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RESEARCH

Designing for diversity: a feminist technoscience and behavioural fabrication approach in human–robot collaboration education for Industry 5.0

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Abstract
This research addresses the gap between technical advancement and human factors in human–robot collaboration (HRC) education for digital fabrication. Current pedagogical approaches predominantly focus on technological capabilities while neglecting critical aspects of user diversity, accessibility, and contextual adaptability essential to Industry 5.0 implementation. We present a human-centered HRC design methodology integrating feminist technoscience (FTS) dimensions with behavioural fabrication techniques. The framework consists of three components: (1) an FTS framework and framework to guide and evaluate HRC design; (2) a cyber-physical system enabling real-time sensor-driven robot behavior; and (3) a modified Double-Diamond Approach (DDA) that systematically guides students through creative processes, for iterative design. The methodology was tested through a four-day workshop with graduate architecture and engineering students, who developed four distinct HRC workflows incorporating voice control, gesture recognition, computer vision feedback, and multilingual interfaces. Using the FTS rubric, we observed that students were able to translate abstract concepts—such as user diversity, agency, and bias—into concrete design decisions, despite limited prior experience in robotics or feminist critique. These outcomes suggest that the integrated approach effectively supports students in addressing practical HRC challenges while remaining attentive to the social and ethical dimensions of automation. This work contributes a reproducible methodology for preparing future practitioners to design HRC systems that are technically robust while remaining responsive to user needs, thereby advancing the transition from Industry 4.0 to 5.0 priorities.
This paper opens with a theoretical foundation situating Industry 5.0 goals within human–robot collaboration (HRC) in construction and introduces feminist technoscience (FTS) as a critical framework. Chapter 2 presents the state of the art in HRC research in prefabrication and construction, and the researchers' previous work: an FTS framework and behavioural fabrication. The following chapters 3 and 4 describe the research's objectives, and outline a methodology integrating the FTS framework with behavioural fabrication through a modified Double-Diamond Approach (DDA). Chapter 5 describes the workshop used to test the methodology, culminating with our research hypotheses. In chapter 6, the resulting student-developed HRC workflows are described and evaluated using the FTS framework. This paper concludes with a discussion of methodological insights in Chapter 7; design implications, and future directions for inclusive HRC education and practice in chapter 8.

Keywords Human–robot collaboration · Feminist technoscience · Behavioural fabrication · Collaborative robots · Agent-based modeling

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1 Introduction

1.1 Human-Centric Fabrication in the Era of Industry 5.0

Construction automation faces a persistent challenge: the sectors' urgent need for increased efficiency, reduced carbon footprint, and waste calls for automated solutions, but those proposed lack a human-centered approach and deployment. Industry 4.0 promoted automation with cyber-physical, IoT, and AI foundations (Liaoa et al. 2017), yet exposed gaps in workforce integration, environmental stewardship, and resilience (Inkulu et al. 2021). Consequently, Industry 5.0 now recasts automation around people and planet, mandating technologies that amplify human agency, cut ecological impact, and withstand uncertainties (Breque et al. 2021). At its core, Industry 5.0 advances human–robot collaboration (HRC): collaborative processes where humans and robots work together to achieve shared tasks (Grosz and Kraus 1996), sharing plans and mutually beneficial interactions (Thomson et al. 2007). By Industry 5.0 vision, HRC leverages technology to enhance user capabilities rather than replace them, and creates complementary systems that optimize machine efficiency and practice expertise (Marino et al. 2023). In construction, where craft knowledge and uncertainties challenge full automation, HRC offers the necessary hybrid of robotic precision and human adaptability.

1.2 Human–robot collaboration (HRC) in construction

HRC leverages the complementary strengths of humans and robots: human creativity and adaptability alongside robotic precision and endurance (Liang et al. 2021). Taxonomies classify collaborative systems by dimensions such as interaction timing and proximity, autonomy levels, task allocation, and communication modes, from direct interfaces to sensor-based gestures and speech (Mukherjee et al. 2022; Liang et al. 2021; Thoma et al. 2019; Chandrasekaran and Conrad 2015; Schulz et al. 2018).

Automated processes in construction, including HRC, have evolved from fixed robotic tasks (Warszawski 1984; Bock 2015) to flexible multi-tool systems (Gramazio et al. 2014; Chen et al. 2018; Melenbrink et al. 2020; Mitterberger 2023). These may include industrial robots, collaborative robots ("cobots"; smaller robotic arms designed for safety), extension axes or rovers; using AI, real-time sensing and adaptive control (Thomaz et al. 2016; Javaid et al. 2021; Kim et al. 2024; Semeraro et al. 2023; Zhang et al. 2023).

1.3 HRC adoption in the construction industry

In spite of these advancements, adoption remains limited due to three persistent challenges. First, HRC's success hinges on user acceptance, sense of safety, and trust in robots (Schelenz 2023; De Simone et al. 2022). Users struggle with opaque or unpredictable robot behavior (Correia Simões et al. 2022), fear of job loss (Walzer et al. 2022), and as a result, reject automation (Kumar et al. 2021). A view of robots as safe and trustworthy is affected by culture (Bröhl et al. 2019) or position as stakeholders (Wu et al. 2024). Second, misrepresentation of site and task: designers assume static or idealized settings rather than dynamic environments, and design for assumed needs (Grangeot et al. 2024; Ron et al. 2024a, b), leading to irrelevant design solutions in HRC (Bardzell 2010). Such a mismatch between tools and task and/or environment may lead to increased user workload (Müller et al. 2018; Weiss et al. 2021; Kumar et al. 2021). Third, accessibility to diverse users. A challenge in automating constructions is the workforce's unfamiliarity with robots and coding. So-called intuitive interfaces rarely address diverse user needs or include end-users in the design process (Wagman and Parks 2021), which can lead to anxiety (Murashov et al. 2016; Bröhl et al. 2019; Weiss et al. 2021) and fall short of Industry 5.0's human-centric aims (Burden et al. 2022; Breque et al. 2021; Wu et al. 2024). This can be traced back to lack of bias awareness, participation and feedback in the design and research process (Bardzell 2010; Rosner 2020; Ron et al. 2024a)

The persistent obstacles to HRC adoption highlight the need for design approaches that move beyond technical novelty, and incorporate reflexive methods: reflecting on user needs, site realities, and prioritizing human experience at the core of robotic integration. There is a pressing need to educate and equip future professionals to design collaborative systems that are intelligent, inclusive, adaptive, and grounded in real-world construction practice. The question remains—how?

1.4 Education for Industry 5.0

A crucial gap exists in preparing future Industry 5.0 professionals to design responsive systems that address users' practical needs in the construction industry. Engineering and architecture schools, which lead most research on automation and HRC in construction, are educated to combine domain expertise with digital literacy, in a research-driven instruction and hands-on experimentation (Brell-Cokcan and Braumann 2013; Gramazio et al. 2014; Benneworth et al. 2017; Knippers et al. 2018, 2021;

Reinhardt and Haeusler 2024), fostering technical proficiency and exploration of novel methods. Despite its interdisciplinarity, this approach often overlooks human-centered design, like ethics and user feedback, and critical reflection on technology's role in shaping practice (Irizarry et al. 2010; Colella et al. 2024; Ron et al. 2024b).

To cultivate future Industry 5.0 professionals for human-centric HRC in this context, curricula should offer critical reflections of design and design processes: relevance, accessibility, power dynamics, biases, user feedback, and its implementation.

1.5 Introduction to feminist technoscience

HRC for the construction industry and its design processes can benefit from feminist technoscience (FTS) insights. FTS is a trans-disciplinary field rooted in feminist philosophy, and the philosophy of science and technology (Gearhart 1979; Collective 1971; Ortner 1974; Piercy 1976; Winner 1980; Harding 1986; Traweek 1988; Lykke and Braidotti 1996; Fox et al. 2006; Barad 2007; Loh 2019). It critiques technology and the design of technological tools, focusing on power, representation, accessibility, biases, safety, and trust (Haraway 1988, 1991, 2016; Suchman 2002; Wajcman 2004; Keeling 2019; Hester 2018; Rosner 2020; Benjamin 2020); its effcts on society (Ahmed 2006; Keeling 2019; Benjamin 2020; D'Ignazio and Klein 2020; Rosner 2020; Hester 2018), and the environment (Haraway 2016; Crawford 2021).

1.5.1 Bias and situated knowledge

FTS offers a critical and practical lens that can enrich HRC design and education, reviewing designs and design processes for biases, situated knowledge, and inclusion. Bias, a deviation from objectivity, is understood as a product of epistemic hierarchies, often white, male, Western, and "expert"—over "others" (Harding 2015). "Situated Knowledge", a complementary term, argues that all knowledge is partial, embodied, historically located, shaped by the "Knowers" positions (Haraway 1988). Recognizing knowledge as situated does not undermine its validity, but holds it accountable to the material and social conditions in which it is produced. These terms are used to challenge the superiority of scientific knowledge over lived, embodied experiences and expertise, and challenge the technologies produced by these scientific endeavors and institutes, embodying the values and biases of its creators, often reinforcing existing gender inequalities (Wajcman 2004).

1.6 Feminist technoscience in design

> "Design does not simply create objects; rather, it configures relationships between people and things, human and nonhuman actors, reconfiguring social and material arrangements."
> — Daniela K. Rosner, *Critical Fabulations: Reworking the Methods and Margins of Design* (2020).

FTS critique of technology is relevant for an equitable design process and designed product: acknowledging embedded biases (Winner 1980; Wajcman 2004), including user participation feedback (van de Poel 2016; Chilvers and Kearnes 2020), and reviewing designs' accessibility, and its impact on individuals, society, and the environment (Winner 1980; Åsberg and Lykke 2010; D'Ignazio and Klein 2020; Ahmed 2006; Harding 2015; D'Ignazio and Klein 2020; Rosner 2020; Hester 2018).

FTS perspectives, fostering an activist approach and ethical practices, are applied in various design fields. In architecture and design, this includes a review of power dynamics, diversity, and imposed gender roles in architecture and design (Frichot et al. 2017; Hayden 1981; Wajcman 1991; Boys 2017; Hamraie 2016; Imrie 2012). In human-computer and human–robot interaction (HCI, HRI), reviewing embedded biases (Friedman and Nissenbaum 1996; Schelenz 2023; Wagman and Parks 2021), and diverse user needs (Suchman 2007; Bardzell 2010; Schelenz 2023). All aforementioned acknowledge the importance of situated knowledge and feedback and encourage users' meaningful participation in the design process (Jacobs 1961; Bardzell 2010; D'Ignazio and Klein 2020; Rosner 2020; Schelenz 2023).

1.7 FTS relevance for HRC in construction

FTS's relevance to HRC in construction is its' focus on human experience and application across design and technology fields. In this context, FTS highlights the importance of designing systems that are responsive to uncertainties, attuned to situated user knowledge, and inclusive of diverse participants.

Following Lucy Suchman's call for accountability to "real-world contexts" (Suchman 2007), HRC systems must respond to dynamic site conditions (such as lighting, noise, movement), and maintain task and user relevance, affecting performance, communication, and user safety.

Equally critical is the recognition of users' situated knowledge and lived expertise. Construction workers bring a tacit understanding of tools, materials, and workflows. FTS advocates valuing this knowledge and incorporating feedback early in the design process to ensure technologies are trusted (Bardzell 2010; Rosner 2020).

This is especially vital in construction's diverse workforce, which spans variations in language, education, digital literacy, and technology affinity (Organization 2016, 2024; Draxler et al. 2023; Desjardins and Warnke 2012; Hanushek et al. 2024). These differences must be reflected in interface design, system flexibility, and training practices.

FTS thus supports participatory, inclusive design practices that acknowledge social context, promote accessibility, and embed ethical responsiveness into technical development. Drawing on these insights, we propose an FTS-informed method for sensitizing designers to user diversity, uncertainty, and embodied expertise. This approach centers user experience and task relevance in collaborative robotics, aiming to make HRC for the construction industry not only technically robust, but socially attuned and ethically grounded. In the context of educating the next generation of Industry 5.0 professionals, i.e., future designers of HRC for the construction industry, FTS has merit in introducing students to acknowledging biases, assessing design for its adequacy, and incorporate participation and feedback.

2 Related work

This section introduces previous work in HRC for the construction industry, an applicable FTS framework informing HRC design and behavioural fabrication for responsive HRC- an approach to digital fabrication and construction automation.

2.1 HRC research in prefabrication and construction

Current trends in research approach robots' adaptive behavior, accessibility, and users' well-being (Thomaz et al. 2016; Chen et al. 2018; Murashov et al. 2016). This correlates with sector-specific needs such as unpredictable site conditions and material variability, craftsmanship and tacit knowledge, labor-intensive workflows, and user safety (Brell-Cokcan and Braumann 2013; Melenbrink et al. 2020; Yang et al. 2024; Li et al. 2023).

Robot's adaptive behavior can improve efficiency and uncertainty-response, using sensing for task progression, site, and materials conditions (Cherubinia and Navarro-larconb 2020; Jang et al. 2023; Grangeot et al. 2024). Machine learning (ML) and reinforcement learning (RL) further enhance robots' capabilities for dynamic responses (Semeraro et al. 2023; Vecerik et al. 2017; Schulz et al. 2018), in training robots in simulation and real life (Brugnaro and Hanna 2018; Xie et al. 2020; Nicholas et al. 2020; Apolinarska et al. 2021; Kramberger et al. 2022; Sardari et al. 2024). Shifting from hard-coded robotics to sensing coupled with AI promotes adaptive behavior and local decision-making. Such tools and algorithms, however, require fallback mechanisms to ensure successful performance despite machine errors (Suchman 2007; Weiss et al. 2021).

Accessibility in robotic fabrication is often regarded as on-demand control by the average user, assumed to possess low familiarity with digital tools. Research on the topic advances intuitive interfaces including in AR (Kyjanek et al. 2019; Betti et al. 2020; Amtsberg et al. 2021), haptic (Kramberger et al. 2022; Gong et al. 2023) and speech (Han and Parascho 2025); AR and wearable devices for multi-user task coordination (Vasey et al. 2016; Atanasova et al. 2020; Yang et al. 2022, 2023), and design improvisation (Doerfler et al. 2013; Mitterberger et al. 2022; Han and Parascho 2023). While promoting technological advancements, these approaches to accessibility remain superficial, lacking genuine user involvement and meaningful feedback—failing to fulfill the European Commission's emphasis on digital literacy development in the HRC workforce (Breque et al. 2021).

Well-being in HRC encompasses both physical and mental dimensions, including safety, comfort, trust, and job satisfaction. Research in this area includes safe path planning and proximity sensing for physical safety (Correia Simões et al. 2022; Kim et al. 2021), as well as tuning robot motion and control to reduce cognitive strain and enhance users' sense of security (Zhang et al. 2023; Saeidi and Wang 2019). Some approaches adapt robot timing or motion style to align with human behavior, further supporting user comfort (Baltrusch et al. 2021). However, these considerations often remain peripheral in technical HRC research.

