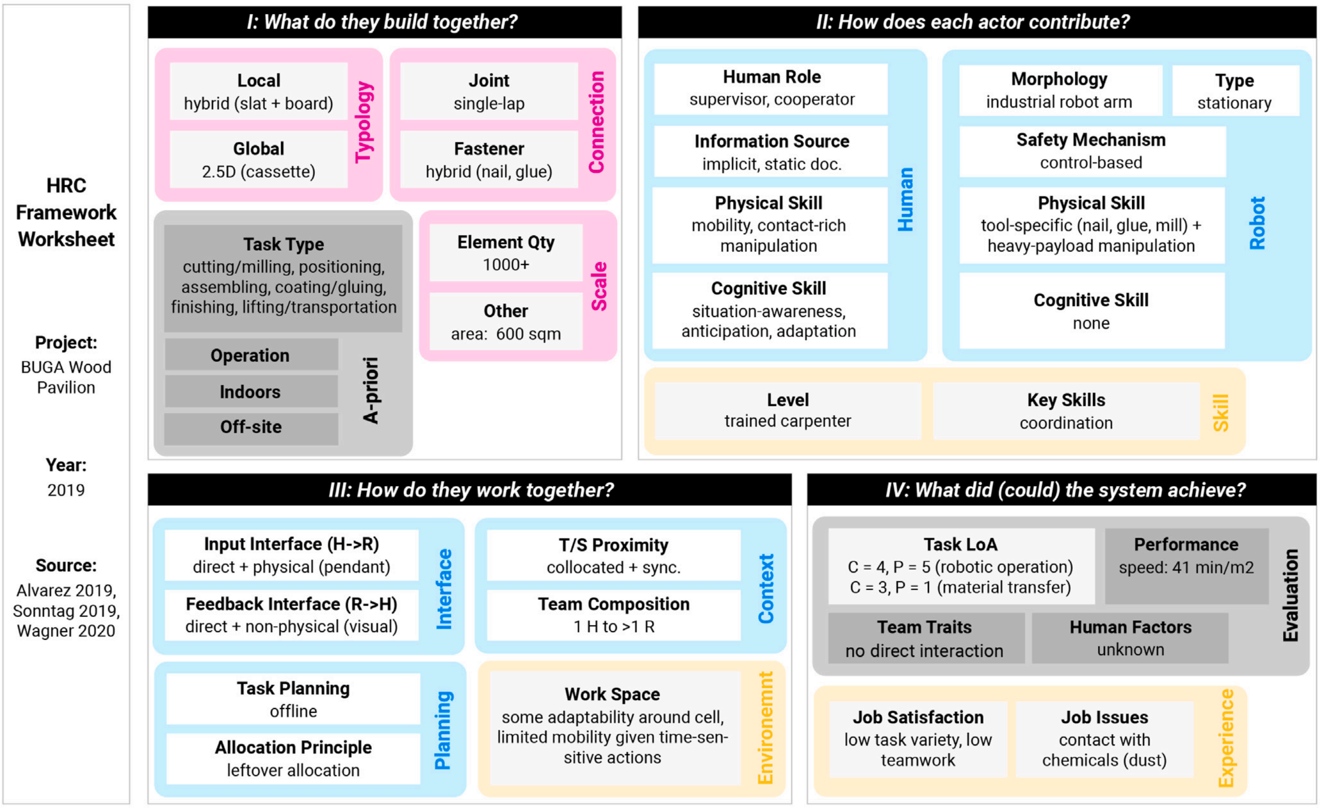


**Fig. 7.** Applying the conceptual framework to an existing project — BUGA Wood Pavilion [3,29,108].

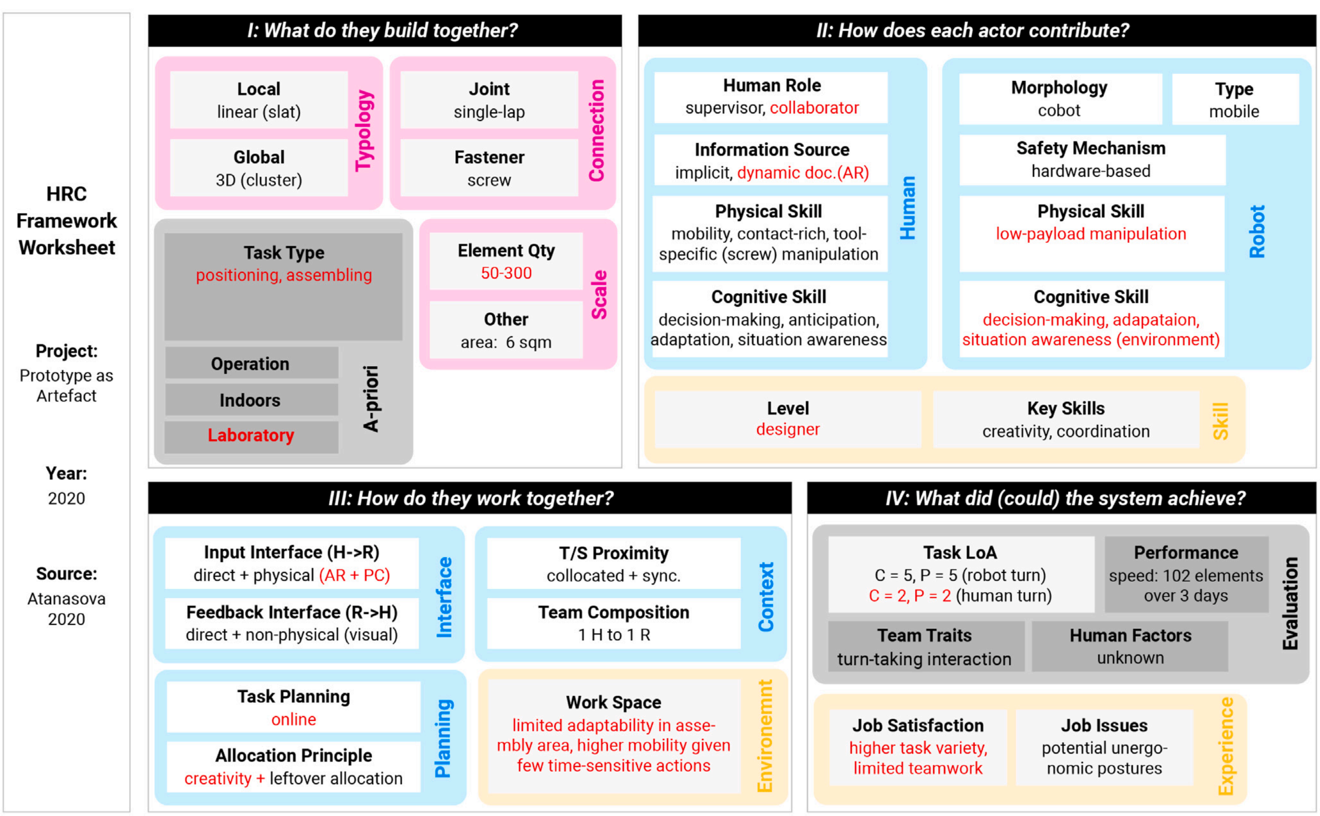


**Fig. 8.** Applying the conceptual framework to an existing project — Prototype as Artefact [92].

**Table 6**
Conceptual framework parameters (A-priori and evaluation).

| I: What do they build together? | | | |
|---|---|---|---|
| Group | Guiding question | Variable | Categorical values |
| Typology | What type of components are used? | Local | Linear (slat, beam, rod, lamella), planar (boards, thin sheets), hybrid |
| | | Global | 2.5D (cluster, cassette, slab, wall), 3D (cluster, truss, timber frame, facade) |
| Connection | How are the components connected? | Joint interface | None, single-lap, butt-joint, cross-lap, peg-in-hole |
| | | Fastener | Bolt, screw, nail, glue, hybrid, custom, none |
| Scale | How large/complex is the assembly? | Element quantity | Under 50, 50–300, 300–1000, over 1000 |
| | | Other | Square footage, element size etc. |
| A-priori | What type of tasks are they expected to accomplish? | Task type | Cutting/milling, positioning, assembling, marking, coating/gluing, recycling/disassembling, transportation/lifting, bending/shaping, finishing, monitoring, installation(service/facades) |
| | What is the overall production setup? | Setting | Laboratory, off-site, on-site |
| | | Training/Learning | Operation, training human, training robot |
| | | Robot location | Outdoor, indoor |
| **IV: What did the system achieve?** | | | |
| Group | Guiding question | Variable | Categorical values |
| Evaluation | What is the level of automation for the task? | Task LoA (cognitive) | 1: Creative improvisation, 2: Action selection, 3: Intervention, 4: Supervision, 5: Autonomy |
| | | Task LoA (physical) | 1: Purely manual, 2: Hand-held power tool, 3: Static machine, 4: Programmable machine, 5: Autonomous robot |
| | What performance metrics are achieved/required? | Performance | e.g. sqm/min, elements/day, mm tolerance |
| | | Team traits | Team and shared situation awareness, shared mental models, fluency and interaction efficiency |
| | | Human factors | Trust, ergonomics, mental workload, and situation awareness scales |
| Experience | What is it like for the humans involved in the process? | Job issues | e.g. contact with chemicals, postures |
| | | Job satisfaction | e.g. teamwork, task variety, the craft of building |

