INFORMING USER-CENTRED APPROACHES TO AUGMENTED CUSTOM MANUFACTURING PRACTICES

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Abstract. This practice-based research presents insights into the potential and challenges for augmented and mixed reality (AR/MR) technology to enhance Australian small-to-medium (SME) custom manufacturers' agility to overcome existing Industry 4.0 (I4.0) workforce productivity and efficiency challenges. Moreover, it seeks to understand the technology's ability to support custom manufacturers and the architectural, engineering and construction (AEC) sector transition to a more human-centric Industry 5.0 (I5.0) model, whereby the well-being of the fabricator is placed back at the centre of manufacturing processes. This qualitative study draws on interviews with eleven Australian custom manufacturing industry professionals to inform pertinent themes around fabricators' current use and perceptions of mixed reality technology. Results indicate benefits for fabricators in reducing 2D drawing and task-related ambiguities in fabrication and assembly practices and reveal factors surrounding underutilisation. Synthesising insights and reflecting on Teixeira et al., (2021)'s XR-PACT framework, key research areas are identified for future AR/MR development centred on fabrication users' distinct needs to improve accessibility, empower fabricators and ultimately assist the competitiveness of custom manufacturers and the AEC sector.

Keywords. Augmented and Mixed Reality, Custom Manufacturing, SME, User-centred Design, Industry 5.0

1. Introduction

The past decades have seen the architecture, engineering, and construction (AEC) industry and adjacent manufacturing sector experience rapid transformation through Industry 4.0 (I4.0) technologies such as robotics, artificial intelligence (AI), the internet of things (IoT), augmented and mixed reality (AR/MR). However, as computation and connectivity drive further automation and increased process efficiencies, often, the human costs of this optimisation can be overlooked (Nahavandi, 2019). In complement to I4.0, Industry 5.0 (I5.0) seeks to place human worker's well-being back at the centre

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of manufacturing processes, whereby human-machine collaboration extends worker capability, circular practices reduce industries' climate impacts, fostering resilient industries, and improved social conditions (Commission et al., 2021).

The current I4.0 paradigm is already challenging Australian custom manufacturing small-to-medium-sized (SMEs) who require support to counter severe skills shortages and increased agility to deliver high-quality products for evolving consumer preferences (DISER, 2020). With further production on-shored due to COVID-19 supply chain disruptions, lack of access to fabricators limits Australian manufacturers' capacity causing significant delays across sectors, including AEC. As such, industry peak body Weld Australia (2022) forecasts shortages of seventy-thousand welders by 2030 to meet Australia's future manufacturing objectives.

Operating at the core of the Australian AEC industry, custom manufacturers' workforces are hampered by challenges in fabricating and assembling increasingly complex products using limited 2D drawings and unintuitive labour-intensive manual processes. In response, some Australian custom manufacturers have embraced the assistive qualities of AR/MR technologies to improve their fabricators' productivity and ultimately contribute to the organisation's overall competitiveness. However, despite the significant benefits of AR/MR, SMEs can be reluctant or lack the time, resources and expertise to explore the technology's integration, contributing to low AR/MR adoption rates (AMGC, 2022).

In this paper, AR/MR is used interchangeably as spatially anchored virtual content, manipulated through natural gesture inputs afforded by the Microsoft HoloLens 2 see-through optical display, as defined in related publications (Liu et al., 2021).

This research seeks to understand how AR/MR technology can benefit custom manufacturers and the reasons preventing further adoption. In doing so, we foster insights around the human-centric theme of CAADRIA 2023 about 'the practical and real-world application of AR/MR technology to advance broader social well-being' by empowering fabricators and enhancing their workplace environments.

2. Toward Industry 5.0

As I4.0 innovation continues unabated, human workers can be left out of the loop in advanced manufacturing systems or unable to adapt to the evolving skillsets required—profoundly changing workforce dynamics and industry's role within society, with implications for broader society (Commission et al., 2021). To address these concerns, I5.0 proposes to extend I4.0s positive aspects by leveraging human ingenuity and machine efficiencies (Maddikunta et al., 2022). Whereby the human needs of the worker are at the core of sustainable processes, emergent technologies adapt to workers' needs and respect their fundamental human rights (Commission et al., 2021).

