A CRITICAL APPRAISAL OF MIXED REALITY PROTOTYPING TO SUPPORT STUDIO DESIGN EDUCATION

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ABSTRACT

Mixed Reality (MR) technologies are widely available and applied in a variety of design and engineering applications. MR prototypes capture the respective benefits of physical and digital prototypes by merging these domains saving the time and resources required to create them. This advantage is compelling in the context of design education where tight time and resource constraints exist. However, it is known that new digital prototyping tools can cause problems for students applying appropriate prototyping tools during practice-based studio design projects. Our paper contributes a systematic appraisal of MR prototyping's proposed dimensions value against constraints and issues in design studio education. This highlights MR Visualisation and Knowledge Management dimensions as most readily realised in education. Recommendations are then reflected on via an illustrative case study into the implementation of MR prototyping via these dimensions. Reflections corroborate the value proposition, but also highlight a need for further research exploring activities to scaffold MR prototyping to further support reflective design thinking.

Keywords: Industrial design, Design education, Fidelity, Prototypes, Virtual reality

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1 INTRODUCTION

Mixed Reality (MR) technologies are becoming more widely available and applied in a variety of design and engineering applications. Prototyping is one such application where MR prototyping tools blend physical and digital domains. An ongoing area of design research is in determining the trade-off in terms of maximising the support offered by various prototyping tools while minimising the resources expended (Starkey et al., 2019). MR prototyping tools are significant as the merging of physical and digital domains offers the possibility to capture the respective benefits of physical and digital prototyping tools (Kent et al., 2021), while saving the time and resources required to create them.

While the technology's availability in industry is growing, its role in design education in terms of supporting students practice based learning via design studio projects is unclear. Furthermore, research shows how educating students in prototyping is not as easy as mimicking industry practices (Crismond and Adams, 2012; Deininger et al., 2017). This is due in part to constraints of the tertiary education setting (limited time, resources, and project scope, prerequisites and threshold skill levels), along with issues identified in extant literature such as, ongoing student preference for high fidelity prototyping (Ranscombe et al., 2020; Robertson and Radcliffe, 2009), sunk cost effects, and fixation (Viswanathan et al., 2014). Hence the potential value offered by MR prototyping tools require appraisal with these factors in mind to understand challenges that could arise from implementation, but also opportunities to support student prototyping and mitigate known issues. Thus, the major contribution of this paper is the a critical appraisal to achieve said goals. The application of said appraisal is then illustrated via an illustrative case study where qualitative thematic analysis is used to reflect on the opportunities to support prototyping efforts in studio design education.

The paper proceeds with a review of literature on practice-based learning and design studio education, known issues in prototyping, and finally recent research on MR prototyping and the value offered to industry (section 2). This forms the basis for the critical appraisal (section 3), resulting in a systematic review of opportunities and challenges in implementing MR prototyping and harnessing the proposed value. An illustrative case is presented in section 4 to illustrate an application of the appraisal in the creation and implementation of MR prototyping within a design studio course. Finally, conclusions and further work are discussed in section 5.

2 LITERATURE REVIEW

Relevant literature is surveyed as follows. First the context of practice-based studio design education is outlined explaining the qualities desired but also constraints and factors that ultimately make student prototyping more complex than the industrial setting. Next literature on key issues experienced by students in prototyping at different fidelities is outlined, further clarifying the extant challenges in teaching and implementing prototyping within practice-based studio design projects. Last, an overview of MR prototyping tools and how they can merge respective strengths of physical and virtual prototyping is given, leading on to the recently established dimensions of value offered by the tools on which this research builds.