Unlike adaptivity and accessibility, which are central concerns in engineering, architecture, and computer science, well-being is more commonly studied in the social sciences, psychology, and science and technology studies (STS). This disciplinary divide limits the integration of embodied user experience, power dynamics, and cultural context into technical HRC design. Bridging this gap is essential to ensuring that robotics systems for construction are not only functionally effective, but also inclusive, accountable, and responsive to the realities of diverse workers. To address this need, the following section introduces a practical framework grounded in feminist technoscience (FTS), offering a lens and a method for critically rethinking HRC design in ways that center user diversity, lived expertise, and social context.

2.2 FTS framework

To link feminist critique with HRC in prefabrication and construction, we introduce a practical FTS framework: an assistive tool, prompting designers to be mindful of design relevance, diverse user needs, power structures, and biases, incorporated into or resulting from design decisions (Ron et al. 2024a, b).

Previous feminist frameworks have shaped HCI and HRI design in different ways. Young's Feminist Design Tool

(2020) targets interaction design for AI agents and chatbots, using reflexive questions across the design lifecycle to address stakeholder representation, bias, team assumptions, and environmental impact (Young 2020). Winkle et al. (2023) build on Bardzell (2010) and D'Ignazio and Klein (2020) to propose feminist principles for HRI that challenge power structures, support pluralism and situated knowledge, and promote user agency and safety.

The framework presented here is adapted from the author's previous work Ron et al. (2024a, b). It is an assemblage of FTS and Science and Technology Studies (STS) theory, composed of four dimensions: Embodiment, Reconfiguration, Interrelations, Participation and Reflection. Each dimension is coupled with four reflexive questions to guide and evaluate HRC. The framework as a critical tool is described in Sects. 4, and 6.

2.2.1 Embodiment

Embodiment for HRC design draws attention to diverse bodies, genders, ages, and their needs and preferences, when designing interaction, collaboration, and their supporting interfaces (Bardzell 2010; Ahmed 2006; Rosner 2020; D'Ignazio and Klein 2020; Hester 2018; Keeling 2019). Embodiment encourages "artful integration"—adjustable design solutions that “embrace heterogeneity and local adaptability over uniform solutions” and universal design (Suchman 2007; Rosner 2020). Adjustable tools for HRC can include adjusted displays, sensors, auditory devices, physical devices like wearables or furniture, and modes of robotic operation like speed, duration, and proximity range.

Embodiment: Reflexive Questions

1. Were the current users, their strengths, barriers, problems, concerns, and needs accounted for?
2. Was user well-being considered beyond task success?
3. Does the design fit diverse bodies, intelligences, and perceptions?
4. Were users' needs of safety and trust accounted for?

2.2.2 Reconfiguration

Reconfiguration, as explored in Lucy Suchman's Human–Machine Reconfigurations (Suchman 2007), examines whether technologies empower people or contribute to them losing skills and agency. When designing and reviewing HRC design, it prompts reviewing tools, interfaces, and processes for their capacities and limitations, and the actions they enable or disable (Suchman 2007), for matching site and work conditions (Suchman 2007; Rosner 2020), for inclusions of professional experience and user preferences (Haraway 1988; Bardzell 2010), and for maintaining relevance across changing conditions and uncertainties (Suchman 2007; Bardzell 2010), to complete a task successfully.

Reconfiguration: Reflexive Questions

1. Were all interfaces, tools, and procedures proposed accounted for the actions and choices they enable and disable?
2. Do they fit with the task, environment, routine, and diverse users?
3. Do they assist in solving real, and not assumed, challenges?
4. Do they remain relevant and useful across changing conditions?

2.2.3 Interrelations

Interrelation is a concept used in HRI, adapted from STS and Actor-Network Theory (ANT; "relational practices") (Latour 2005), sees all participants (human and non-human, like robots, sensors, computers, materials, environment, etc) as interacting "agents" in a dynamic system, all capable of actions and mutual effects. Interrelations account for their mutual effects, illuminating dynamics, shared agency and power: collaboration, augmentation, dependency, control, etc. Relevant to HRC, where operations are mediated by tools and software, this allows a scrutinized view of changes and interdependencies between participants, tools, interfaces, and processes in relation to one another: how roles and responsibilities are distributed, interobjectivity is managed, and which interdependencies arise (Haraway 1988; Ahmed 2006; Suchman 2007; Bardzell 2010; Åsberg and Lykke 2010).

Interrelations: Reflexive Questions

1. Were all humans and non-humans participating considered for their characteristics, tasks, needs, and co-productive potentials in HRC?
2. Does the task distribution fit with the humans' and non-humans' characteristics, strengths, needs, and co-productive potentials?
3. Do they augment each other in positive ways?
4. Which new relationships and power structures are emerging as a result of using the new interfaces, tools, and procedures?

2.2.4 Participation and reflection

Participation promotes users' meaningful involvement in the design process to enhance HRC inclusivity, usability, and acceptance. It reflects on design decisions' relevance (Wajcman 2004; Suchman 2007; Bardzell 2010), and can acknowledge stereotypes and biases embedded into the design (Winner

1980; Haraway 1988; Ahmed 2006; Harding 2015; Keeling 2019). A design guided by user feedback early on is more attuned to practice-needs (task specification, routines, and tools), user needs and well-being, and their feelings of safety and trust (Åsberg and Lykke 2010; Bardzell 2010). Testing with diverse users prompts more accessibility (Rosner 2020). Equally important is the participatory process itself, ensuring a safe, transparent and accessible participation process, employing critical reflection on how participation is performed (sequence, power dynamics), and analyzed (van de Poel 2016; Chilvers and Kearnes 2020).

Participation and Reflection: Reflexive Questions

1. Was diverse feedback collected? Were stakeholders accounted for in their expertise and needs?
2. Was feedback properly analyzed and included in the design process?
3. Did the designers/researchers account for their assumptions and biases?
4. Was the design process visible, inclusive, and self-reflective?

2.3 Behavioural fabrication

Behavioural fabrication is an approach to robotic automation where robots are not just programmed with predefined tasks or sequences, but respond dynamically to real-time conditions, materials, and environmental inputs during the construction process. It uses mixed reality, sensors, and AI (Menges 2015). Data collected in the fabrication process is utilized to inform future steps in the fabrication process. Robotic programming involves the development of behaviors that process this collected data and relate it to specific robotic outcomes rather than the definition of instructions for the robot to follow. In the context of construction, behavioural fabrication has been implemented for the materialization of woven architectural structures (Brugnaro et al. 2016), in the design and fabrication of 3D printed structures (Stuart-Smith et al. 2020), and in the exploration of robotic swarms in assembly processes (Leder and Menges 2023).

In this research, behavioural fabrication is used as an approach for considering how to augment a robot with behaviors in an HRC process. Information from the current state of the assembly process, the environment, as well as information from the user, is utilized to affect robotic trajectories. Responding to a user is achieved by equipping the robots with behaviors.

3 Objective

This paper presents a human-centered, feedback-driven HRC design methodology aimed at the next generation of Industry 5.0 professionals who design for the construction industry. The proposed method integrates the FTS framework and behavioural fabrication techniques to systematically discover, define, develop, and deliver collaborative assembly processes.

The methodology cultivates awareness of the challenges inherent in human–robot collaboration and automated fabrication by encouraging direct, hands-on engagement. Design work begins with active participation in and observation of HRC tasks, prompting critical reflection on the difficulties encountered. This experiential foundation supports the development of inclusive, task-relevant design responses, which are iteratively refined and tested through collaboration with diverse participants.

The effectiveness of this approach was evaluated through a workshop involving master's level students. Their experiences and outcomes form the basis for the analysis presented in this paper.

Key contributions of this paper are:

1. *A Novel Approach to HRC Education Using FTS*: This paper introduces a unique pedagogical approach to HRC

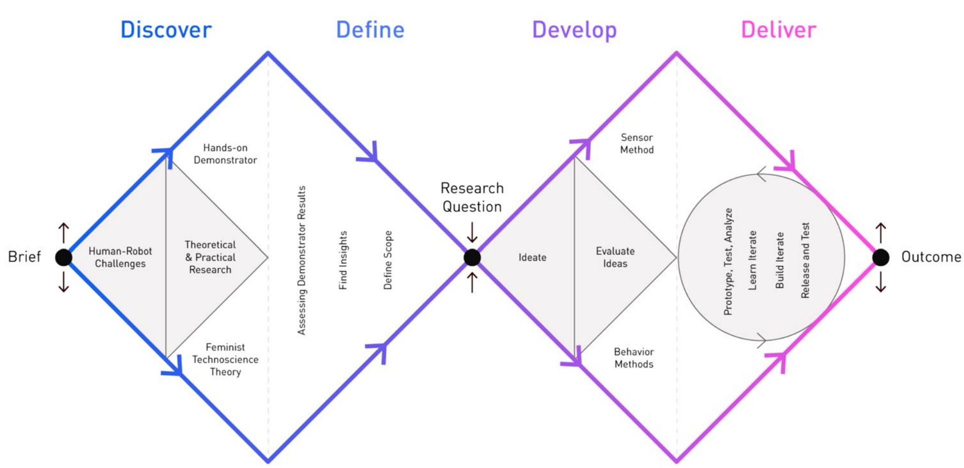

Fig. 1 The Double-Diamond Approach (DDA) (Council 2025), a pedagogical framework, modified to incorporate FTS and behavioural fabrication

education by leveraging the FTS framework. The pedagogical approach promotes diversity and critical thinking in HRC design,
2. *Participation and Feedback via Demonstrator*: The method centers participatory design practices by engaging students in task performance, observation, and peer feedback. This iterative cycle fosters inclusive, context-aware design responses and supports critical reflection on HRC challenges.
3. *A Cyber-Physical System for Teaching HRC in Digital Fabrication*: A robust cyber-physical system supports designing responsive HRC. Its key features include accessible deployment, real-time simulation, development of responsive robot behaviors, and open-ended programming using C# and Python, with support for mixed reality HRC.
4. *Evaluation Through a Pedagogical Workshop*: The effectiveness of the proposed approach is assessed via a dedicated workshop. This study evaluates the impact of the method on student awareness of HRC challenges and their ability to develop industry-relevant competencies.

4 Methodology

Building on the objectives outlined, this section translates those aims into a concrete methodology that equips emerging Industry 5.0 professionals to turn real-world feedback into effective, human-centric HRC workflows.

The methodology builds upon the Double-Diamond Approach (DDA) (Council 2025), a pedagogical framework used to integrate the previously presented FTS framework (Ron et al. 2024a, b) and behavioural fabrication. The four phases of DDA are defined specifically in the context of developing HRC workflows. The DDA approach's implementation involves two key methodological developments:

- an HRC demonstrator, where practitioners observe and participate in a collaborative assembly task, to understand the challenges of HRC and experience how people may interact with a robot differently.
- a cyber-physical fabrication system, composed of a physical fabrication system and a corresponding digital model, for practical design implementation for responsive HRC.

Combined with the previously presented FTS framework for HRC design, this method aims to sensitize designers to the practice, to diverse users' needs, acknowledge systematic and self-biases, and meaningfully include feedback in their design processes.

4.1 Double-Diamond Approach (DDA)

DDA is a methodology developed by the Design Council to foster iterative design processes relying on experimentation and user feedback. It is used to organize creative processes into four distinct phases: *Discover*, *Define*, *Develop*, and *Deliver* (Council 2025). DDA emphasizes a balance between divergent and convergent thinking, enabling the exploration of a broad spectrum of ideas before narrowing the focus to user-centered solutions. Its emphasis on iterative problem-solving and user-centric outcomes provides a robust methodology for tackling complex challenges. DDA's versatility applies to other domains, including HRC.

To explore human-centered, feedback-driven designs for HRC, the four key phases of the DDA model are as follows: Fig. 1:

1. *Discover:* This phase focuses on sensitizing designers to real-world challenges in human–robot close collaboration with robots. It is composed of two parts: a theoretical part and a practical part.

   The theoretical component covers an introduction to HRC in prefabrication and construction, current research achievements and challenges, an overview of FTS theory, and a practical FTS framework that guides design solutions to be practice-relevant, accessible, diverse, and free from biases. It also introduces the guiding principle of behavioural fabrication as a method for addressing user needs.

   The practical component provides hands-on experience in an HRC assembly demonstrator, offering insights into users' diverse needs: demographic, experience, preferences, and feelings of safety and trust.

   Together, the theoretical and practical experiences ensure that HRC processes evolve based on real-world insights, emphasizing the importance of inclusive design and safe working environments.
2. *Define:* In this phase, designers assess their experience in the HRC assembly demonstrator through documentation, observation, and feedback, refining objectives to address key challenges and demographic needs.
3. *Develop:* This phase focuses on designing and developing an HRC workflow that responds to the challenges and needs identified during the Define phase. It involves augmenting the robot with sensor data used to make informed decisions in the collaboration process.
4. *Deliver:* This phase focuses on deployment and user testing, emphasizing the quality performance of the robot and testing with diverse participants. Both efforts aim to refine the design process based on feedback, ensuring it addresses real needs rather than assumed ones. The cycle then loops back to the *Develop* stage for further refinement.

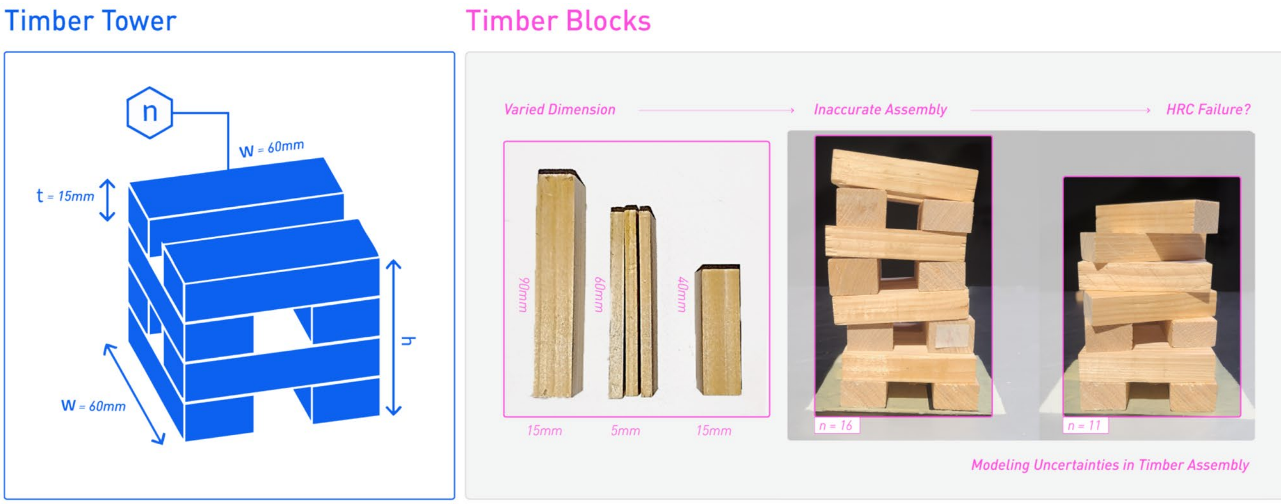

Fig. 2 Timber assembly design, a small-scale tower assembled twice: with even and uneven blocks. The tower's design is sensitive to fabrication errors, which, with non-responsive cobots, would lead to machine errors. This prompted students to come up with robots' responsive behaviors and human–robot interactions for a successful, accurate, and stable assembly

The four phases are essential for collecting first-hand insights into HRC processes and their refinement, developing task and user-relevant design proposals, and validating them through user testing. The phases occur sequentially with feedback that informs the continuous evaluation and redevelopment of the HRC process.