Increasingly I4.0 transformation impacts the fabricators at the heart of custom manufacturing practices producing low-volume and bespoke products such as architectural elements, facades and large-scale artworks. Increased computational power allows designers to create increasingly sophisticated parametric 3D computer-aided (CAD) designs. However, fabricators still rely on interpreting complex 3D digital designs using limited 2D drawings to materialise intricate 3D artefacts. Managing complex digital design data in this inefficient manner bottlenecks production and is among SMEs' and the AEC industry's greatest challenges (Côté et al., 2013). Moreover, fabricators often materialise complex artefacts using labour-intensive manual machine processes. These machines rely on the operators' tacit skills as they lack the assistive visual feedback that expensive computer numerically controlled (CNC) machines provide. Although CNC and robotics can be beneficial, the financial, process and human implications may not align with SMEs' current business strategy.

This paper addresses the following research question: "How can Australian custom manufacturers integrate AR/MR technology in their fabrication and assembly processes?" In exploring this question, we seek to understand the experiences of industry experts who have integrated AR/MR and those exploring its use to guide future research agendas which extend the technology's benefits to further SME workforces. We propose that AR/MR technologies are valuable for custom manufacturers as they enhance human workers' agency and productivity and contribute to more enjoyable working environments. AR/MR has been shown to facilitate positive outcomes for fabricators by improving task cognition and reducing reliance on 2D drawings, markedly lessening error, re-work and waste (Jahn et al., 2018) while synergising human and human-machine collaboration (Hahm et al., 2019). All critical factors to consider in moving to a more human-centric I5.0.

AR/MR technology has been researched across many facets of AEC (Davila Delgado et al., 2020) and manufacturing (Bottani & Vignali, 2019), addressing aspects such as prototyping, training and assembly. However, AR/MR use has been limited in practice by factors such as accessibility, user interface design, accuracy and latency (Cheng Jack C. P. et al., 2020). In the following sections, we describe the methods, findings and reflections on Teixeira et al., (2021)'s XR-PACT framework, identifying key areas for future research to focus AR/MR development on fabricators' requirements in response to the sentiments, needs and experiences of industry experts.

3. Methods

This paper reports on eleven semi-structured interviews conducted between February to June 2022 with custom manufacturing professionals from five Australian SMEs across AEC and complementary industries, summarised in Table 1.

Table 1. Summary of interview participants, accompanying SME, job role and

Participant ID	SME ID	AEC background	Role	Interview Format
1	A	AEC consultants in manufacturing, design development and management	Technical Supervisor	Virtual
2	A	AEC consultants in manufacturing, design development and management	Head of Fabrication	Virtual
3	B	AEC consultants in manufacturing, design development and management	R&D Manager & Robotics Engineer	Virtual
4	C	Custom manufacturing consultant	Senior Engineering Supervisor	Face-to-face
5	C	Custom manufacturing consultant	Project Development Manager	Face-to-face
6	C	Custom manufacturing consultant	Mechanical Engineer & CAD Drafter	Face-to-face
7	C	Custom manufacturing consultant	Mechanical Engineer & CAD Drafter	Face-to-face
8	C	Custom manufacturing consultant	Head of Fabrication & CAD Supervisor	Face-to-face
9	C	Custom manufacturing consultant	Managing Director & Chief Engineer	Face-to-face
10	D	AR/MR software development company/integrator	Co-founder & CEO	Virtual
11	E	Custom manufacturing consultant	Project Manager & Lead Engineer	Face-to-face

interview format.

Participants ranged in experience from 4-30 years. They included custom manufacturers' technical staff responsible for developing AR/MR responses, such as engineers, designers, CAD drafters and supervisors, managers solely responsible for the technology's adoption, software developers/integrators and lead fabricators responsible for undertaking and coordinating fabrication and assembly tasks. Noting that P4-P9 from SME C were exploring AR/MR adoption, whilst all other participants were experienced users of AR/MR technologies.