**Table 7**
Conceptual framework parameters (HRC design).

| II: What does each actor contribute? | | | |
|---|---|---|---|
| Group | Guiding question | Variable | Categorical values |
| Planning | How are the tasks planned and allocated? | Task planning | Online, offline, hybrid |
| | | Allocation principle | Leftover allocation, error correction and takeover, knowledge and creativity |
| Robot | What do the robots do? | Cognitive skill | Situation awareness (environment/ team/ goal), decision-making, motion-planning, adaptation, anticipation |
| | | Physical skill | Manipulation (contact-rich/ tool-specific/ payload-specific), mobility (3Dof/ 2Dof/ 1Dof) |
| | What kind of robots are involved? | Type | Stationary, mobile, wearable |
| | | Morphology | Robot arm, humanoid, zoomorphic, exoskeleton, swarm |
| | | Safety mechanism | Control, hardware, prediction, motion-planning, psychological factors |
| Human | What do the humans do? | Cognitive skill | (same categories as robot cognitive skills) |
| | | Physical skill | (same categories as robot physical skills) |
| | | Human role | Operator, supervisor, cooperator, collaborator, bystander |
| | | Information support | Static documentation, dynamic documentation, communication, implicit |
| Task-Skill | What type of human participants are expected? | Roles | Novice, craftsperson, master craftsperson, other (e.g. designer) |
| | | Key skills | Construction knowledge, teamwork. communication, coordination and management |
| **III: How do they work together?** | | | |
| Group | Guiding question | Variable | Categorical values |
| Context | How do humans and robots collaborate? | T/S proximity | Colocated + synchronous, colocated + asynchronous, non-colocated + synchronous, non-colocated + asynchronous |
| | | Team composition | 1 Human 1 Robot, >1 Humans 1 Robot, 1 Human >1 Robots, >1 Human >1 Robots |
| Interface | How do humans and robots communicate? | Input (H → R) | Indirect (prediction-based), direct + physical (pendant, control, haptics), indirect + non-physical (speech/gesture), multi-modal |
| | | Feedback (R → H) | (non) augmented + physical, non-physical (visual/audio), multi-modal |
| Environment | What is the production site layout? | Spatial constraints | Mobility, adaptability (within job), adaptability (between-job) |

design, and human standpoints. This provides a descriptive tool to analyse existing studies and aids the comparison and evaluation of future research.

Fig. 7 shows the framework applied to the example project [3,29,108]. The majority of physical skills related to prefabrication were already delegated to the robot, and the human was in charge of final finishing, cleaning, and material transfer tasks that relied on mobility, contact-rich manipulation, and higher-level coordination skills. In comparison to another project [92] the difference in the HRC approach can be seen highlighted in red in Fig. 8. The robotic actors in the BUGA project had few cognitive skills and used offline planning to ensure predictable run-time behaviour. Because the fabrication was carried out in an industry off-site environment, the human participants were trained carpenters and the process placed little emphasis on creative inputs from the human.

#### 5.1.2. Guidance on study design and evaluation

Second, the framework can offer design guidance for new HRC studies by (1) providing a matrix that reveals a set of key variables for designers to consider and improve upon, and (2) informing the organisation and collection of data and providing a richer lens for evaluation. At the moment of writing, there is little quantitative data connecting the different parameters. However, as more data accumulate, findings from past studies can be tapped for evaluation and prediction, e.g., by integrating the framework into a computational design tool. These data-enriched frameworks have been demonstrated in existing co-design research [109,110] and could help teams evaluate the fabrication setup across both conventional productivity metrics as well as human-centred considerations.