4.2 HRC assembly demonstrator

An HRC demonstrator was designed to expose participants to the challenges of automated assembly and close-proximity human–robot collaboration (HRC). It helped participants attend to site-specific conditions, task constraints, sources of uncertainty and failure, and diverse user responses and needs in collaborative settings (see Fig. 2).

In this demonstrator, a user and a non-responsive UR10e cobot—mounted on a work table and equipped with a finger gripper—alternately placed timber blocks to construct a small-scale tower (Fig. 3). The tower had a footprint of 60 × 60 mm and consisted of 14 timber blocks, with a base (2 blocks) already assembled. Participants were asked to follow assembly instructions Fig. 2 to build an accurate and symmetrical tower and were free to make corrections as needed.

The demonstrator featured two test scenarios, presented in random order:

- Type A: Using uniform blocks (20 × 60 × 10 mm)
- Type B: Using blocks of varying dimensions (20 × 60 × 10 mm; 20 × 60 × 15 mm; 20 × 60 × 5 mm), simulating production uncertainties that lead to machine errors in Pick-and-Place sequences.

The towers' design had minimal tolerance for errors, where misplaced, asymmetrical, or missing blocks could compromise the entire structure's stability Fig. 2. In both scenarios, the cobot was hard-coded to initiate the process, move at a slow pace, and wait 5 s after placing a block for the participant to add theirs. Each sequence introduced programmed errors in the cobot's actions, such as misaligned picks, misplaced blocks, or failed grips, to simulate real-world uncertainties and prompt human adaptation.

The task reflected key aspects of real-world construction: it required high accuracy, was sensitive to manufacturing errors, and demanded manual improvisation to overcome robotic limitations.

The demonstrator involved specific role distributions among participants:

- User 1: Active collaboration with the cobot
- User 2: Observation and recording of cobot behavior
- User 3: Observation and recording of participant actions
- User 4: Cobot safety stop management

Roles rotated after the first assembly sequence, with observers becoming active participants and vice versa. This rotation allowed for a broader range of insights into HRC dynamics.

Participants received a printed instruction sheet with text and annotated illustrations of the target structure and assembly sequence. They were introduced to HRC safety guidelines and were introduced to the demonstrator by an experienced operator.

The demonstrator immersed students in HRC, working in physical proximity, adapting to the robot's pace, anticipating its movements, and making on-the-fly decisions in a

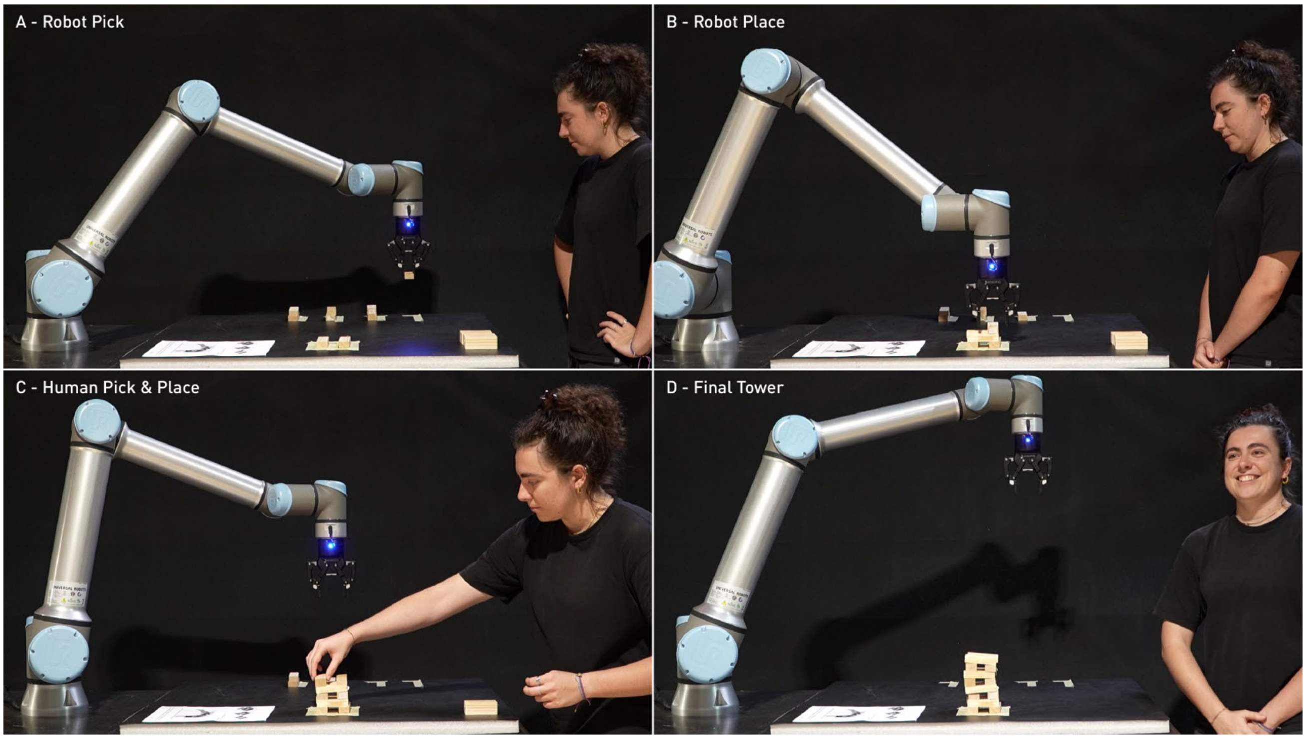

Fig. 3 A student co-assembles a timber structure with a non-responsive UR-10 cobot using unequal elements (Type-B). Without sensing, fabrication uncertainty and unequal blocks caused assembly errors and higher user workload. Acknowleding limitations in the demonstrator phase as well watching diverse participants in HRC, guided students' design interventions and promoted design relevance

noisy, dynamic environment. The process aimed to foster a more situated understanding when designing HRC solutions, prompting participants to address practical challenges encountered during the demonstrator phase. Participants confronted practical challenges, including technical limitations, ambient noise, safety concerns, and the need for accessible interaction methods and digital assistance.

Combining firsthand experience with peer observation allowed participants to recognize the diverse needs and reactions users may have in HRC settings. This approach is especially valuable in educational workshops, where time is limited and participation is typically restricted to students as industry stakeholders and workers are often unavailable.

By alternating between direct participation and structured observation, students develop empathy and gain a view "from within" the HRC experience, even when exploration with user responses is necessarily limited to the workshop participants themselves. This helps bridge the gap between theoretical understanding and the practical realities of designing for diverse human–robot interactions.

Following the assembly tasks, participants completed a questionnaire and engaged in a discussion session to provide feedback on their expectations of HRC and their lived experience.

4.3 Cyber-physical fabrication system

A cyber-physical fabrication system was developed to allow for the augmentation of the demonstrator based on feedback from the real world. The system comprises two interrelated components: a physical fabrication system and a corresponding digital model. The digital model allows for iteration of robotic behavior, simulation of the HRC process, and deployment of HRC workflows in real time. Utilizing principles of behavioural fabrication, the digital model relates bespoke robotic behaviors to sensor data collected from the physical fabrication system.

4.3.1 Physical setup

The physical system includes a user, a cobot, and sensors that can detect changes in the environment—such as the cobot's position, tracking construction elements, and serving as interfaces for interaction (Fig. 4). A Universal Robots UR10e equipped with a Robotiq gripper was mounted on a table, enabling a user to work comfortably alongside the cobot (Fig. 4). The system was developed using a publisher–subscriber communication protocol, which facilitates easy plug-and-play functionality. This

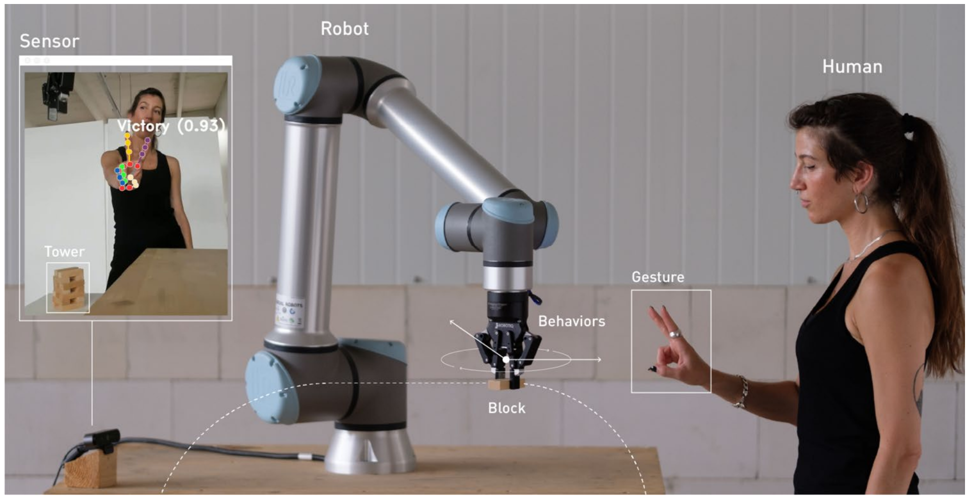

Fig. 4 Cyber-physical setup for a responsive HRC in timber assembly, stacking timber blocks into a small tower. A UR10e robot controlled in real-time by users' hand gestures, detected with a camera

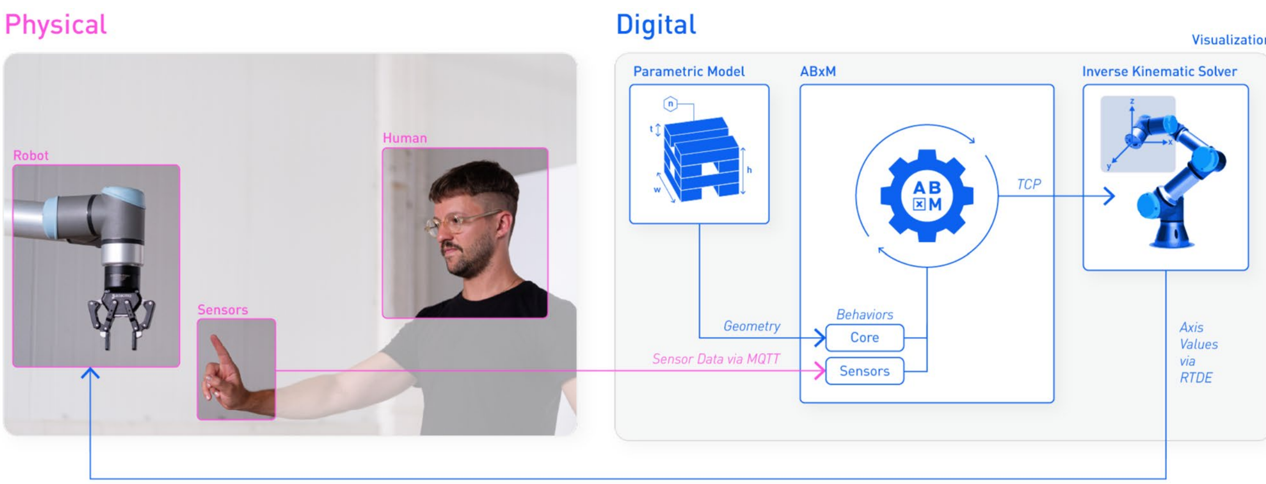

Fig. 5 Cyber-physical workflow developed with communication between the ABM, the physical cobot and any additional sensors

enables the addition or removal of various sensors as needed, without requiring major system modifications.

A webcam served as the primary sensor for initial development of the cyber-physical fabrication system, providing video feeds processed by Python and a Google MediaPipe model to recognize seven distinct gestures (Lugaresi et al. 2019). The classified gestures were transmitted to the digital model via the Message Queuing Telemetry Transport (MQTT) protocol, chosen for its simplicity and low client-side computational demands (Hunkeler et al. 2008). Leveraging a cloud-based MQTT broker further streamlined prototyping and testing, allowing designers and users to conduct experiments more efficiently.

4.3.2 Digital model

The digital model is responsible for coordinating the timber assembling process, taking inputs from a user, physical cobot, and any sensors. Agent-Based Modeling and Simulation (ABMS) is employed as the behavioural modeling method. As a framework for modeling complex systems through the actions of individual entities, ABMS enables the development of robotic behaviors that respond directly to sensor input. Its extensive use in architecture and construction (Stieler et al. 2022) supports its applicability in this context (see Fig. 5).

The digital model was developed using Rhinoceros 3D, a widely used CAD software in AEC, integrated with the visual programming environment Grasshopper. It consists of four main parts: (i) the tower's parametric design model, (ii) the agent-based model (ABM), (iii) the robotic inverse kinematics solver, and (iv) the visualization (Fig. 6) and communication modules.

