Multi-Actor Fabrication for Digital Timber Construction

Extending the flexibility of prefabrication setups through the incorporation of multiple human actors

Felix Amtsberg[1], Xiliu Yang*[1], Lior Skoury[1], Aimée Sousa Calepso[2], Thomas Wortmann[1], Michael Sedlmair[2], Achim Menges[1]*
[1] Institute for Computational Design and Construction, [2] VISUS,
[1, 2]Cluster of Excellence Integrative Computational Design and Construction for Architecture, University of Stuttgart, Stuttgart, Germany
[1,2]{felix.amtsberg|xiliu.yang|lior.skoury|thomas.wortmann|Achim.menges }@icd.uni-stuttgart.de [2]{Aimee.Sousa-Calepso|Michael.Sedlmair}@visus.uni-stuttgart.de

The research presented in this paper focusses on the prefabrication of wood building systems using human craft and robotic machines as equal actors in collaborative fabrication processes. It uses self-developed components such as a data managing framework system to generate and exchange fabrication data between the design elements and the fabrication environment. Human robot collaboration via augmented reality (AR) technology is facilitated through a software framework and applied in the prefabrication of timber structures. Based on previous research, this iteration uses the concept of multi-actor fabrication and extends the number of human actors in the fabrication process. A case study was conducted for the collaborative fabrication of a timber structure. Five actors (four humans and one 7-axis robotic system) received instructions based on their individual skill set and collectively manufactured a timber structure in an organized workflow.

Keywords: *Human-Robot Collaboration, Augmented Reality, Multi-Actor Fabrication, Timber Construction.*

CONTEXT

This generation of planners is confronted with the crucial task to develop new sustainable building systems to reduce the environmental impact of the construction industry, which is still the largest global producer of waste, and consumer of energy and natural resources (UN 2009). One key for improvement lies in digitization, which has proven its potential to increase the productivity of almost any industry but hasn't yet fully impacted the architecture engineering and construction (AEC) environment effectively (Destatis 2023).

This issue has been addressed continually and generated a new stream of building systems, usually influenced by concepts from the car industry among others. The proposed solutions are usually product-oriented, meaning that they aim for standardized solutions, such as timber building modules that are designed to be prefabricated with highly automated prefabrication in high batch sizes (Katerra 2021). Some even work on fully automated consequently human-free lights-out factories (Randek 2021). While these concepts show an undeniable potential for a fast creation of living spaces under certain conditions, there are several issues which cannot be addressed appropriately.

Studies have shown that a significant amount of living space will have to be generated in the inner cities due to urbanization (UN 2009). Here, product-oriented timber building systems don't provide sufficiently flexible solutions for the manifold architectural demands, such as non-rectangular floorplans. Also, the building regulations change due to different policies, or different environmental conditions (snow, wind earthquakes). As a result, resource-saving and livable architecture remains on the project level and requests adaptive prefabrication solutions suitable for an efficient production of small batch sizes and one-off building components. Examples have shown that fully automated fabrication lines are difficult to be applied even in the car industry (Guardian 2018), where huge companies focus on the mass production and customization of products. In the landscape of the construction industry, where over 77 percent of sales volumes are generated by small and medium size enterprises (Destatis 2023), the financial and system resources for highly automated setups are simply not available.

Evolution: Levels of Multi-Actor Collaboration

The research of Multi-Actor Fabrication proposes a different approach. Instead of solely increasing the level of automation, it aims for a smart cooperation between humans and heavy payload machines (e.g., industrial robots) in fabrication setups. Augmented reality (AR) is used to facilitate this collaboration and a fabrication management system sorts the tasks, organizes the fabrication sequence, and distributes it to the actors over a web-based platform.

This paper presents a new iteration of this concept. In previous case studies one human worker and a 14-axis fabrication setup were similarly skilled to execute the task of slat placement but differed in their method to fix them: robot via wood nails, human via screws (Amtsberg et al 2021). This led to a fabrication sequence, where human and robot could take over for each other, and the human could correct robotic fixing failures caused by splitting nails, using stronger steel screws. Now, in this human-centered approach, multiple workers can execute their tasks in parallel and collaboratively. They can receive different tasks based on their individual skill set, enabling a reactive, more adaptive workflow, useful for the demands of timber prefabrication.