In the reference project (Fig. 7), for instance, the HRC design team could use the framework to question how the setup can be improved when considering the workspace requirements and job issues for the craftspeople involved. The exposure to milling dust (which periodically required manual labour to clean up) and the lack of an integrated communication channel (which meant the person had to wait around the cell until the robot was finished) may be remediable through digital interface technologies. Although the project provided a thorough evaluation of *task performance* metrics [3], there was no report on human factors and team traits, which makes it difficult to evaluate the joint human–robot system.

#### 5.1.3. Hypothesis generation

Last but not least, the framework could serve as a blueprint to generate hypotheses for future research. The integrative aspect enables these enquiries to cross domain boundaries and facilitate co-design and co-evolution between HRI research and the human- or design-centred aspects of timber prefabrication. In other words, the framework can be used as a generative tool for interdisciplinary teams to explore new ideas and hypotheses. An example combining the HRC and design concerns could be — would the construction of two identical structures with different jointing methods (therefore different structural performance) affect the interaction fluency of a novel communication interface (since the task characteristics are different)?

For the reference project in Fig. 7, team members in charge of the HRC system design could, for instance, propose an alternative study by hypothesising that the skill level of the human worker has a positive or negative correlation with collaborative task performance. Since experience levels might affect not only the distribution of attention and timeliness of response but also the level of acceptance and information needs, the findings from following this line of thinking could point towards more informed and diverse choices for human labour in future projects.

### 5.2. Usage scenarios for application and research

Since HRC is a highly interdisciplinary topic, project goals and focuses often vary depending on the research context. The application of the framework may differ in these cases, for which three key scenarios (Fig. 9) are outlined below and illustrated with references from existing literature. Notwithstanding some research may be a hybrid among the three, in each case, the framework serves as a tool to inform, contextualise, and reflect on the design and evaluation of human–robot collaboration for timber fabrication.

- *Technology-driven*: This scenario describes the bulk of HRI research where novel technological components are developed and tested in an HRC case study, e.g., new control mechanisms [72] or human-machine interfaces [111]. The framework can be applied to validate the applicability and inform more holistic evaluations of the proposed technical solutions. This could take the form of questions such as — how well does the study's task design exploit the strength of the technical system, and facilitate under-explored design parameters (e.g., challenging element typologies or joint conditions)? What are the strengths and weaknesses of the solution with regard to the needs of the humans (e.g., skill profiles, communication and mobility requirements)?
- *Design-driven:* In the AEC community, research in robotic construction is sometimes design- or project-driven, where the HRC system is subservient to the overarching purpose of producing a novel design, component or building [29,112]. Since most fabrication processes inherently require cooperation between humans and robots, it is possible to more explicitly address the allocation and combination of roles by leveraging the framework to find appropriate parameters for the production setup. Even projects where HRC is not an explicit goal might benefit from considering some parameters as a checklist to inform a more human-centred design approach.
- *Worker-driven*: When HRC procedures are developed to improve task performance, ergonomics, or job satisfaction of the human operators, the scenario can be considered user- or worker-driven. This approach is rather common in research on teleoperation interfaces [113,114] and assistive robots such as robotic exoskeletons [115], where the needs of the human operator are of primary concern. The framework can inform the broader user context and provide contextualisation, e.g., to examine the range of design possibilities or identify key tasks in which the proposed system is applicable.

### 5.3. Challenges and opportunities for HRC in timber prefabrication

Finally, the framework pointed out some under-explored areas for future research by connecting three interrelated domains.