The digital model operates through a feedback-driven process as illustrated in (Fig. 5). The parametric model serves as input for the agent-based model (ABM), providing

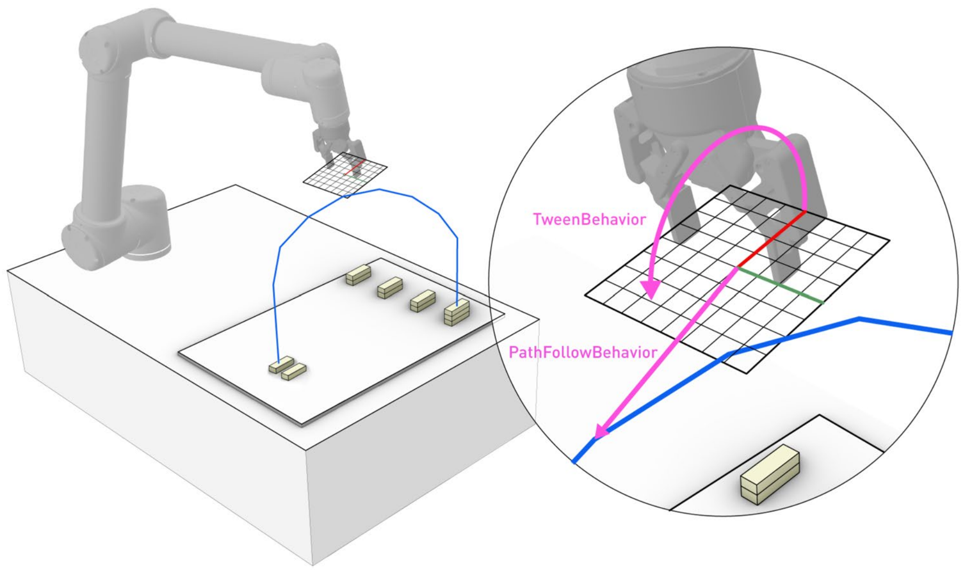

Fig. 6 Digital visualization of the HRC Setup, including a close-up of the gripper whose TCP corresponds to a plane agent. In the current state, the Path-Following and Tween Behaviors are affecting the position and orientation of the agent

a predefined path for the cobot to travel along using a set of core behaviors. Utilizing the core behaviors, the cobot follows a predefined path to place a block, then pauses to wait for the human to place a corresponding block before proceeding to the next position, as specified by the demonstrator. Additional sensor behaviors, which comprise the primary design space for human–robot interaction, can be added to the ABM to allow the cobot to react to changes in the environment. Together, the behaviors defined in the ABM calculate the location and orientation of the Tool Center Point (TCP) of the cobot. The TCP is then sent to the robotic inverse kinematic solver, which informs the visualization as well as the eventual control of the cobot in the real world. A key feature of the digital model is its ability to operate either entirely in simulation or in conjunction with the physical cobot. This flexibility allows sensor input to be sourced from real-time data or manually specified, and enables the robot's actions to be executed in a physical or virtual environment. In turn, the definition of new sensor behaviors for the augmentation of the ABM can be tested in simulation before being deployed.

Parametric Design Model

The parametric design model generates a 3D representation of the tower, its blocks, their dimension, and their orientation. A change to the model's parameters results in new tower designs. The 3D representation serves as input to the assembly process and robotic path-planning by creating a predefined path for the robot to travel along. The distance that the cobot travels between steps of the ABM is defined through the adjustment of this path.

Agent-Based Model using ABxM

The ABM serves as the control center of the cobot, calculating the next TCP. The ABM is implemented using the open-source agent-based modeling framework, ABxM (Nguyen et al. 2022; Groenewolt et al. 2018). The model is organized hierarchically, beginning with the agent system, which comprises both the environment and the agent itself. The agent encapsulates a set of behaviors. The primary constructs of the ABM developed in this research are outlined below, with their derivation from the ABxM core illustrated in (Fig. 7).

Environment contains information on boundary conditions, block pick-and-place locations, and predefined cobot paths.

Agent in the model represents the UR10e robot, specifically the cobot's TCP. A new agent type, called the Plane Agent, was developed for this model from the base implementation in ABxM (Fig. 7). The Plane Agent is a plane in Cartesian space designed to coordinate with the cobot's TCP, which is also a plane. Additionally, the Plane Agent maintains functional information, such as the cobot's location and orientation, the state of the gripper, its position along the predefined path, and sensor-related data.

Behaviors drive changes in the cobot's TCP. In this context, behaviors are defined as internally coordinated responses of the system, encompassing both actions and inaction, to internal or external stimuli, as articulated by Levitis et al. (2009).

For the Plane Agent, behaviors produce geometric outcomes to affect the TCP by either generating translation vectors to move the TCP or applying quaternion rotations to adjust the TCP's orientation. Behaviors can also modify the agent's state information, such as toggling the state of the gripper.

Two types of behaviors were developed for the ABM: core behaviors and sensor behaviors. As ABxM was designed for cooperative behavior coordination with no hierarchy between behaviors, a weighted sum of all

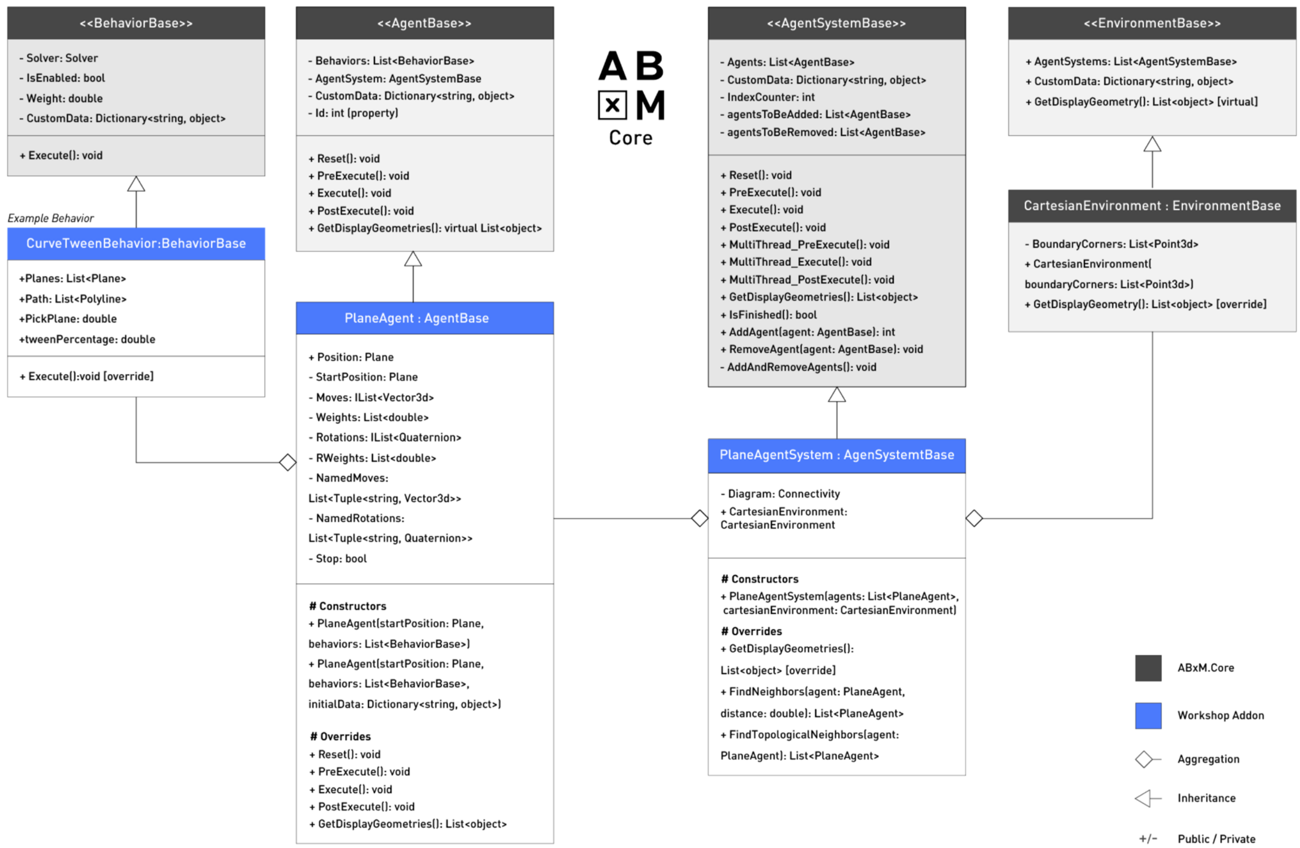

Fig. 7 UML Diagram illustrating the Plane Agent and Plane Agent System as derived classes from the ABxM Core

translation vectors and rotations is applied to determine the TCP when the model is running with the core behaviors alone. An additional delineation was made for sensor behaviors, as being either static or dynamic, in order to introduce competitive behavior coordination within the model. Competitive behavior coordination is achieved with static sensor behaviors, which interrupt the core behaviors and solely dictate how the agent should move. Dynamic sensor behaviors contribute to the total weighted sum of behaviors, maintaining cooperative behavior coordination.

Core behaviors are essential for the model's operation and include:

- *Path Following*: Calculates a translation vector to move the cobot toward the nearest point on the predefined path from the parametric model, adjusting movement based on the gripper's state and proximity to endpoints.
- *Safety Orientation*: Corrects the orientation of the cobot before it is about to pick up a block.
- *Containment*: Acts as a safety mechanism, generating a translation vector to keep the agent within defined boundaries.
- *Pick/Place Pause*: Toggles the gripper after a set number of iterations, moving the agent vertically during pick-and-place actions, and resetting after each operation.
- *Update*: Triggers the ABM to generate a new TCP only after the physical cobot reaches the previously sent TCP. This behavior is only utilized when the digital model controls the physical assembly process.

These core behaviors are constantly running and govern the cobot's execution of the demonstration, enabling it to advance or pause along the predefined path as required.

Static and dynamic sensor behaviors manipulate the cobot's TCP using sensor data. The sensor behaviors are added to the digital model in order to respond to humans and the overall construction environment. The ABM supports the inclusion of an unlimited number of sensor-driven behaviors. Each sensor-behavior is activated or deactivated based on incoming data from the sensors. For instance, in the case of the webcam setup, a specific hand gesture like *Victory* can trigger a corresponding sensor-behaviors within the model, like stopping any movement of the robot, which would be a static sensor behavior. If *Victory* is no longer detected, then only the core behaviors run and the demonstrator is continued.

Static sensor behaviors interrupt the execution of the core behaviors and define a set of actions or inaction for the robot to follow. Examples of static sensor behaviors include:

- *Stop*: Halts the cobot when a specific sensor value is detected.
- *Pattern*: When active, this behavior loops through a collection of predefined vectors, resulting in actions such as the cobot waving in the base implementation.

When the static sensor behaviors is deactivated, the ABM continues where it left off in the demonstration.

Dynamic sensor behaviors contribute to the cooperative behavior coordination logic inherent to ABxM. They actively adjust the location and orientation of the TCP, use or change the state information of the agent, contributing to the continuation of the demonstrator process. These behaviors add vectors or rotations to a weighted sum as the ABM is running. The final TCP position is influenced by the cumulative effect of all behaviors rather than a single action in the case of static sensor behaviors. Using the webcam example again, different hand gestures, like *ILoveYOu*, can trigger different sensor behaviors within the model. An example of the behaviors would a vector or rotation that forces the agent away from the person. An example implementation of such a dynamic sensor behavior is presented in Algorithm 1. In this example, the agent is rotated conditionally based on the state of the sensor, *trigger.Value*, and the state of the agent, *planeAgent.CustomData[Pick]* and *planeAgent.CustomData[Place]*.

Algorithm 1 Example Dynamic Sensor Behavior: Add Rotation

```
procedure EXECUTE(agent)
    if Enable then
        planeAgent ← Cast agent to PlaneAgent
        step ← planeAgent.CustomData[PauseCount]
        trigger ← Cast this.CustomData[Trigger] to GH_Boolean
        if trigger.Value then
            if step = 0 and !planeAgent.CustomData[Pick] and !planeAgent.CustomData[Place] then
                plane1 ← planeAgent.Position
                plane2 ← planeAgent.Position
                Rotate plane2 by angle × π/180 around plane2.XAxis
                moveQuaternion ← Quaternion.Rotation(plane1, plane2)
                Add moveQuaternion to planeAgent.Rotations
                Add Weight to planeAgent.RWeights
            end if
        end if
    end if
end procedure
```

Robot Inverse Kinematic Solver

The cobot's TCP is translated into joint values using a custom robotic kinematic solver for Grasshopper. These joint values provide precise control over the cobot's movements. Once calculated, the joint values are transmitted to the cobot via Universal Robot's Real-Time Data Exchange (RTDE) protocol, which supports a communication frequency of 500 Hz, offering a significant improvement over traditional socket communication.

Visualization

A key component of the digital model is the visualization of both physical and digital elements. The digital model includes a real-time visualization of the cobot in its current position as well as its anticipated position in the next step. Additionally, the visualization displays the positions of blocks and the cobot's paths. Furthermore, the ABM visualization illustrates the influence of each behavior through transition vectors and rotations around the TCP.

5 Workshop

To test the practical application of the integrated DDA method, FTS framework, and cyber-physical system, a workshop was conducted with emerging Industry 5.0 professionals from design, engineering, and robotics backgrounds. The workshop ("Considering Human-Centric HRC through the lens of Feminist Technoscience") took place at the (Institute for Advanced Architecture, Catalunia; Barcelona, Spain). Its goal was to explore intuitive communication in HRC while supporting inclusivity, safety, and trust in HRC

5.1 Participants

Seventeen participants from the (blinded) program—representing diverse genders, ages, and nationalities—took part in the workshop. They were divided into four independent groups. A detailed overview of each group's composition is provided in section 6.

5.2 Set-up

The workshop was conducted across two spaces: a classroom for instruction and coding, and a dynamic fabrication area housing the HRC assembly demonstrator. The fabrication space was visually shielded with black screens but remained audibly active due to ongoing construction work. Two UR10e cobots with Robotiq 2-finger grippers were mounted on a shared table serving as both a base and a collaboration zone. Coding and cobot testing occurred concurrently, supported by a team of four instructors.

5.3 Procedure

The workshop took place over four days. Following the hybrid approach, participants in the workshop engaged in the following sequence:

1. *Discover:* The workshop began with lectures and technical tutorials covering an introduction to HRC and HRC in construction, FTS critique and the FTS framework, and behavioural fabrication. Topics included transparency of error, designer responsibility, and bias in socio-technical systems. Technical sessions introduced the ABM/ABxM frameworks and sensor-cobot communication (See Sects. 1.2, 1.5, 2.3, 2.2, and 4.3.2).

   Participants then engaged in a collective, hands-on experience with a non-responsive HRC assembly demonstrator. Rotating between direct interaction and peer observation, participants documented challenges through video, note-taking, and discussion Sect. 4.2. This activity grounded participants in the practical complexities of HRC and foregrounded user diversity, bias, and perception as design factors.
2. *Define:* Each group reflected on their observations to identify key user needs, breakdowns in collaboration, and opportunities for improvement. These were refined into actionable design objectives through discussion and feedback, culminating in early concept presentations.
3. *Develop:* Groups developed new robot behaviors to address the challenges identified in the previous phase. Using sensor data and the ABxM framework, each team created interactive workflows that allowed the cobot to respond more intelligently to human input. To ensure independent exploration and avoid bias, groups worked in isolation and tested their solutions separately. Design iterations were informed by continuous testing, troubleshooting, and reflection on task performance.
4. *Deliver:* The final HRC workflows were deployed and, where possible, tested with participants who had no prior experience in the workshop or program. While all groups completed their implementations, only two managed to test their designs with external users on the final day, thereby completing all four phases. The workshop concluded with group presentations and a collective reflection on usability, inclusivity, power dynamics, and future development.