The interviews employed open-ended questions to understand users' experiences and perceptions of AR/MR technology. Examples of questions employed include: "What are some of the key learnings to adopting and integrating new technologies such as AR/MR in your design and manufacturing processes?" and "What are some of the main challenges you face when implementing new technologies?

3.1 ANALYSIS

A reflexive thematic analysis (Braun & Clarke, 2021) was used to interpret and analyse patterns across the qualitative dataset to develop themes based on the analysis of audio-recorded transcripts. Initial open codes were tabulated in NVivo software with refinement phases culminating in visual clustering of higher-order themes through affinity mapping.

In the results section, we outline findings from the reflexive thematic analysis by referring to participants' (P…) quotes around significant themes.

4. Results

In revealing Australian custom manufacturing professionals' experiences with AR/MR, the interviews raise significant questions about SMEs and the AEC sector's future adoption of the technology. For example, according to a software integrator, AR/MR is embraced as a valuable tool in fabricators' "toolkit to produce some high-quality goods" (P10), providing useful information during fabrication and assembly tasks, with fabricators reporting improved agency and confidence. However, fabricators exploring AR/MR adoption felt stymied by technical staff and management uncertain about the necessity for the technology's adoption.

4.1 FABRICATORS WELCOME AR/MR USE, BUT TECHNICAL STAFF ARE APPREHENSIVE

Among non-AR/MR users, some technical staff felt fabricators required considerable convincing of the technology's feasibility and "proving that it would work" (P6), anticipating sentiments of "this sort of stuff is futuristic, Sci-Fi… not in my lifetime" (P4). However, in discussing SMEs' experiences integrating the HoloLens, fabricators' responses appeared to be typically positive, "once they put it on, they can immediately understand how it is going to assist them in their fabrication approaches" (P1). In particular, "HoloLens is that one piece of technology that fabricators on the floor have always positively engaged with" (P1) as it "enhances worker capability across all skill levels" (P10). Improving the fabricator's capability in custom manufacturing is critical due to the prototype often being the product sold. As an experienced fabricator stated, “We have got one shot, and these glasses give us the best shot” (P2).

In contrast, management and technical staff appeared apprehensive about the technology correlating with P1s’ experience “usually, there is a real positive association with people who aren’t programming the technology”. According to AR/MR software developer and integrator P10, SMEs desire turn-key and off-the-shelf solutions and do not want to “do the time investment”. Currently, effective use of the technology requires on-site development support to iterate and adapt real-time responses to nuanced production processes, “if you aren’t able to adjust your workflow… suddenly, it becomes quite useless to you” (P1). In addition, while the initial device cost is relatively low, there is the “investment in someone actually to manage that and run it” (P1).

SMEs may also need to factor in issues around interoperability with existing CAD systems and potentially upgrade their digital infrastructure to leverage the technology’s potential. For example, custom fabricators may lack certain digital skills, as “often … the digital information that the manufacturers have… it’s not enough” (P10). Moreover, according to P11, technical staff may have difficulty or resist learning new applications due to feeling “it’s not in their best interest personally”. Fabricator P2 suggested management staff could fear AR/MR adoption due to their staff’s better understanding of the technology and not being “on top of it” enough to manage it.

4.2 AR/MR helps reduce numerous ambiguities fabricators face in the workshop

Discussions with participants highlight that the descriptive limitations of 2D CAD drawings cause miscommunication between designers and fabricators, who also contend with numerous task-related ambiguities to materialise complex artefacts. The following sections explore how fabricators identify AR/MR as a powerful tool for reducing these ambiguities.

4.2.1 AR/MR Removes 2D Drawing Ambiguities

AR/MR technology provides fabricators with at-scale, contextual visual information, improving comprehension of complex 3D CAD geometry; as P1 explains, “there’s no way you’re going to draw it and understand it better than just looking at it in AR” (P1). Using AR/MR, fabricators can overlay 3D content to compare virtual objects with their physical counterparts, which “shows you where there are any clashes… before we have to deal with it” (P2). Fabricators found virtual cross-references improved their confidence to move projects forward, as traditional 2D drawings did not alert fabricators to accumulating errors, leading to costly downstream impacts, whereas AR/MR “takes out that guesswork” (P2). An integrator explained how AR/MR helps fabricators by providing “digital information, in situ, on location, in reference to where you are (P10)” in doing so, it makes “the work environment… more enjoyable… by reducing that ambiguity and making workers’ lives easier” (P10).