In the HRC design space, cognitive robotic skills such as environment awareness and adaptation were tested in many studies, but skills such as team awareness, goal awareness, and anticipation were not developed. Modelling the robotic execution loop in a way that allows for these higher-level representations of the fabrication task is an interesting area that could open up novel teamwork and task-sharing procedures. Control-based safety mechanisms are the dominant mode for HRC with large industrial robots, leaving many flexible mechanisms unexplored, which are important to move collaboration in heavy-payload scenarios to real-world deployment. Articulated arms are the sole typology found in the surveyed studies. Including more diverse morphologies, such as groups of smaller machines that currently communicate with each other but not yet with other humans, could expand the collaboration potential and task diversity. Human skills leveraged in current research demonstrate the flexibility of humans and their versatility in a wide range of tasks. However, cognitive contribution befitting the knowledge of skilled craftspeople rather than that of designers is

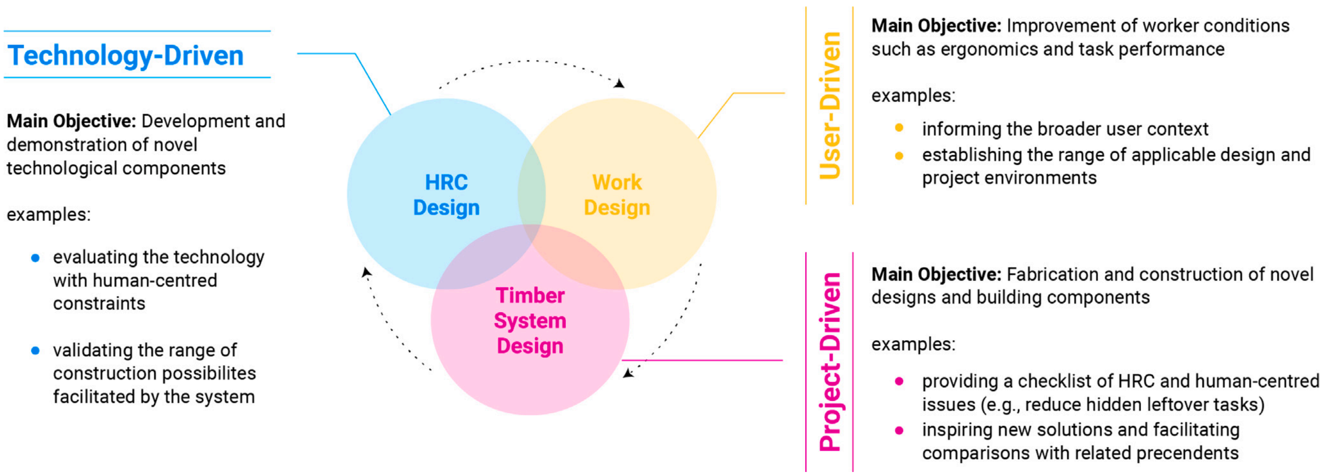


**Fig. 9.** Application scenarios for design guidance using the conceptual framework.

still an open question. Novel communication interfaces such as AR have been used as input mechanisms, but most HRC studies do not explicitly address the feedback interface or information support for operators. This leaves significant gaps in understanding the experience of humans in digital fabrication processes and human factors of the fabrication procedure in general.

By linking the HRC design space with the parameters of the timber system design space, one can consider the co-evolution of possibilities in both domains. Contact-rich manipulation enables more design freedom in joint types and connection methods. However, large-scale (both in terms of robot payload and number of repetitions) procedures that could support their implementation in timber construction are still rare, although employing distributed machines together with robotic arms has shown promising results to address this [75]. The global typologies of the timber structures focused primarily on 2.5D clusters which stack the elements. Stepping out of the range of these assembly logics and embracing more novel design typologies could perhaps diversify the HRC setups and uncover new modes of collaborative timber construction.

By connecting the practical perspectives of human labour with the HRC design space, human-centred constraints can be also considered. Skilled craft, beyond the knowledge of materials and tools, includes an implicit body of construction knowledge (the ability to "think inside of a building"). The challenges of cultivating (for apprentices) and furthering (for more experienced workers) such craft is a consideration little explored in task allocation strategies, as prefabrication favours information systems that capture both high and low-level details of an assembly process. The teamwork and high communication demands of a carpenter's work environment also call for HRC parameters that embrace collectiveness and high flexibility, for instance through non-dyadic team compositions and more diverse T/S proximity. The promise of robotics liberating craftspeople from "dull, dirty, dangerous" tasks [106,107] could only be possible if a wider range of robot skills are developed for manipulation demands used in these unpleasant tasks (e.g., soft insulation material or chemical applications). Last but not least, it is an interesting challenge to consider systems designed not only to reduce drudgery or enhance execution capacity but also to augment the *joy of building* inherent to the profession itself.