   A detailed discussion of the group projects and outcomes follows in Sect. 6 (see Fig. 8).

5.4 Hypotheses

The following hypotheses were outlined in order to guide the analysis of the results of the workshop:

- *H1 - Role of FTS Framework:* Having been introduced to FTS theory and the FTS framework (Ron et al. 2024b), we expected workshop participants to be more aware of design failure and biases, and address issues relating to user diversity, needs, and user-comfort in their design proposals for robotic behaviors in HRC.
- *H2 - HRC Demonstrator:* Having participated in collaborative assembly with non-responsive cobots, we expected workshop participants to gain a better understanding of the task, tools, and routines of HRC in timber assembly, leading to design proposals that address related challenges.
- *H3 - Cyber-Physical Fabrication System:* Having been introduced to ABM and taught the cyber-physical fabrication system, we expected workshop participants to gain an understanding of the system, use the example scripts as a base for behavior design, and add new behaviors.
- *H4 - Role of DDA:* We expected workshop participants to use the DDA to explore varied, user-centric design options for robotic behaviors in close HRC in timber assembly, and approach both technical issues and user feedback.

6 Results

The workshop produced four distinct interactive HRC workflows (Blog 2025a, b, c, d), each developed using the FTS framework (Fig. 9). After interacting with a non-responsive cobot, each group identified specific challenges and created

Fig. 8 Impressions from the workshop's development phase

targeted behaviors within the ABxM cyber-physical system. These behaviors were triggered by sensor inputs, such as audio, video, and their real-time analysis. The resulting workflows incorporated diverse interaction modalities—including sound, motion detection, hand gestures, and vision—to enhance communication and address observed limitations.

The following section examines the workshops' outcome, including: a description of each group's backgrounds and expectations (summarized in Table 10); their demonstrator reflections, design objectives, HRC workflow and implementation approaches.

Individual group HRC workflow and implementation approaches are provided for each group: BlabberBot (item 2), Being Humane (item 1), Hey Jarvis, Let's Collaborate! (Fig. 2), and Robot of Babel (Table 7).

Each project is then evaluated using the FTS framework introduced in Sect. 2.2, based on four categories: Embodiment, Reconfiguration, Interrelations, and Participation and Reflection. For each category, "yes" answers to the reflexive questions earn one point, partial answers earn half a point, and "no" answers receive zero points—yielding a maximum of four points per category.

Individual FTS evaluation summaries are provided for each group: BlabberBot (Table 2), Being Humane (Table 4), Hey Jarvis, Let's Collaborate! (Table 6), and Robot of Babel (Table 8). A comparison of overall FTS scores is shown in Fig. 13.

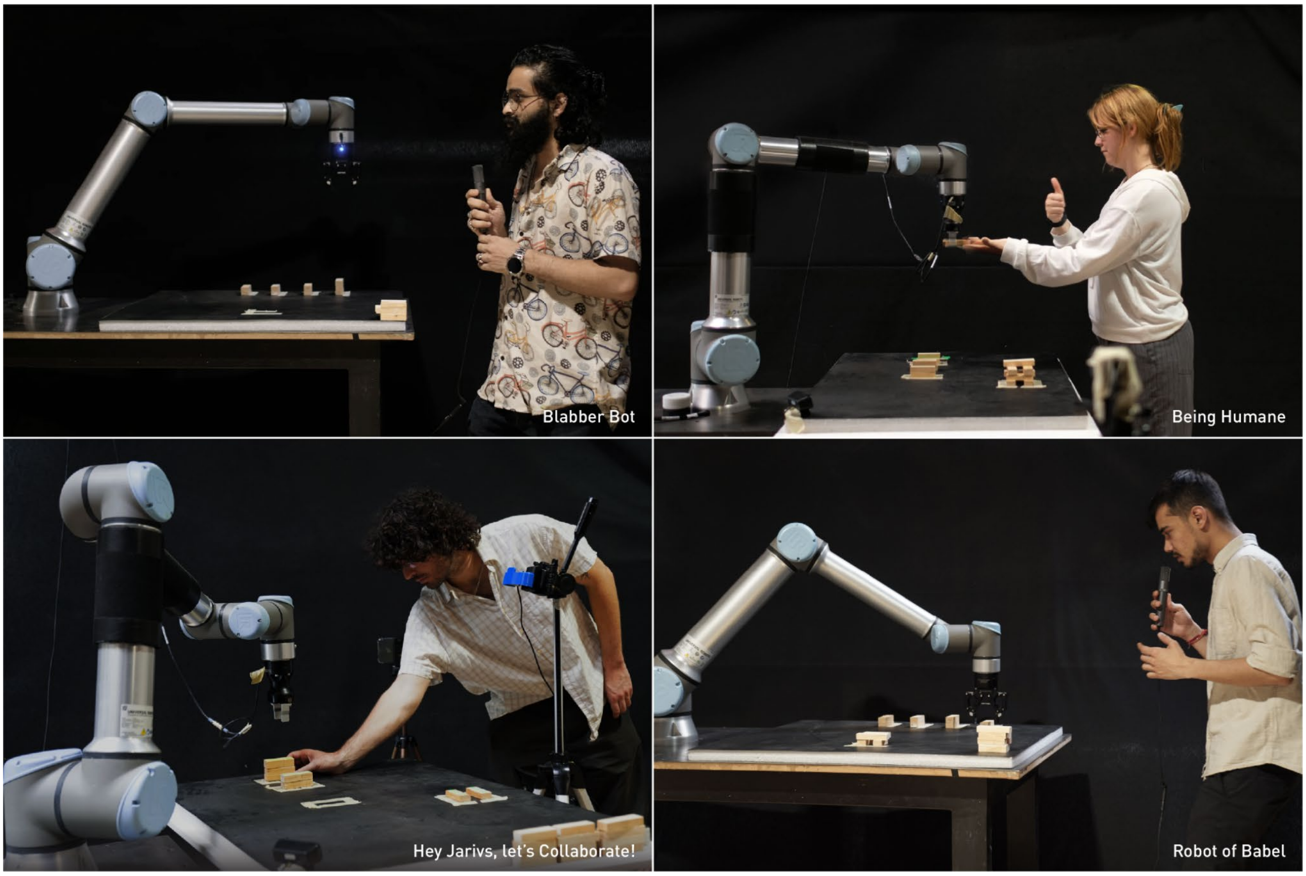

Fig. 9 Shows the four HRC responsive workflows: BlabberBot, which used LLMs for speech-based bi-directional communication (top left) (IaaC Blog 2025b); Being Humane, which employed hand-gesture control and user distance detection (top right) (IaaC Blog 2025a); Hey Jarvis, Let's Collaborate!, which combined a depthcamera verification workflow with LLMs for user communication (bottom left) (IaaC Blog 2025c); and Robot of Babel, which integrated multilingual interaction and robot gestures for user communication (bottom right) (IaaC Blog 2025d)

6.1 Group 1: BlabberBot

1. **Group Info:**
   - ***Participants:*** The group consisted of three male architects and one male engineer. Three members were aged between 20 and 30, while one was aged between 30 and 40. Three of the four members had more than 5 years of work experience. The group members were from Mexico, India, and China.
   - ***Previous Experience in Robotics and HRC:*** The group reported being highly familiar and passionate about digital tools, generally not anxious about working in close collaboration, and possessing little to no experience working with cobots.
   - ***HRC Expectations:*** One participant felt positive about HRC, while another did not.
   - ***HRC Realizations:*** Upon completing the demonstrator, one participant preferred performing the task with humans, whereas the other preferred collaborating with a cobot.
2. **Demonstrator Reflections:** The group observed users' need for assistive communication to clarify the task, like assembly instructions or the importance of accurracy, and the cobot's actions. Reflections suggested that these should be available in speech form.
3. **Workflow Description:** The group's workflow, BlabberBot, facilitated dynamic, human-like human–robot interaction through verbal communication: the cobot recognized and processed spoken commands ("hello", "start", "continue", "stop", "help", "your turn") using a microphone, and provided verbal feedback through a computer speaker. The group employed text-to-speech and speech-to-text (TTS/STT) technologies, using OpenAI's API. The relationship between speech and robotic behaviors is explained in (item 2). The workflow demonstrated the potential for bi-directional communication, allowing the human and the cobot to express their intents

during the assembly process. The group tested with one user, a student not involved in the workshop development, who successfully operated the system using voice commands. The user noted background noise as a limitation, disrupting the collaborative workflow and highlighting the need for noise-robust communication strategies.

4. **BlabberBot FTS Framework Evaluation:**

- ***Embodiment: (2.5/4)***

  BlabberBot's contribution focused on speech-based user assistance, based on the demonstrator's reflection, identifying user needs in clarifying task instructions and progress (1/1).

  While speech-based feedback aimed to support a smooth interaction and reduce users' cognitive ambiguity during the task, these features were primarily designed to ensure task completion and accuracy rather than user engagement, stress, cognitive load, or psychological safety (0.5/1).

  BlabberBot's framework assumes users are English-speaking with unimpaired auditory and verbal abilities, and restricts interaction to speech without alternative interaction modalities or interface adaptability to accommodate user differences (0.5/1).

  Trust-building relies on familiar social cues and verbal feedback. However, the speech options are limited without adapting to user states or feedback, which may not suffice for clarity and trust across diverse users. Safety concerns from miscommunications due to background noise were identified in the design phase, but not addressed in the final iteration (0.5/1).

- ***Reconfigurations: (2.5/4)***

  BlabberBot's bi-directional communication through simple prompts ("Start," "Stop," "Your Turn") framed the cobot as a semi-autonomous participant with limited agency, and restricted users to fixed commands without room for nuance or correction (0.5/1).

  BlabberBot's workflow supports a collaborative routine of multiple users, common in prefabrication and construction. However, noise and its effect on audio-dependent collaboration were not taken into consideration, and alternative modes weren't proposed (0.5/1).

  The team identified and approached a need for task clarification (repeating instructions, explaining the next task, whose turn is it to assemble), delivered through speech, which is relevant for multi-user collaboration and common in prefabrication and construction (1/1). Site and task constraints- background noise and assembly precision- were not approached (0.5/1).

- ***Interrelations: (1/4)***

  Users' needs for task clarification were addressed. However, the communication context, intent, nuance, and robotic performance, which is tightly scripted and not interpretive, are limited. The system's dependency on sensors/ microphone/ speaker for successful HRC wasn't addressed (0.5/1). BlabberBots' workflow placed responsibility for initiating and interpreting almost every action on the human, with the cobot depending on human input; executing commands or providing prompts. The collaboration lacked shared agency and offered limited cobot autonomy (0.5/1). The system positioned the cobot as an assistant rather than a collaborator, thus limiting responses to uncertainties. When the user struggled to hear the cobot due to background noise, this asymmetry was reinforced: communication failures defaulted responsibility back to the human (0.5/1) The workflow made instructions accessible, but tied the cobots' actions to human input, potentially overloading users (0.5/1).

- ***Participation & Reflection: (1.5/4)***

  The single-user study with a student uninvolved in the workshop provides a limited opportunity to gather diverse feedback across age, ability, cultural, or linguistic dimensions, and test assumptions regarding the ease of use and limitations of speech in HRC (0.5/1). Their reflections marked the importance of clarity in communication and the need for assistive guidance through speech in HRC. In the design process, noise was identified as challenging in hearing the cobot's voice responses (1/1). The group didn't reflect on how their own design ambitions or characteristics, like strong digital skills and limited robotic experience, might have shaped design assumptions (0/1). Safety and trust were approached indirectly through the cobot's use of human-like social cues. Time limitations constrained an evaluation with a broader user base or iteration based on diverse feedback (0/1) (see Table 1, 2).

Table 1 Speech to robotic behavior developed in Blabber Bot project

Word	Behavior type	Robotic behavior
Start	Static	Start ABM
Stop	Static	Stop
Continue	Static	Continue Demonstrator after Stop
Your turn	Static	Continue Demonstrator after Human place Block
Help	Dynamic	Move to Safe Position

Table 2 FTS framework evaluation summary for BlabberBot

FTS dimension	Score	Notes
Embodiment	2.5 / 4	Speech-based support aided clarity but assumed verbal/auditory ability, with no multi-modal alternatives
Reconfiguration	2.5 / 4	Addressed task clarity but relied on fixed commands and lacked a fallback for noise or sensor failure
Interrelations	1 / 4	Cobot had low autonomy; user held primary responsibility. No co-adaptation or role flexibility
Participation & Reflection	1.5 / 4	Single-user test with some feedback integration; no deep reflection on design bias or accessibility

6.2 Group 2: Being Humane

1. **Group Info:**
   - ***Participants:*** The group consisted of two male architects, one male interior designer, and one male engineer. Three members were aged between 20 and 30, while one was aged between 30 and 40. Two of the four members had more than 5 years of work experience. The group members were from Bangladesh, India, and the UK.
   - ***Previous Experience in Robotics and HRC:*** The group reported feeling positive and generally not anxious about working in close collaboration with a cobot, being very familiar with digital tools but possessing little to no experience working with cobots.
   - ***HRC Expectations:*** Participants expected a high physical and mental effort working in a close collaboration with a cobot.
   - ***HRC Realizations:*** Upon completing the demonstrator, participants reported their confidence in the cobot decreased, feeling they corrected it more than collaborated with it.
2. **Demonstrator Reflections:** The group observed that active human correction of the cobot's pick-and-place errors was necessary but felt uncomfortable and anxious about the cobot's speed. Some members were made anxious by its sudden movements, while others were unsettled by its slow movements, which led to a lack of focus on the task. Also noted was that the cobot was addressed while looking at its end-effector as a "face".
3. **Workflow:** The group aimed to increase user feeling of safety and control during HRC in assembly. Their workflow used hand gestures detected by a web-cam to easily control the cobot in noisy environments (starting and pausing the robot's motion) (Figure 10). Additionally, they implemented proximity-based detection using an additional camera, which slowed down the cobot's speed when a human stepped closer.

   The relationship between webcam-captured hand gestures and the resulting robotic behavior is explained in the table (item 1).

   The workflow was tested with two volunteers: a workshop participant from another group and a student who did not participate in the workshop. Neither was familiar with the group's work. Both volunteers learned to use the gesture-based controls and successfully collaborated with the cobot, demonstrating effective interaction even when the cobot initially failed to grip an object. The workflow showcases the use of multiple sensors of the same type to enable the incorporation of various interaction types within a single HRC workflow.
4. **Being Humane FTS Framework Evaluation:**
   - ***Embodiment: (3.5/4)***

     Being Humane's framework valued emotional comfort and physical safety, allowing users to start and stop the pick-and-place sequence and adapt the cobots' speed to the users. Both enhance predictability through adaptive behavior and promote safety (1/1).