Participants indicated AR/MR’s ability to reduce ambiguity as instrumental in fabricating amorphous and highly irregular artefacts, which can be difficult to describe given 2D drawings’ limited descriptive abilities. Resulting in fewer chances of fabricators “misinterpreting complex drawings” (P1) and avoiding the following scenario an integrator described, “the shop drawings didn’t really show me… I went and made it… the designer was like that's not what I meant" (P10). AR/MR allows fabricators to interpret better what is intended, spot issues earlier, and communicate concerns more fluently to design teams. Improving communication with design teams can empower fabricators, help them voice insights, and bridge transdisciplinary understanding. In AR/MR, fabricators can walk designers through fabrication issues in context, explain why certain design aspects are unachievable and propose alternate fabrication approaches. For example, P10 described how fabricators had walked designers through a particular issue, "that is going to be too weak of a joint. I am not going to be able to do that" as a result, designers developed a timely design response.

Collaborative AR/MR experiences can also help reduce ambiguities within fabrication teams by assisting collective problem-solving, as it is "easy to workshop how you're going to build something" (P1). Within a shared AR/MR environment, fabricators can better impart their tacit knowledge to co-workers, as it is "almost impossible to instruct someone … with traditional approaches" (P2). Also, AR/MRs' ability to synchronise multiple workers in the construction of artefacts can increase the "speed that you can produce things dramatically" (P10).

The fabricators using AR/MR in this study found that "AR is really good for getting things about right… good for approximation… it is not a precision-based tool" (P1). As such, the technology has been embraced by SMEs in the AEC industry, working with wide tolerances, where any improvements in tolerance through AR/MR are "hugely beneficial" (P1).

4.2.2 AR/MR Reduces Manual Process Ambiguities

Using AR/MR helped fabricators reduce laborious manual markup and set-out of difficult-to-datum curved-shaped objects, resulting in improved worker confidence due to less time spent double-checking, "It gets rid of all the squares, the levels, the laser lights, the plumb bobs; it is amazing" (P2). One task typically requiring an entire day now only takes P2 forty-five minutes to complete, with a "higher level of accuracy".

Fabricator P8 expressed a desire to adopt AR/MR to realise similar benefits for their practice, "to be able to mark something up quickly, double-check it… speed the process up immensely". For example, manual press brake machine limitations made it difficult for experienced fabricators to fold complex curve-shaped artefacts "if I'm doing something straight, it is fine… if it's not square, this one doesn't excel at it" (P8). Moreover, P8 had difficulties recruiting skilled fabricators to fold sheet metal parts, impacting the organisation's approach to product design "we try and avoid large milling jobs, we've got a lathe and mill, but only one person (P8) can operate them" (P5). As such, P8 suggested AR/MR is needed for training apprentice fabricators, "I can show them a couple of times… give them a digital twin of the overlays, more confidence, quicker turnaround, and quicker training".

P8 also wanted to improve the entire sheet metal folding process, beginning with manual scribing operations, a time-consuming, error-prone task relying on a "measure twice, cut once" philosophy. In contrast, P8 proposed using AR/MR to replace manually scribed lines at given fold locations with 2D virtual lines. Also suggesting sheet metal parts and the machine could have attached QR and ArUco markers to allow the HoloLens 2 device to track part orientation, position, and fold progress in relation to physical press brake operations. There was also a need to prototype and test part folding on the fabricator's machinery, which consumed large amounts of wasted material and time, "have buckets of test pieces… just got test piece, test piece, test piece" (P8). Finally, P8 sought an AR/MR overlay simulating the entire fold sequence in-situ to help fabricators pre-empt task requirements and use the machine more confidently, as the manual press brake offers workers little visual feedback or indication of progress during tasks, "it is the feedback… if I can get that feedback right here while I'm doing it…I would be keen to try it".