## 6. Discussions and outlook

In summary, this research proposes an integrative conceptual framework by triangulating human-, system-, and design- factors in robotic timber prefabrication. In the design science literature, conceptual frameworks provide a way of *knowing, framing, and designing* for a particular problem [116]. More concretely, the proposed framework provides a holistic lens to reveal the **challenges and potential of HRC in timber prefabrication** and guides future designers and researchers to **describe, evaluate, and generate** HRC designs. In this last section, concluding thoughts on the limitations of this research and proposals for future work are described.

### 6.1. Limitations

There is a growing number of studies around human–robot collaboration in the AEC context. To capture the factors related to timber construction, the data collection methods and literature review criteria are focused on studies that explicitly make use of wood. This is necessary for finding data points that connect these two areas but might have missed out on important HRC contributions and strategies. Automation design for the industry also needs to consider the organisational design space, where the requirements of the enterprise and business context are incorporated [12]. This perspective is not included as it requires multiple, cross-referenceable data points from industry, which were not tenable in this research.

The worker interviews have a small sample size (N = 6) and the participants are sourced from a single medium-sized timber construction company in Germany. Despite the varied demographics of the interviewees, this somewhat limits the diversity of human-centred perspectives. Future work could build upon the initial findings with a larger sample size and potentially include quantitative methods [85].

Existing HRC studies do not yet cover the whole range of design typologies relevant to timber prefabrication. As more research becomes available, relevant design parameters in this area will expand and the connections between the design and HRC fabrication space can be strengthened. Similarly, as advancements in robotics, AI, and human-machine interfaces evolve, the current HRC design space formulation would likely need to be improved.

On-site construction and prefabrication are closely linked due to the tight process integration required in prefabricated construction. Therefore prefabrication cannot be considered in complete isolation from on-site processes. This is also obvious from the carpenters' perspective as most do or have worked in both environments. On-site robotics are increasingly deployed for construction tasks, and how can the framework adapt to incorporate unique requirements of the job site and connect prefabrication and on-site construction is an important consideration but out of the scope of this research.

Though the framework is focused on timber, the majority of building methods in the construction industry utilise other material systems such as masonry and concrete. Bricklayers and concrete workers far exceed the number of carpenters in Germany [40]. Each skilled craft profession has its unique job profiles and each material system its unique design parameters. It is difficult to generalise the findings on human–robot collaboration in construction at large. However, for future studies, the development of this framework can hopefully provide a methodological reference.

### 6.2. Outlook

More than a decade ago, concepts like production-immanent design [117] emphasised the integration of robotic fabrication into computational design. Since then a vibrant community of researchers has developed ecosystems of robotic fabrication tools which were then made available to architects and designers to democratise the access and advancements of digital fabrication research (e.g., COMPAS, HAL, KukaPRC). This enabled novel design possibilities for materially efficient and fabrication-aware structures that contribute to ecological sustainability challenges faced by the construction industry through innovative, resource-aware design solutions.

An expansion of this toolbox to include human-centred concerns may be appropriate in the near future. On the one hand, robotic fabrication is moving ever closer to real-world deployment [118,119] where these systems must be embedded in human work environments and account for socio-economic factors. On the other hand, strategic initiatives like Industry 5.0 and SDG 8 (Decent Work and Economic Growth) call for urgent attention to issues of social sustainability to foster the health of the workforce and society [6,7]. These require considerations of the impact of technologies on the need for upskilling or reskilling. How robotic fabrication research will evolve to meet these challenges is an interesting question.

An attempt to answer this question likely requires interdisciplinary efforts from many perspectives and teams from HRI, human factors, and social sciences along with architects. Rossini and Porter distinguished three levels of integration in interdisciplinary research — externally linked disciplinary analyses, externally and internally linked analysis where each discipline provides substantive input to another, and an overarching theoretical framework [120]. Moving from an integrative framework to a truly interdisciplinary one requires much more future work to refine and deepen the connections mentioned above. The authors hope to contribute this framework towards these interdisciplinary efforts to create more holistic and human-centred designs of automation in construction.

## CRediT authorship contribution statement

**Xiliu Yang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration. **Felix Amtsberg:** Funding acquisition, Supervision, Validation, Writing – review & editing, Project administration. **Michael Sedlmair:** Methodology, Supervision, Writing – review & editing. **Achim Menges:** Funding acquisition, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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