     The framework improves HRC's accessibility by adapting the cobot's speed to the user. Its gesture-based robotic control relieves a reliance on scripting know-how. However, it restricts interaction to gestures alone and assumes able-bodied users with unimpaired motor abilities (0.5/1).

     Safety and trust are central concerns, with on-demand robotic control over start, stop, open gripper functions, and user sensing to avoid collision and risk (1/1).
   - ***Reconfigurations: (3/4)***

     Being Humane's interface adjusts the cobot's speed and position with proximity sensing and hand gestures, complementary to the pick-and-place task and frames the cobot as a semi-autonomous participant (1/1). The workflow addressed the challenge of communication in noisy work-sites, supports auditory diversity, and considers user distraction and safety, with proximity sensing. However, it assumes hand gestures support all bodies alike (0.5/1).

     The team identified anxiety and distraction caused by robotic movement in shared space, and designed for contextual adaptability that is well-suited to close-proximity physical assembly tasks in HRC routines. Rather than expecting users to adapt, the

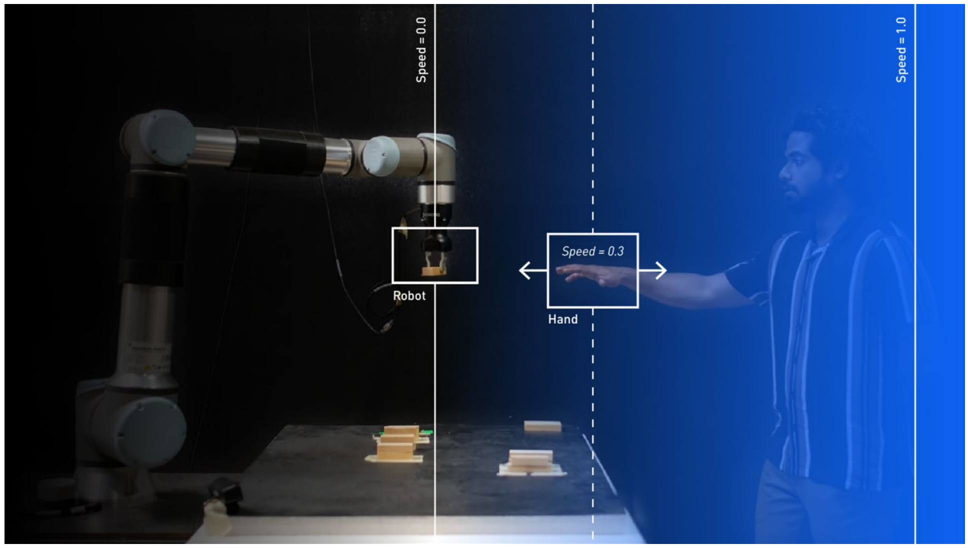

Fig. 10 In the Being Humane workflow, a camera-based proximity detection system was used to slow the cobot's speed when a user approached (IaaC Blog 2025a)

design allowed users to regulate the cobot's behavior, prioritizing comfort and control (1/1). The workflow is partially adapted to the environment, with camera sensitivity to light conditions and color contrast. It lacked fallback mechanisms in the event of gesture detection failures, proximity sensor misreads, or environmental shifts such as changes in lighting (0.5/1).

- ***Interrelations: (2.5/4)***

  Users' needs and cobot performance were considered for task success and convenient work rhythm, actively performing (human) or passively sensing and responding (cobot). Sensor dependency and failure were not considered (0.5/1).

  Being Humane's workflow tasked users with cobot performance supervision and correction, and a camera that senses the users and adjusts the cobot. There is room to explore more back-and-forth dialog, responses to diverse users, and role division over time (0.5/1). Users were assigned with a supervisory and corrective role, intervening, pausing, or resuming actions using intuitive gestures. The team didn't question this task division over longer time periods (0.5/1). The interaction was designed for complementarity: humans regulated the robot's pace through proximity and gestures, while the robot's predictable responses supported user confidence and focus (1/1).

- ***Participation and Reflection: (1/4)***

  The workflow was tested with two users- students uninvolved in the workshop- providing some view of diverse feedback across age, ability, cultural, or professional dimensions, and tests assumptions regarding the ease of use and limitations of gestures and sensing in HRC (1/1). Demonstrator impressions were effectively integrated into the design process, and user feedback was discussed in the final presentation (1/1). User study participation reflection was included, but the designer's reflection on their own biases and influences (identity, body, technology affinity) was missing (0.5/1). Being Humane's design process demonstrated visibility, inclusivity, and self-reflection through openly shared uncertainties and design based on observed reactions. They addressed user study feedback in Future Steps (1/1) (see Tables 3, 4).

Table 3 Hand gesture to robotic behavior developed in Being Humane project

Hand gesture	Behavior type	Robotic behavior
Victory	Static	Start Assembly Process
ILoveYou	Static	Continue Assembly Process
ThumbsUp	Dynamic	Close Gripper
ThumbsDown	Dynamic	Open Gripper
OpenPalm	Static	Stop

6.3 Group 3: Hey Jarvis, Let's Collaborate!

1. **Group Info:**

   - ***Participants:*** The group consisted of five members, including one female engineer and four male designers. All five members were aged between 20 and 30. Three of the five members had more than 5 years of work experience. The group members were from Australia, Germany, Colombia, Spain, and India.

Table 4 FTS framework evaluation summary for Being Humane

FTS dimension	Score	Notes
Embodiment	3.5 / 4	Gesture-based control and proximity sensing enabled user regulation of robot behavior, enhancing safety and predictability. However, interaction assumes unimpaired motor ability and excludes alternative input modalities
Reconfiguration	3 / 4	System addressed noise and distraction in real-world sites, with adaptive robot behavior and intuitive user controls. Yet, fallback strategies for gesture or sensor failure and changing light conditions were missing
Interrelations	2.5 / 4	Workflow enabled human oversight and cobot responsiveness, fostering productive collaboration. No dynamic role redistribution or mutual adaptation over time; sensor dependencies were underexamined
Participation & Reflection	3 / 4	User testing with two external participants included. Design followed feedback, but deeper designers' reflexivity on self and embodied bias wasn't present

- ***Previous Experience in Robotics and HRC:*** The group reported feeling positive and generally not anxious about working in close collaboration with a cobot, familiar and passionate about with digital tools, though inexperienced with cobots.
- ***HRC Expectations:*** Participants expected close collaboration with a cobot to have high mental efforts and medium physical efforts.
- ***HRC Realizations:*** Upon completing the demonstrator, participants had opposing impressions regarding feelings of confidence working with the cobot: one maintained their high level of trust in it, while the others' decreased.

2. **Demonstrator Reflections:** The group identified a need for improved operational prompts and real-time feedback mechanisms, focusing on the cobot's and human's accuracy in pick-and-place, and a change in the cobot's speed and movement for ease of collaboration, making the motion faster and more organic.
3. **Workflow:** Drawing from their demonstrator experience, the group developed a verification workflow for their collaborative assembly process using computer vision, TTS communication, and custom robotic gestures to facilitate human–robot interaction. The setup and workflow are detailed in Fig. 11. Their step-by-step verification approach using a webcam-guided block alignment. Using OpenAI and OpenCV libraries, the system employed a camera to monitor block placement and validate positions, while a microphone captured human voice inputs The system would provide verbal prompts to the users, reporting on the blocks' accurate or inaccurate position, and asking them to adjust when necessary, with the camera focused exclusively on the tower construction area. Only one additional behavior (Fig. 2) was created, as the majority of time was spent on the overall workflow development in this group. The group encountered challenges with their validation system, primarily false positives caused by shadows and camera angles during tower construction. These were mended with bespoke scene lighting. While time constraints prevented user testing during the workshop, the Hey Jarvis,Let's Collaborate! group successfully demonstrated how verification mechanisms could be incorporated into a human–robot collaboration workflow. Their implementation highlighted the value of real-time feedback in collaborative task completion, pointing to promising opportunities for advancing human-robot interaction.
4. **Hey Jarvis, Let's Collaborate! FTS Framework Evaluation:**

- ***Embodiment: (2/4)***

  Responding to inaccurate block placing in HRC in pick-and-place, the "Jarvis!" group's approach centered on minimizing machine and human errors via system validation and control. The team observed users' unease relating to the cobot's speed and motion, but did not address them (0.5/1).

  Spoken notification via camera sensing to TTS workflow, informed users about the placement's accuracy, and prompted them to improve their performance. When users were "spoken to", the cobot was designed to assume a "speaking position" in which it faces the user. The overall system assumes users will adapt to the cobot's workflow instead of designing for human variability (0.5/1).

  The camera validation system is beneficial for accurate performance, and reporting on the task's step-by-step performance is beneficial for task success, but the interaction model remains limited ("block assembled correctly/ incorrectly"), and the design doesn't accommodate users with alternative hearing levels or linguistic diversity (0.5/1).

  While a speaking interface may promote familiarity and accessibility, safety and trust were notably absent as primary design concerns (0.5/1).
- ***Reconfigurations: (2/4)***

  The "Jarvis!" group's workflow included a webcam, an OpenCV algorithm, and TTS to improve

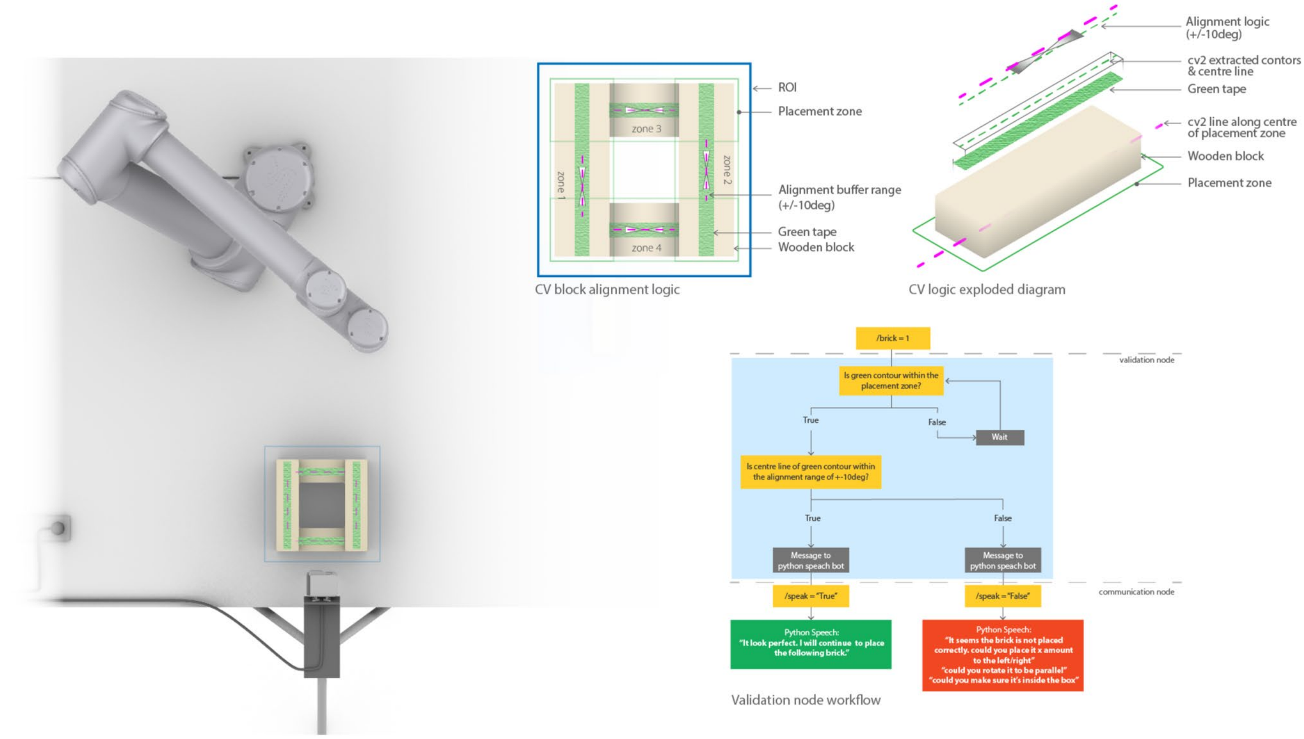

Fig. 11 In the "Hey Jarvis, Let's Collaborate!" project, camera detection was used to verify accurate cobot placement, and comment on users' performance. TTS / STT were used to communicate with users

error detection and cobot-to-user communication for accurate pick-and-place performance. While technically advanced, the team didn't consider the HRC's overall speed and the communication's limited input to the user: command and reports (0.5/1). The visual validation is beneficial for sequential construction and promotes the cobot's autonomy in simple tasks. The cameras' light sensitivity required bespoke scene lighting and colored adhesive film on the blocks for reliable function. It wasn't tested for diverse users (0.5/1). The solution assists in solving a real problem (1/1).

The system's heavy reliance on environmental consistency (lighting, fixed camera angle) undermined its adaptability. Alternative methods or overrides were not implemented (0/1).

- ***Interrelations: (2/4)***

  At the focus of the "Jarvis!" workflow is accurate assembly. The cobot is used in repetitive, accurate tasks; camera vision, and OpenAI/OpenCV APIs are used to guide user and cobot performance, and to communicate the assembly status to the user. Other needs were not included (0.5/1).

  The workflow uses a camera, APIs, and prompts to inform the user when to correct their or the cobots' assembly. It lacks opportunities for shared improvisation or flexible redistribution of roles, especially under changing conditions or evolving user needs (0.5/1).

  The rigid workflow offers unidirectional feedback flowing from tools to the user, with little mutual adaptation or learning (0.5/1).

  The "Jarvis!" workflow had little shared or fluid distribution of agency, with a user following machine prompts and correcting the cobot's performance. Both user and cobot were dependent on camera sensing, and no alternative interactions were proposed (0.5/1).

- ***Participation and Reflection: (1/4)***

  The group did not conduct user testing and had limited insight into the system's broader applicability (0/1).

  The group's reflections marked the importance of structured verification. These reflections shaped design decisions but remained limited to technical improvements (0.5/1).

  The group didn't reflect on how their own design ambitions or characteristics, like strong digital fluency and work experience, might have shaped design assumptions (0/1).

  While the group clearly documented their process and identified technical gaps, the design remained internally focused and lacked participatory openness, and self-reflection was on broader design implica-

Table 5 Robotic behavior developed in Hey Jarvis, Let's Collaborate! project

Sensor	Behavior type	Robotic behavior
Speech Detection	Static	Move to Safe Position

tions such as user agency, accessibility, or ethics (0.5/1) (see Tables 5, 6).