Related work

The concept of AR has been investigated in the car and aviation industry to improve the efficiency of humans involving tasks since the early 90s (Thomas 1992). In the AEC context, Newnham et al. (2018) presented a tool to establish a real-time connection between Mixed Reality devices (MR) and the Rhinoceros/Grasshopper software. It was used in many studies since, to support design and assist the fabrication and assembly processes of one-off building elements via in-situ visualization on AR-Head-mounted displays instead of drawn plans. Atansova et al. (2021) presented a workflow connecting several human workers through AR for a collaborative onsite assembly, where the design model is updated on the fly based on human decision making, which was then registered by the digital system.

Human-robot collaboration (HRC) is an ongoing field of research in many industries and has seen a strong focus on assembly tasks (Matheson 2019). Previous research investigated concepts of how (HRC) in the AEC environment can benefit from the use of AR. The project "collaborative robotic workbench" by Kyjanek et al. (2018) presented an approach where AR was used to provide access to the control system of a collaborative robot the KUKA iiwa. It allowed the sequential collaborative assembly of a timber structure. Mitterberger et al. (2022) enabled an intuitive way for human-robot interaction, transferring human gestural input into robotic motion for on-site plastering via projection-based AR. In addition to novel human-machine interface systems, digital fabrication processes involving one or multiple actors require an appropriate design-to-fabrication modelling flow to allow for smooth data handover and communication. This can be achieved by a data-model ontology that entwines design and fabrication data (Ng et al., 2022). Flexible systems for robotic control and feedback loops in digital fabrication show high potential for increasingly automated fabrication processes (Eversmann et al., 2017, Wagner et al., 2020). A scalable data structure here is important to allow for rapid changes in the design, fabrication environment, and tasks. The presented work distinguishes itself using industrial robots with high payload, usually unsuitable for HRC. It connects several humans and machines with different skill sets and enables a dynamically adaptive fabrication setup for the prefabrication of one-off components.

METHODS

As described in Amtsberg et al. (2021) and Skoury et al. (2022), the fabrication of designed building elements is broken down into fabrication tasks and match these tasks with the skill set of available fabrication actors. To implement such a process, human and robotic actors need to be integrated in the same production workflow. This requires methods to address both planning and execution stages. During the planning stage, each actor's individual skill sets are taken into consideration and matched with the required fabrication task, resulting in a task database with assigned actors. During runtime, a fabrication control system (fabrication manager) dispatches tasks and manages the progress. Machine actors receive their instructions in the form of automatically generated machine codes. Human workers' participation introduces diverse and dynamic factors which are handled by a human-oriented system that considers the skill profiles of the workers and controls the augmented reality information displayed on the headset of the work team. These methods are described in detail below.

Fabrication Manager

The methods used in this research extend a framework for managing data in multi-actor fabrication processes developed in Skoury et al. (2022). This framework features a uniform task data model that represents the different processes in the fabrication procedure while maintaining a link to the design elements. Furthermore, the framework allows the universal task data model to be communicated to the different actors in the fabrication process for execution. In this research, the framework was extended in two ways. First, by defining an actor abstraction to serve as a guideline to implement the necessary functionalities of an actor and to generalize the communication between the main server and the physical actors in the fabrication environment. Second, introducing hierarchy to the task execution process allows for each task to have a main actor and auxiliary actors, which means that one task can be sent to multiple actors either for collaborative execution or for visualization.

Actor Abstraction. The abstraction of the fabrication actors is a crucial component that enables communication with multiple actors. Abstracting and generalizing this model serves two main functions: enabling a general and actor-independent execution in the server's main loop and the flexibility to add new actors to the system quickly and easily. This abstracted model contains several essential functions that facilitate effective actor communication. The 'connect'/'disconnect' function establishes/closes a connection between the virtual and physical actors. The 'pre-send' function prepares the task to be sent to the actor, ensuring that the necessary information is formatted correctly. The 'send-task' function transmits the data to the physical actor and waits for a confirmation that the data has been received. The 'wait-for-execution' function monitors the task's progress and waits for the physical actor to inform the server that the task is completed. Finally, the 'post-send' function analyses the response data from the executed task and updates the results in the database enabling the server to move onto the next task in the process.

The actor abstraction is designed to be flexible and adaptable, enabling it to work with a wide range of communication protocols. For example, some actors may use standard communication protocols, while others may use proprietary protocols specific to their hardware or software. By using an appropriate level of abstraction, the digital fabrication server can communicate regardless of their communication protocols. Furthermore, new fabrication actors can easily be integrated into the fabrication environment regardless of their specific hardware or software requirements. This flexibility enables the framework to adapt quickly to changing needs and remain relevant and useful over time.