4.3 tHE use CASEs FOR AR/MR INTEGRATION are NOT CLEAR

While there is evidence that AR/MR is used for fabrication and assembly tasks (in the AEC sector), our participants reported that there are uncertainties regarding use cases for AR/MR in custom manufacturing processes, "no one knows what they are doing with the technology… no one knows the best practices for it…the best use cases for the technology" (P1). However, an area where AR/MR technology appears to excel at is assisting fabricators in assembling complex objects by providing easy-to-follow instructions "they build the entire apartment in a factory… ship it out, and like Lego bricks, stack it up" (P10). Assembly instructions are common to most projects and follow a similar methodology, "the most straightforward application… assisting the assembly of complex objects is easy to see the value in many projects" (P1).

In discussing the technology's benefits for fabrication tasks, AR/MR responses seemed best suited to highly repeated processes as significantly more development was required than augmenting assembly processes. Depending on the complexity of the fabrication process, expert teams could take several months to develop a suitable AR/MR response, "and after months of development, the AR application is not used" (P1). AR/MR fabrication approaches appeared most useful when they can be easily adapted to similar tasks "they're the same process where it's shipbuilding, building a railway car, you're all bending steel, they're welding things together… they all hit the same problem" (P10). SMEs can also experience distinct advantages by developing augmented fabrication approaches. For example, "if there is a modular construction company, there would be enormous benefits for them to develop a particular fabrication workflow for something they continually repeat" (P1).

4.4 tHE BUSINESS CASE FOR AR/MR INTEGRATION IS UNCLEAR

Given the limited knowledge around AR/MR use cases, participants expressed doubts about adopting the technology, posing questions such as "what's the return on investment" (P4) and "how can it be monetised" (P9), and "it's the justification… quantifying the ROI… that is the tricky part" (P4). This lack of clarity around the technology's use is apparent when talking to technical staff, "I feel it takes a little while before it's accepted and…needed" (P6) and "it's new, people don't have an understanding of the business model" (P9). The ambiguity around the AR/MR business case made getting management buy-in for the head fabricator impossible. P8 explained that integration was stymied largely due to management's previous negative experiences with emerging technologies "so many either over promise and under deliver…fail or they're just not there yet".

Fabricator P2, explained that companies may be unsure whether to invest resources now or "wait till the technology is better… we're going to spend all this money, and it's not going to be 100%". P11, who implemented the first digital transformation of an Australian custom manufacturing SME from 2D paper-based workflows, agreed that it is difficult for SMEs to adopt AR/MR technology when there is ambiguity around the use case, as "people just don't want to wrap their head around it" and suggest SMEs require further research and use case examples as "it helps to create pathways, …makes it easier for the industry to get on board".

AR/MR adoption is perceived as a risky investment for SMEs compared to larger enterprises; as P2 explains, "the R&D… is not as big an impact for large companies as it is for small or medium companies", along with the price point of current devices, "I think the price is going to be the biggest killer in the smaller market". In addition, technical staff expressed concerns about headset use on the factory floor and on-site due to potential health and safety risks around visual distractions. Whilst fabricators experienced issues around latency "as it can be glitchy, can get drift sometimes" (P2). Management staff also expressed concerns about how the technology will be supported to avoid extended downtimes and avoid the following scenario, "here are the glasses…good luck…we'll see you in six months when you've smashed them (P9).

5. Discussion and Conclusion

In discovering Australian custom manufacturing experts' challenges and opportunities in adopting AR/MR technology, the themes identified in this study raise important questions on how future AR/MR development can make the technology more accessible to fabricators in the manufacturing and AEC sectors. While technical obstacles with current-generation AR/MR devices require further development, discussions indicate significant cultural barriers contribute to low adoption rates. SMEs require further knowledge of AR/MR use case benefits to inform prospective business models that consider the unique and complementary nature of AR/MR technology to bridge fabricators' information and communication gaps in practice.