6.4 Group 4: Robot of Babel

1. **Group Info:**
    - ***Participants:*** The group consisted of four members: one female and three males, all trained as architects. Three of the four members had more than 5 years of work experience. The group members were from Sudan, Portugal, India, and the United States.
    - ***Previous Experience in robotics and HRC:*** The group reported feeling positive and generally not anxious about working in close collaboration with a cobot, being very familiar and passionate about working with digital tools, and having some previous experience working with cobots.
    - ***HRC Expectations:*** Participants expected a high physical and mental effort working in close collaboration with a cobot.
    - ***HRC Realizations:*** Upon completing the demonstrator, participants reported enjoying their collaboration with the cobot and feeling a sense of working together with it. However, they also noted that they did not fully trust the cobot.
2. **Demonstrator Reflections:** The group observed several cobot errors: in gripping and placing objects, and lacking adequate sensing and communication capabilities. They also discussed the construction industry's demographic, where construction workers are often immigrants, and highlighted how technology interfaces are poorly adapted to the diverse workforce within the construction sector.
3. **Workflow:** The group, entitled "Robot of Babel," drew from its members' diverse backgrounds and expertise in addition to the demonstrator experience. They developed a multilingual speech-to-toolpath interface, accessible to users who speak different languages. Their system designed cobot behaviors to respond to different detected languages, leveraging OpenAI libraries with a microphone to control the robot's responses. The relationship between languages detected and the resulting robotic behavior is explained in the table (Table 7). Similar to the BlabberBot project, the main challenge emerged from using voice recognition in noisy environments, which resulted in delays in language detection and occasional misidentification of languages. While time constraints prevented external user testing, the group's workflow raised important questions about accessibility and usability in diverse HRC scenarios. They also highlighted the need for real-time sensing to prevent structural failures and suggested incorporating precision indicators for pick-and-place tasks.
4. **Robot of Babel FTS Framework Evaluation:**
    - ***Embodiment: (2/4)***
      The Robot of Babel team emphasized linguistic diversity in HRC design, drawing on their multicultural backgrounds and the reality of the construction industry, where much of the workforce consists of migrant and non-native speakers—an often overlooked user group in HRC development (1/1).

Table 7 Robotic behavior developed in Hey Jarvis, Let's Collaborate! project

Language	Behavior type	Robotic behavior
English	Static	Face Human and Nod
Hindi \ Arabic \ Urdu \ Tamil	Dynamic	Rotate Around Z-Axis
Spanish \ Portuguese	Static	Draw a Circle

Table 6 FTS framework evaluation summary for Hey Jarvis, Let's Collaborate!

FTS dimension	Score	Notes
Embodiment	2 / 4	Task accuracy supported via camera and TTS; user unease and safety not addressed. Interaction assumed user adaptation, limited trust-building, or accessibility.
Reconfiguration	2 / 4	Visual verification enabled feedback but relied on fixed lighting and lacked a fallback for sensing failures. No accommodation for user diversity.
Interrelations	2 / 4	Interaction was unidirectional; cobot prompts guided users with little mutual adaptation. Roles were fixed; agency remained with the system.
Participation & Reflection	1 / 4	No user testing; design reflection focused on technical goals. Lacked inclusivity and critique of design assumptions.

The team explored diverse robotic responses to languages with users' well-being in mind (1/1).

Other dimensions of diversity relating to auditory inputs, like speech impairments, hearing difficulties, or diverse sensory inputs, remained unexplored (0.5/1).

While user trust is indirectly approached via linguistic accessibility and a human-like voice, other explicit trust-building mechanisms like transparent error reporting or adaptable behavior in uncertain situations were not addressed (0.5/1).

- ***Reconfigurations: (2.5/4)***

  Robot of Babel's multilingual voice interfaces, using a microphone and OpenAI's API, enable a more accessible cobot control and frame the cobot as a conversation partner. However, interactions were limited to speech-only input, and the speed of speech analysis can vary (0.5/1).

  The system is suited to workflows requiring verbal coordination and supports diverse languages. The absence of fallback modes represented a significant limitation, especially for prefabrication and construction sites where noise is expected (0.5/1). Robot of Babel's project context—multinational construction sites— is a real need addressed, making a strong case for linguistic inclusivity (1/1). The voice-based interaction system is highly sensitive to noise, leading to delays and recognition errors. The absence of fallback input methods and real-time adaptive sensing reduced system resilience (0.5/1).

- ***Interrelations: (2/4)***

  Users' needs and the cobot's extended agency in conversation are supported with a microphone, speaker, and OpenAI API. However, the framework overlooks users' diverse needs, like hearing impairments, speech variations, and cognitive diversity; and sensors' sensitivity to environmental factors, lacking in adaptive solutions (0.5/1). Robot of Babel's interaction is limited to the cobot's execution that follows users' speech input. It lacks adaptation to user errors, intentions, or behaviors, and shared agency (0.5/1). The multilingual interface lowered the HRC entry barrier for diverse users, but didn't mutually enhance task performance or adapt to diverse users' pace, speech clarity, or confidence with the cobot. For example, an adjustment for background noise to help users recover, clarify, or retry a command (0.5/1). The design empowers non-English-speaking users to participate more fully in robotic workflows, but the cobot and user could use role sharing beyond command-response for HRC success (0.5/1).

- ***Participation and Reflection: (1/4)***

  The Robot of Babel team explicitly considered the diversity of the construction workforce in their design rationale, but lacked testing with users (0/1). The group's shared backgrounds and professional experience inspired the focus on language barriers and inaccessible interfaces, but its integration remained limited (0.5/1). The team didn't account for their assumptions of speech as an accessible interface, and their biases- identities: highly digitally fluent, professionally experienced, and architecturally trained (0/1). Robot of Babel's process remained internal, with no participatory mechanisms or iterative co-design steps. The self-reflection focused on technical limitations (e.g., noise sensitivity), not on relational dynamics or ethical implications (0.5/1) (see Fig. 12, Tables 7, 8 and 9, 10).

7 Discussion

A four-day workshop served as a live proving-ground for the FTS framework, the HRC demonstrator, the cyber-physical fabrication system, and the DDA method. We revisit each original hypothesis (H1–H4) from Sect. 5.4, distilling the main insights and charting next steps.

- **H1 - Role of FTS Framework:** The introduction to FTS theory and its practical FTS framework compelled participants to foster a more inclusive and reflective mindset in HRC design, including accounting for HRC errors and design relevance, designing for the specific needs, and valuing user feedback. This was evident in the workshops' final debate on practice relevance and user needs regarding trust, safety, accessibility, and design accountability for the prefabrication and construction industry. Analysis of the four resulting workflows reveals strong correlations to the FTS framework's principles, particularly in addressing diverse user needs through heterogeneous interaction methods, cultural sensitivity, user comfort, and site and task relevance.

  Voice and Gesture-Based Interfaces for Accessibility and Adaptation.

  BlabberBot, Robots of Babel, and Being Humane addressed automation deployment challenges within the construction industry workforce, often unfamiliar with new tools or coding knowledge, by implementing intuitive communication modes like gesture and speech-based interaction. BlabberBot focused on bi-directional verbal communication, with STT/TTS features enabling

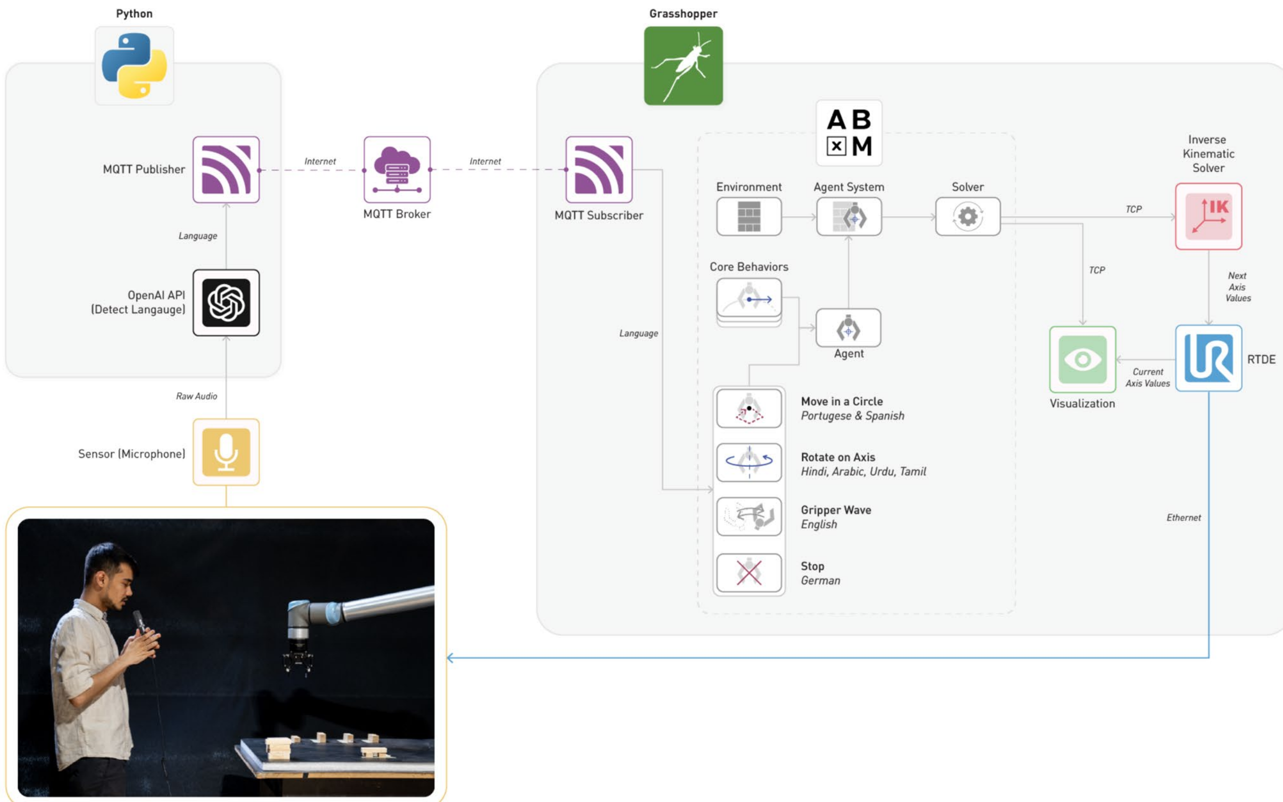

Fig. 12 Cyber-Physical Workflow of "Robot of Babel": the base model is open to diverse inputs and sensors

dynamic interactions. Robots of Babel extended this concept to multilingual contexts, reflecting the Participation dimension by making their system accessible to linguistically diverse users. Being Humane acknowledged site parameters like noise and developed hand gesture-based cobot control. All workflows emphasized Embodiment, relating to diverse users' needs, and Reconfiguration, through site, task, and tool relevance, by addressing challenges such as background noise and language detection errors. These interfaces are particularly relevant for the prefabrication and construction industries as they eliminate coding requirements and promote bi-directional HRC responsive to user needs, accommodating current and future diverse demographics.

Safety, Control, and trust. Being Humane emphasized safety and control through gesture-based interfaces and proximity sensors. These design choices aligned directly with Embodiment, ensuring users felt physically safe and maintained control during interactions. The group's workflow tests with external volunteers demonstrated Participation, proving it was effective even during robot grip failures. All groups used familiar communication forms to increase trust and humanize robots in HRC. An interesting approach from Robot of Babel and Jarvis!

Table 8 FTS framework evaluation summary for robot of Babel

FTS dimension	Score	Notes
Embodiment	2 / 4	Addressed linguistic diversity via multilingual voice interface. Lacked support for other sensory and cognitive differences. Safety and trust are not explicitly considered.
Reconfiguration	2.5 / 4	Enabled speech-based control in multilingual contexts. Lacked fallback modes; highly sensitive to noise and light conditions.
Interrelations	2 / 4	Lowered language barriers but retained rigid command-response roles. No mutual adaptation or role-sharing mechanisms.
Participation & Reflection	1 / 4	Design drew on the team's multicultural background but lacked user testing and participatory methods. Limited critical reflection.

Table 9 Summary of the Workshop Group Results

	Group name			
	BlabberBot	Being Humane	Hey Jarvis, Let's Collaborate!	Robot of Babel
Aim	Enhance human-robot collaboration with bi-directional communication using natural speech.	Create a feedback system using hand gestures for cobot communication (no voice needed).	Introduce verification at each step of human-robot collaboration to avoid mistakes.	Make human-robot collaboration accessible via multiple languages in a speech-to-toolpath interface.
Focus	- Building user trust with transparent cobot actions. - Supporting user commands.	- Gesture-based commands for prompting or pausing the robot. - Shared responsibility.	- Voice and gesture interfaces. - Validation of each action before the cobot placement.	- Speech-triggered cobot actions in various languages. - Visual feedback for planned paths.
Features	- Language detection for adaptive responses. - TTS/STT. - Two-way conversational potential.	- MediaPipe Studio for gesture detection. - Robot adjusts speed, position, or halts based on recognized gestures.	- OpenAI API. - OpenCV libraries. -A camera for tower observation and a microphone for voice commands.	- Multi-language STT/TTS pipeline. - Optional visual feedback for showing the robot's next move.
Workflow Overview	1. Audio input from a microphone. 2. Speech-to-Text to interpret commands. 3. MQTT communication for instructions. 4. TTS for robot responses.	1. Camera captures user gestures. 2. Gesture recognition triggers robot actions (e.g., pick, place, or pause). 3. Users can correct or reposition blocks if needed.	1. Voice/Gesture input. 2. Real-time verification. 3. Robot places blocks after confirming alignment.	1. Speech input in different languages. 2. Interpretation of commands. 3. Cobot picks and places locks as per logic. 4. Parallel visual feedback for the robot's path (prototype idea).
Behaviors Developed	Blocking: 3, Dynamic: 0	Blocking: 3, Dynamic: 1	Blocking: 1, Dynamic: 0	Blocking: 3, Dynamic: 1
Additional Libraries	PyAudio	MediaPipe Studio	OpenAI, OpenCV	OpenAI
Design Evaluation	- User studies with 2 participants revealed helpful verbal instructions but issues with background noise and misunderstandings. - Feedback indicated real-time reactions would improve usability.	- User studies with 2 participants found gestures fun, but slow reaction times reduced flow. - Uncertainty about correct hand positioning was noted.	- Internal trials highlighted precision but slow speed. - No formal user studies conducted.	- User studies with 2 participants highlighted instability due to misalignment and cobot errors. - Towers collapsed occasionally due to incorrect placements.
Key Challenges	- Background noise interfered with voice commands. - Users occasionally skipped assembly logic.	- Camera positioning and user awareness of gesture clarity. - Robot reaction time impacted user comfort and flow.	- Balancing real-time verification without slowing the process. - Reducing user wait times.	- Sticky gripper causing misplacement. - Robust sensing needed for tracking tower position and angle.
Observations	- Verbal commands were fun but occasionally unclear. - Step-by-step instructions were appreciated.	- Fun to test, but unpredictability was unnerving. - Users felt responsible for showing correct gestures at the right time.	- Internal testers requested faster, more organic movements. - Precision was appreciated, but speed was a concern.	- Users suggested positional knowledge for better alignment. - Real-time sensing could enhance correction.
Collaborative Insights	Interactive speech commands fostered better engagement, but accuracy challenges due to background noise.	A gesture-based interface enabled dynamic interaction but required user familiarity for optimal use.	Verification process was reliable, but slowed overall task execution.	Multi-language speech interface was innovative but required robust error-handling.