Main-Auxiliary Actors. In a fabrication environment, it is common to have multiple fabrication actors working together to complete a job. The introduction of main actor and auxiliary actors provides a mechanism for task reassignment when unexpected issues disrupt the process. The main actor is the primary fabrication actor responsible for executing the task. This actor is typically the most capable or specialized actor for the specific task at hand. A task is initially sent to the main actor, who takes control and executes.

However, in some cases, the main actor may encounter issues or may not be able to complete the task. In this case, the auxiliary actors come into play. Auxiliary actors are other fabrication actors in the environment that can perform the same or similar tasks as the main actor. When the main actor is unable to complete the task, one of the auxiliary actors can take over the execution. For instance, humans often act as auxiliary actors and receive visualizations of the task being executed by the main actor, allowing for better observation and coordination of collaborative processes.

AR System

An augmented reality interface is used to connect human actors with the fabrication process (Figure 1). The AR system used in the study was based on a framework presented by Yang et al. (2022). The framework defined a set of message structures that describe human and machine task visualizations in the AR environment. It also provides an integration between the head-mounted AR displays (HoloLens 2) and the fabrication manager and supports workflow prototyping through a Grasshopper plugin. The plugin allows visualizations to be constructed in the same digital environment as the design model and robotic setup, such that AR tasks can be tested prior to their inclusion into the general task model. Because visual clutter in the AR scene causes confusion and distraction for the user who operates in an environment that is already highly unstructured, this prototyping stage during task data generation is important to ensure that the AR representations are clear and user-friendly for the specific environment.

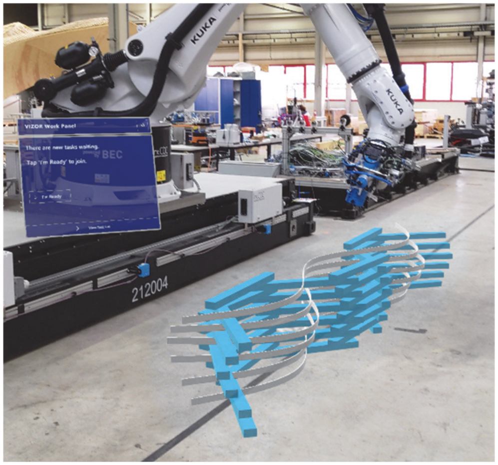

Figure 1
AR interface shown to a user at the start of the fabrication process.

To facilitate the participation of multiple users with diverse skill sets, the framework was extended with a worker pool component that orchestrates the AR information sent to each HoloLens device based on the person's individual skill profile and the skills required for each task. For the case study, these skills were assigned using results from a demographic survey which collected the participants' existing experience with robotic and timber fabrication tasks. The worker pool keeps track of the AR devices in the multi-actor fabrication system and sends the necessary information to the appropriate HoloLens. This AR system communicates with the fabrication manager through a custom client that implements the main-auxiliary actor relationship.

User Experience Evaluation
Since AR technology is integrated to facilitate the interaction between actors, it is also important to consider how such systems would be accepted from a usability point of view. A simple user evaluation was using methods from the of Human-Computer Interaction. System Usability Scale (SUS) questionnaires (Brooke 1996) were given to the participants to collect feedback about the AR interface and short interviews were conducted with the participants after they completed the tasks.

Given the multidisciplinary nature of the topic, details of the user evaluation are not addressed in this paper. Nevertheless, it is important to point out the need to implement new technology in a way that takes into consideration the acceptance by users. Given that expectations about technology from stakeholders often diverge from the actual implementation results (Wortmeier 2023), understanding best practices to implement it in real world use cases is essential.

CASE STUDY
To conduct the fabrication workflow experiment, a timber structure was designed with the goal of providing a clear rationale for dividing human and robotic tasks based on available individual skill sets. The fabrication tasks and individual actor roles are described in the following section.

Task-Skill Assignment
The timber structure is represented by a fence with even and odd layers. The odd layers (1, 3, … 11) consist of four straight timber slats which need to be placed and nailed. The even layers (2, 4, … 12) consist of three timber slats like the odd layers, in addition to a 3 m long lamella fixed with custom connectors. To build this structure four humans and one robotic actor collectively execute the fabrication tasks (Figure 2).