Fabricators identified AR/MR as a valuable tool for reducing ambiguity in their fabrication and assembly activities, reporting increased task confidence and improved work lives. AR/MR was perceived as less threatening to livelihoods than other I4.0 technologies, such as robotics; as P10 stated, "I am not worried about losing my job because someone still needs to wear the headset". However, as an emerging technology confined to small pockets of use, custom manufacturers' management and technical staff were uncertain about how to integrate the technology and whom to seek integration assistance from. SMEs require support to equip their workforce and acquire the necessary skill sets to implement the technology as, according to fabricator P2, AR/MR will be demanded by "the young people who are coming up through the trades now…they are really excited by this technology".

Based on findings and moving toward an I5.0 model, a user-centred focus is sought to ensure fabricators do not become passive adopters of AR/MR but rather play an instrumental role in SMEs and the AEC sectors' long-term use of the technology. As such, we consider Teixeira et al., (2021)'s XR-PACT framework employing Benyon, (2018)'s People-Activity-Context-Technology (PACT) analysis to advocate for user-centred extended reality (XR) development approaches in the AEC industry. In doing so, XR-PACT, described in Figure 1, outlines a comprehensive approach to user-centred XR development by considering and making explicit the intertwined relationships comprising the technology's use.

In line with sentiments expressed by participants and reflecting on Teixeira et al., (2021)'s XR-PACT framework, we propose further framework development centred on the AR/MR use needs of custom SME fabricators. As described in the shaded rectangles shown in Figure 1, we outline two prospective areas for consideration. First, we seek an improved understanding of the type of digital information fabricators require during tasks and how to convey best and express this information to enhance their practice. Second, explore further the opportunities and limitations of AR/MR solutions to assist fabricators across various custom fabrication and assembly practices.

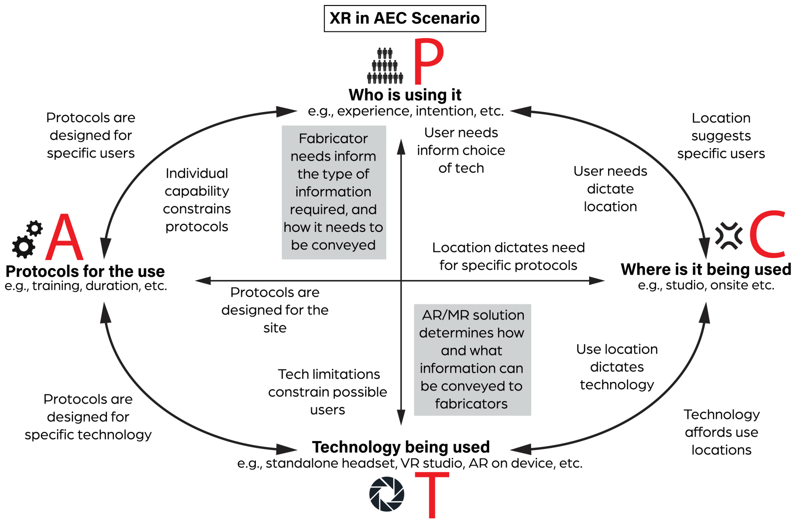

Figure 1. The author's recreation of Teixeira et al., (2021)'s XR-PACT framework. Key areas for future research are described in the shaded rectangles adjacent to Participants and Technology.

Historically, industrial process improvements have tended to spend significant amounts of time refined in the manufacturing sector before filtering through to the AEC sector. However, this study highlights how AR/MR approaches informed largely by AEC practice can also benefit fabricators in the manufacturing sector, outlining to the CAADRIA community the need for improved dialogue and cross-sectoral learnings to enhance fabricator practices and work lives across industry.

The next phase of this study aims to build upon Teixeira et al., (2021)'s user-centred XR-PACT framework in developing an AR/MR PACT framework, informed through a series of AR/MR custom manufacturing workshops with expert fabricators. The workshops will aim to foster insights around the two key areas outlined in Figure 1 and potential areas indicated by fabricators to help guide the development of future AR/MR responses centred on the specific user needs of fabricators.

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