Table 10 Workshop participants background

	Group name			
	BlabberBot	Being Humane	**Hey Jarvis, Let's Collaborate!**	Robot of Babel
No. Members	4	4	5	4
Gender (M/F)	0/4	0/4	1/4	1/3
Age Group	20–30 (3) 30–40 (1)	20–30 (3) 30–40 (1)	20–30	20–30
Nationality	China, China, India, Mexico	Bangladesh, India, India, UK	Australia, Colombia, India, Germany, Spain	India, Portugal, Sudan, US
Educational background ratio: Engineers vs. Designers	1:3	1:3	1:4	0:4
Occupational experience: Students vs. Over 5 Years of Experience	3:1	2:2	3:2	1:3

Design proposals offered diverse solutions for HRC, building on the users' diverse backgrounds

groups was the implementation of robotic gestures, a designed tool-path that is communication-focused and not fabrication-focused, to simulate a real conversation and add meaning.

Verification Systems for Error Prevention. Hey Jarvis, Let's Collaborate! developed a comprehensive verification system for accurate pick-and-place performance, combining computer vision, voice communication, and robotic gestures. This design exemplified Reconfiguration by addressing real-world implementation challenges in visual detection (object recognition, shadow interference). The system also aligned with Interrelations by fostering collaborative roles where both humans and robots contributed to error-free assembly processes. Verification systems, their calibration, and shifting agencies between humans and machines are viable in fabrication processes that are sensitive to uncertainties and can ease user frustration and fatigue.

Human-Robot Shared Agency. Human-robot dynamics and agency varied across the four workflows, heterogeneous in interface design and cobots' roles. For instance, Hey Jarvis, Let's Collaborate! positioned the cobot as a meticulous assistant providing step-by-step guidance, while Being Humane emphasized a collaborative partnership. Meanwhile, BlabberBot and Robot of Babel highlighted the cobot as a facilitator, adapting to users' languages and communication styles. This diversity underscores the FTS frameworks' effectiveness in sensitizing participants, despite the homogenous background, to diverse user needs, real-world contexts, adaptability, and effective collaboration in HRC design. These attempts prompt thinking about shifting power relations between human and machine, responding to will, need, and task context.

- **H2 – Role of the HRC Demonstrator** The HRC demonstrator bridged design theory and practice by exposing participants to automation errors and uncertainties. That exposure drove each group to craft context-specific solutions, as evidenced by the groups' HRC reflection and their project focus. They addressed hardware limits, environmental factors such as noise, and user needs, including accessibility, digital guidance, and safety perception.

Despite their homogeneous background (male, 20–23, similar educational background; see Table 10), self-reflection and peer observation during close human-robot collaboration highlighted diverse user needs and considerations. The resulting HRC solutions varied significantly in focus, approach, methodology, and the human-robot relationships they established.

This diversity manifested across projects: BlabberBot observed communication challenges and noise interference, developing a speech-based interaction system to improve assembly instructions and robot action comprehension. Being Humane addressed anxiety-inducing robot movements by creating a gesture-based interface with proximity detection and adaptive speed control. Jarvis! recognized issues with operational prompts and placement accuracy, and implemented a comprehensive verification system with real-time feedback. Robots of Babel tackled gripping errors and multilingual workforce challenges by designing a language-adaptive interface that also accounted for noise obstacles. The demonstrator's constraints and hard-coded limitations proved valuable, enabling participants to analyze timber assem-

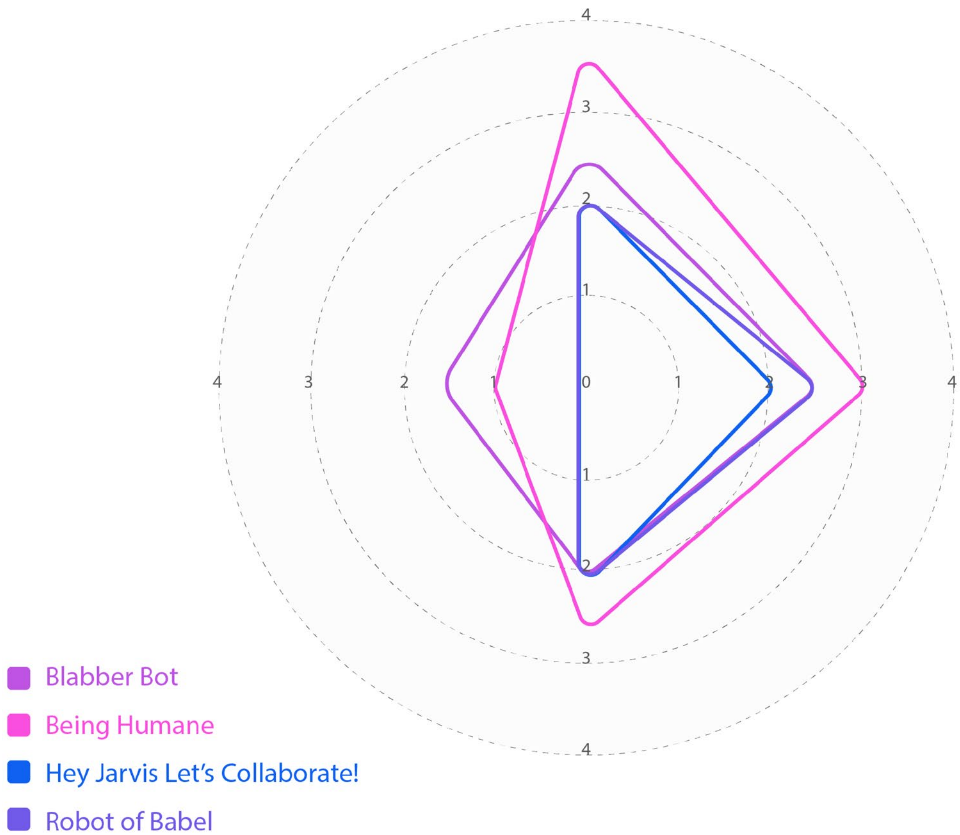

Fig. 13 FTS analysis and comparison of the four students' responsive HRC designs, developed over a four-day workshop. Students were introduced to feminist technoscience critique and its practical framework as an assistive tool, in designing for uncertainty, and for diverse users. Projects are scored points from 0 (lowest) to 4 (highest) based on their design consideration of: (1) Embodiment: user needs, well bodies, feelings of trust and safety. (2) Reconfiguration: analysis of users and tools and their contribution to the task, site, users across changing conditions. (3) Interrelations: characteristics and co-productive strengths of users and tools, task allocation, augmentation, and dependencies. (4) Participation and Reflection: diverse user feedback, its analysis, consideration and implementation, and acknowledgment of design biases. Aside from a low score on user feedback, which is the result of the short workshop timeline, the students managed to implement diverse design solutions in HRC, emphasizing user support and augmentation while being mindful of site and task relevance

bly HRC from "within" and address actual rather than assumed needs.

A notable observation was how project teams assigned different roles to the cobot. Some positioned it as an assistant, assuming most responsibilities, reinforcing a traditional command-execution hierarchy. For instance, one system explicitly framed the cobot as a subordinate rather than a collaborative peer, without critically examining how its conversational interface might restructure authority, responsibility, or trust dynamics. This static power relationship became evident when a student participant struggled to hear the cobots' voice interface amid background noise—communication failures defaulted accountability to the human rather than triggering design adaptation or shared recovery mechanisms.

While the demonstrator effectively addresses many educational objectives, one limitation was the absence of industry stakeholders, particularly workers. Future iterations could benefit from collecting feedback from these stakeholders through questionnaires, online interviews, or existing data resources prior to the workshop. This would enrich the on-site activity by allowing students to correlate their HRC hands-on experience and observations with industry realities, directly incorporating perspectives from the intended end-users.

- **H3 – Role of the Cyber-Physical Fabrication System**

  The cyber-physical fabrication system implementation by the four workflows demonstrated its accessibility and applicability. The system enabled participants to rapidly prototype and implement diverse solutions, as evidenced by their successful integration of multiple sensor types and interaction modalities. BlabberBot implemented text-to-speech and speech-to-text (TTS/STT) technologies with simple command phrases like "Start," "Stop," and "Your Turn," while Robots of Babel expanded this concept to multiple languages. Being Humane utilized computer vision for both gesture recognition and proximity detection, automatically adjusting robot speed based on users' presence. Jarvis developed perhaps the most integrated solution, combining OpenCV for position validation, voice inputs, and custom robotic gestures in a step-by-step verification system.

When facing technical and environmental challenges, the cyber-physical system's flexibility allowed adaptation and obstacle resolution. This diversity in approaches validated the hypothesis about participants' ability to understand and extend the system while demonstrating how it could support solutions that respond dynamically to real-time conditions and environmental inputs. Although the system was designed to process vision-based sensor data, three out of four groups opted for language-based interaction models. This unexpected preference for language over vision-based solutions suggests evolving trends in HRC design that merit further exploration, highlighting the growing relevance of language-based techniques and the need to explore their optimal application alongside other sensing modalities.

The projects also connected technical development to broader social issues of equity and accessibility, particularly evident in Robots of Babel's consideration of immigrant construction workers' needs and Being Humane's attention to user comfort and safety through adaptive speed control. The diverse workflows developed in three days and their testing with non-workshop participants (three volunteers total, who managed to control the robot even during grip failures) demonstrated the system's potential as a pedagogical tool, though the flexibility of the digital model underscores the importance of longer development phases for full optimization.

- **H4 - Role of the DDA Model:** The students' success in acquiring multidisciplinary skills, designing critically, and developing four diverse HRC workflows demonstrated the DDA model's value. The model effectively linked the FTS framework with technical teaching (ABxM), practical experimentation, and design exploration, culminating in responsive and varied HRC frameworks. Its congruence with the FTS framework, both emphasizing design alternatives through experimentation, reflection, and feedback, promoted situated design approaches and resilient solutions.

In the Discover phase, participants gained crucial insights through hands-on demonstrator experience. Despite limited prior experience with on-site HRC and timber construction, they recognized diverse user needs in collaborative assembly. Being Humane identified anxiety with robot movements and the need for intuitive control; BlabberBot recognized communication challenges in assembly instructions; Jarvis observed the need for error prevention in block placement; and Robots of Babel noted the construction industry's linguistic diversity. These findings helped translate real-world challenges into design priorities.

During the Define phase, students explored design goals based on their own and peers' experiences with cobots and sensors in the fabrication environment. A clear correlation emerged between encountered problems (e.g., noise interference, gripping errors) and designed solutions, leading to need-based approaches. Robot of Babel prioritized accessibility for diverse language speakers, while Being Humane emphasized safety and control in noisy environments. Observations from the HRC demonstrator served as both design drivers and evaluation criteria, featuring prominently in the culminating discussion of intents and outcomes.

In the Develop phase, structured feedback loops proved critical in refining design proposals, enabling groups to focus on specific challenges. The workshops' structured periods of design and deployment, shifting between scripting sessions, and deployment and testing with the cobot and sensors on site, illuminated additional technical challenges and user needs.

The Deliver phase demonstrated both strengths and limitations during real-world testing. Being Humane successfully tested their solution with volunteers who managed effective interaction even during grip failures. BlabberBot validated its system with a non-workshop participant who could control the robot despite noise interference. Jarvis demonstrated real-time feedback mechanisms but required bespoke lighting solutions to address shadow-induced false positives. These outcomes highlighted design scalability and inclusivity while identifying areas for further iteration.

7.1 Future Steps

Participatory Processes and Methodological Validation. To keep HRC designs both relevant and adaptable, designers must acknowledge their own biases and positionality, conduct tests with a diverse range of users, and engage in rigorous design reflection. Future workshops would benefit from longer design periods, a discussion on one's own biases, and diverse user testing, preferably with diverse industry partners or other target audiences, to illuminate industry challenges and needs, like work conditions viewed from the employees' perspective.

Extended Use and User Experience Considerations. Long-term evaluations of tasks and interfaces put the design in context: they uncover user fatigue, stress, cognitive load, and frustration. Future work in HRC for prefabrication and construction could benefit from long-term reviews, inspecting user experience, and tool adequacy over time and with changing site conditions.

Technical and Interface Improvements. Future research can explore adaptive measures in responsive HRC workflows and interfaces for diverse user needs. Such can include adjusted audio volume and display sizes, or dynamically shifting between modes of communication and collaboration to accommodate multitasking or tool use.

Methodological Contributions. HRC design workshops would benefit from a sociological review of their methods, specifically addressing how power dynamics in academic-industry collaborations affect solution development and implementation, ensuring technological advancement empowers rather than marginalizes construction workers of diverse backgrounds.

8 Conclusions

This research demonstrates how designer participation in addressing fabrication challenges and sensitization to diverse needs in HRC can lead to effective workflows in construction environments. By integrating FTS principles with behavioural fabrication through the DDA model, the study establishes a human-centered, feedback-driven educational approach that prioritizes inclusivity, trust, and safety. Tested in a 4-day workshop, it was demonstrated that theoretical frameworks can be operationalized into actionable workflows that address real-world challenges despite participants' limited prior experience with robotics or collaborative assembly. It empowered students to co-develop solutions, balancing technical innovation with social responsibility. The cyber-physical fabrication system enabled flexible integration of multiple sensor types and interaction modalities, facilitating creative, heterogeneous solutions as detailed in the Discussion.

Future validation requires deeper engagement with actual construction workers and stakeholders as design drivers, test subjects, and active co-developers. The correlation between student backgrounds and project focuses highlights both the value of diverse perspectives and the need to directly incorporate construction industry voices. Several FTS principles require further attention, particularly addressing power dynamics in user studies and including construction workers and industry stakeholders in academic discourse.

This study advocates for a more sustainable, responsive, and equitable approach to automation that serves the broad needs of diverse, dynamic construction workforces. By bridging theory and practice, it establishes foundations for inclusive, adaptive HRC processes that address current challenges while anticipating future construction industry needs, aligning with Industry 5.0 principles through participatory, feedback-driven methodologies.

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Data Availability The data is partially provided in the manuscript including a supplementary video. Additional data is currently under review for the DARUS online database: https://doi.org/10.18419/DARUS-4737. The workshop, HRC demonstrator are approved with an Ethics Committe from the Stuttgart University, AZ 23-062. All workshop participants gave their consent to participation, recording and were informed of their rights to revoke their participation.

Declarations

Competing interests The authors declare no competing interests.

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