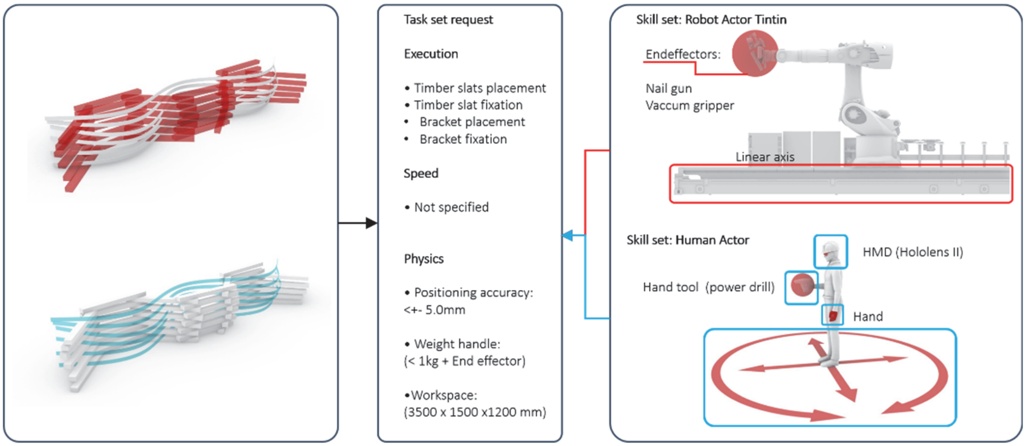

Figure 2
The timber cluster fabricated in the case study, highlighting human and robotically assembled portions in relation to the task set request and skill set availability of the relevant human and robotic actors.

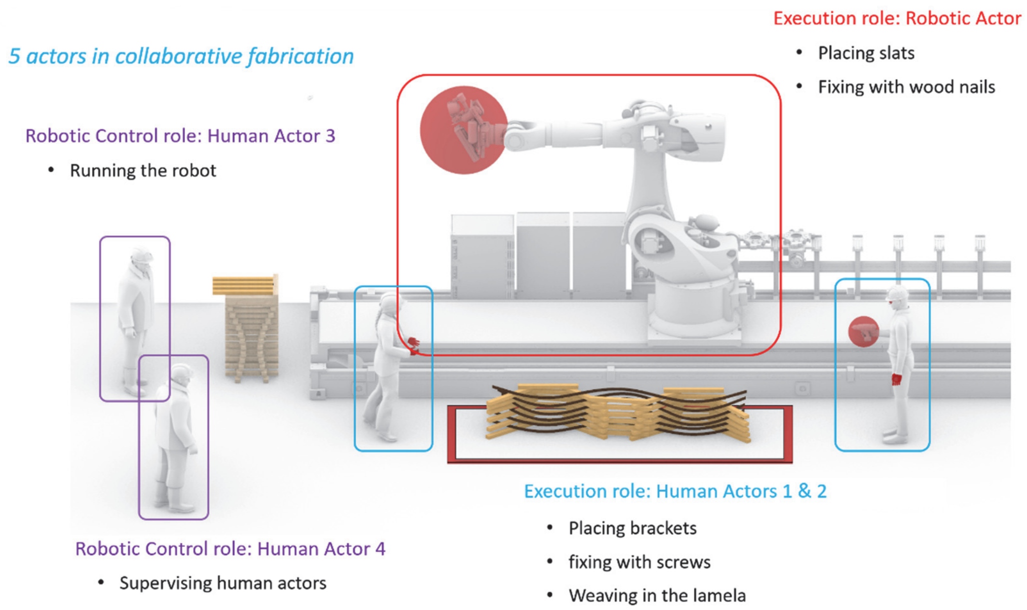

Figure 3
The Fabrication setup in the case study assigned human and robotic actors to specific roles. Purple: Control and supervision, Blue: human execution, Red: robot execution.

The industrial robot (a KUKA K 420 R3330 with a payload of 420 kg and a reach of 3330 mm) is mounted on a linear axis with a travel of 4500 mm. The end-effector is a vacuum gripper with an integrated wood nail gun. This setup enables the robot to execute the odd layers, placing the timber slats in the workspace and fixing them via nailing. The connectors and lamella could potentially be fixed with different end-effector designs, but especially the lamella requests high dexterity. They are assigned to human actors. All workers are equipped with a HoloLens 2 AR HMD, and the two workers of the execution group with a cordless power drill. They have the skills to place the connectors within the requested tolerance of <5.0 mm individually. The fitting of the timber lamella is assigned to two workers for collaborative assembly

Actor Roles

Each fabrication group involves five actors – four humans and one robot (Figure 3). The human actor tasks were designed to include not only manual execution but also other important human roles that require decision making and communication in the digital fabrication environment.

Execution Role (robot). The industrial robot places the timber slats and fixes them via nailing. After the successful execution it sends a message to the fabrication manager.

Execution Role (human). Human actors 1 and 2 carry out primary manual fabrication tasks such as fixing the custom connector and bending and positioning the lamella. Though these tasks can technically be carried out by one person alone, the execution quality and speed benefit from simultaneous participation, as one person can hold the piece steady while the other fixes it with a screwdriver. AR information shown to these two workers is synchronized, and completion of the task requires both to acknowledge.

Robotic Control Role (human). The robotic platform was run in high-speed manual mode (T2), which requires one worker to hold the robot control pendant to run automatic tasks. In all collaborative workflows tested with large industrial robots, this role is critical as the person is responsible for the actions of the robot to avoid damage to the machine tools or causing danger to other humans. Worker 3 primarily needs to focus on the movement of the robot, so they see only a list of robotic tasks which can be positioned in the AR environment and no other holographic information to avoid distraction. They also do not need to acknowledge task completion.

Supervisory Role (human). Worker 4 acts as a supervisor of the fabrication process. They do not need to execute anything manually but are tasked with detecting issues during the process and keeping an eye on safety conditions. When the robot is moving into a shared area where workers 1 and 2 might still be executing their tasks, this person is required to acknowledge a "safety check" task, to ensure the robot can continue.

RESULTS AND CONCLUSION

The research in this paper presents a new iteration of the concept of Multi-Actor Fabrication. It successfully integrates multiple human actors in a collaborative fabrication process, together with a large-scale robotic system using AR. Building up on the previous research it represents a setup more relevant for the complex environments encountered in industry. As a result, it offers a new method to equip prefabrication setups for the dynamically changing requirements of project-oriented solutions in the AEC sector.

The case study presents a situation, where human dexterity meets machine precision. All actors complement each other in the prefabrication of an expressive timber structure. The individual qualification of human craft is reflected for the first time via participation based on the individual experience levels. This marks a first step towards an individualized task assignment to the human actors. Previous research had a clear sequence and hand over between the participating actors. While one actor was working the other would pause. The collaborative task execution with more than two actors has shown that the coordination especially between multiple human actors requires a detailed planning of information distribution (what to show) and a well-coordinated workflow management (when to show it).

This aims to enable better coordination in the vibrant environment of highly automated prefabrication setups with multiple human and machine actors involved (Figure 4).

Figure 4
Robotic pick and place task (left) and human collaborative execution of the manual task by the workshop participants (right)

User evaluation collected feedback regarding participants' views on sharing the working space with the robots, on how they felt using the AR equipment and if they could see themselves using this type of tool in the future. The evaluation was done with a relatively small number of participants, but it showed that people in general enjoyed the experience with AR. They rated the interface as good (73.6/100 on SUS) and were excited about trying something new. They also mentioned feeling insecure when the robot was too close to them, which is an aspect that needs to be more deeply explored in assistant tools like the one proposed in this paper.

Outlook

Multi-actor fabrication presents an alternative approach to highly automated prefabrication setups by allowing the skill sets of individual actors to contribute fluidly towards the goals of the fabrication project. While the explicit skill set description of the robotic actors has been used for task simulation / assignment already, the human qualification is only represented on an abstract level. The implementation of individual human skills will be closely investigated in the following research period.

Similarly, machine actors can be extended beyond industrial robots to reflect a growing family of increasingly intelligent heavy-payload machinery in construction and prefabrication. These additional actors require new data formats and workflow coordination and provide new opportunities for human interaction and collaboration.

A human-centered approach to these systems is increasingly important as they begin to permeate real-world practices. Implementing technologies like this in real world scenarios should take into consideration not only the users' personal experience, but also other factors like how long a task takes and how much effort they felt was required through an extensive number of people to get significant results. It is also worth mentioning that among the participants there were people with a lot of experience in robotic fabrication and people that saw it for the first time, so further evaluation with more participants is needed for the next steps. These results will help us to improve the AR interface considering the human perspective. While this study provided us with a first opportunity to evaluate the user experience of sharing workspace and collaborating with industrial robots, careful examination of the system usability and human factors are also under way.

As part of the Cluster of Excellence Integrative Computational Design and Construction for Architecture the integration of this research into the fabrication of realistic construction typologies in full-scale fabrication scenarios is actively investigated.

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REFERENCES

Atanasova, L., Saral, B., Krakovská, E., Schmuck, J., Dietrich, S., Furrer, F., Sandy, T., D'Acunto, P. and Dörfler, K., 2022, September. Collective AR-Assisted Assembly of Interlocking Structures. In Towards Radical Regeneration: Design Modelling Symposium Berlin 2022 (pp. 175-187). Cham: Springer International Publishing.

Amtsberg, F., Yang, X., Skoury, L., Wagner, H.J. and Menges, A., 2021. iHRC: an AR-based interface for intuitive, interactive and coordinated task sharing between humans and robots in building construction. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 38, pp. 25-32). IAARC Publications.

Brooke, J. (1996), "SUS-A quick and dirty usability scale." Usability evaluation in industry, CRC Press .

Destatis Statistisches Bundesamt Website (2023). (Accessed: 28 March 2023) . Available at: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Untern ehmen/Kleine-Unternehmen-Mittlere-Unternehmen/aktuell-umsatz.html (Accessed: 28 March 2023)

Eversmann, P., Gramazio, F., Kohler, M., 2017. Robotic prefabrication of timber structures: towards automated large-scale spatial assembly. Constr Robot 1, 49–60. https://doi.org/10.1007/s41693-017-0006-2

Ghammad, B., Hu, R., Bock, T., 2022. Transforming Building Renovation: A Holistic, Strategic Approach with Construction Robot Management. Int. J. Archit. Eng. Technol. 9, 52–70. https://doi.org/10.15377/2409-9821.2022.09.5

Katerra. Transforming construction through innovation of process and technology. Online: https://katerra.com/, Accessed: 20/07/2021.

Kyjanek, O., Al Bahar, B., Vasey, L., Wannemacher, B. and Menges, A., 2019, May. Implementation of an augmented reality AR workflow for human robot collaboration in timber prefabrication. In Proceedings of the 36th international symposium on automation and robotics in construction, ISARC (pp. 1223-1230). International Association for Automation and Robotics in Construction (IAARC) Banff, Canada.

Matheson E, Minto R, Zampieri EG, Faccio M, Rosati G. Human–robot collaboration in manufacturing applications: A review. Robotics. 2019 Dec 6;8(4):100.

Newnham, C., van den Berg, N. and Beanland, M., 2018. Making in mixed reality. In Proceedings of ACADIA (pp. 88-97). Bar Harbor, ME: Acadia Publishing Company.

Ng, M.S., Chen, Q., Hall, D.M., Hackl, J., Adey, B.T., 2022. Designing for Digital Fabrication: An Empirical Study of Industry Needs, Perceived Benefits, and Strategies for Adoption. J. Manage. Eng. 38, 04022052. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001072

Randek. Zerolabor Robotic Systems. Online: https://www.randek.com/en/wall-floor-and-roof-production-lines/zerolabor, Accessed: 20/07/2021.

Skoury, L., Amtsberg, F., Yang, X., Wagner, H.J., Menges, A. and Wortmann, T., 2022, September. A Framework for Managing Data in Multi-actor Fabrication Processes. In Towards Radical Regeneration: Design Modelling Symposium Berlin 2022 (pp. 601-615). Cham: Springer International Publishing.

Thomas, P.C. and David, W.M., 1992, January. Augmented reality: An application of heads-up display technology to manual manufacturing processes. In Hawaii international conference on system sciences (Vol. 2). ACM SIGCHI Bulletin.

United Nations, “Buildings and Climate Change: Summary for Decision Makers,” pp. 1–62, 2009, doi: https://doi.org/10.1127/0941-2948/2006/0130.

Guardian, https://www.theguardian.com/technology/2018/apr/16/elon-musk-humans-robots-slow-down-tesla-model-3-production (Accessed: 28 March 2023)

Wagner, H.J., Alvarez, M., Groenewolt, A., Menges, A., 2020. Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion. Constr Robot 4, 187–204. https://doi.org/10.1007/s41693-020-00038-5

Yang, X., Amtsberg, F., Skoury, L., Wagner, H.J. and Menges, A., (2022) “Vizor, facilitating cyber-physical workflows in prefabrication through augmented reality,” CAADRIA proceedings. Available at: https://doi.org/10.52842/conf.caadria.2022.2.141.

Wortmeier, A., Sousa Calepso, A., Kropp, C., Sedlmair, M., Weiskopf, D., (2023) Configuring augmented reality users: analysing YouTube commercials to understand industry expectations, Behaviour & Information

Technology, DOI:
10.1080/0144929X.2022.2163693