2.1 Practice based studio design education and constraints

An essential element of design and engineering education is the undertaking of design projects that reflect industrial realities (Frank et al., 2003). Such studio design projects typically occur via practice-based learning whereby students undertake the creation of an engineering or design solution within a unit. The emphasis on practice-based learning (i.e reflecting engineering and design practice) forms the basis to teach students the design process and designerly ways of thinking. It also scaffolds opportunities to learn and implement essential design skills, such as prototyping, to support efforts in design thinking and process. An assumption that underlies the practice-based studio model, and the research in this paper, is that best practice in industry aligns with best practices taught to students. Thus, we approach the critical appraisal from the standpoint that the value of MR prototyping tools proposed to practitioners is the same for students in the practice-based studio setting.

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Within such projects, it is well understood that the fundamental process of design revolves around the creation of prototypes to be learned from, to in turn further develop and refine an idea (Cross, 1982). This has been referred to as a dialogue with self (Goldschmidt, 1991) or reflection in action (Schön, 1983). For the purpose of this paper we use terminology from Crismond and Adams (2012), "Reflective Design Thinking" describing this practice as an objective for teaching students to become proficient designers. To facilitate reflective design thinking, student design projects must begin without a predefined solution. In other words, the solution space must be broad enough to allow students to practice reflective design thinking via exploring, prototyping and testing designs over multiple iterations, leading to a refined outcome at the end of the teaching period.

Creation of pedagogy that delivers the above experience of reflective design thinking is subject to a number of constraints. First the duration of a studio project is dictated by teaching periods. This puts constraints on the time available to work through the design process. This manifests in the time available to create a given prototype iteration, and subsequently the number of iterations that can be achieved. Second, the project scope needs to be managed in terms of the level of solution searching versus the level of resolution that is required. With limited time, a project requiring a more resolved outcome will trade-off opportunity to explore a broader solution space and vice versa. Finally, the threshold skills of students to create prototypes at the heart of the reflective design thinking process must be considered. Students at the start of their education are less fluent with the range of prototyping tools at the disposal of professional designers. Ideally these skills must be practiced in the context of the design process (Frank et al., 2003). However, the non-prescribed brief and shortened time frames of studio-based projects mean selection and application of suitable prototyping tools varies. In summary, while studio practice-based projects aim to emulate industry, the time and resource constraints along with threshold skills of students create a situation where selection and implementation of prototyping tools is not straightforward. The following section describes some of these issues in more detail with respect to the relative fidelity that different tools can achieve.

2.2 Fidelity and application of design tools in engineering and design education

The influence of new or emerging prototyping tools on both practitioners and students is an ongoing topic of design research. Investigating the influence of CAD tools, it has been found that students have a preference to use tools with capacity for high fidelity compared with other tools suited to low fidelity (Lawson, 2002;Ranscombe and Bissett-Johnson, 2017;Robertson and Radcliffe, 2009). This preference is noted as causing a number of issues related to student's ability to use tools to support reflective design thinking as they progress through the design process. Namely that their capacity for idea fluency becomes more limited (Robertson and Radcliffe, 2009), i.e. their ability to create multiple design alternatives is hindered (Häggman et al., 2015). This can be caused by limited threshold skills to operate tools (Lawson, 2002), but even with higher skills, the embodiment at high fidelity is known to lead to design fixation (Viswanathan et al., 2014), and ultimately an unwillingness to iterate designs (Robertson and Radcliffe, 2009). This is described as the "sunk cost" effect (Viswanathan et al., 2014), referring to the resources invested in creating a prototype leading to the unwillingness to iterate a design. On the reverse, it is known that low fidelity prototyping tools promote idea fluency (Ranscombe et al., 2020). Limited idea fluency, fixation and sunk cost effects are extremely problematic from the perspective of reflective design thinking as inability or unwillingness to iterate is in effect an inability to follow the design process. Within the design process followed during practice-based studio design projects, there is a need for iteration towards a resolved outcome. This requires students to navigate the breadth of prototyping tools available to them, transitioning from lower fidelity tools supporting idea fluency to high fidelity supporting resolution. However due to the issues explained above, prototyping tools themselves can disrupt students reflective design thinking rather than support it. Thus, while potential of new and emerging technologies for prototyping are compelling, they can also create issues in design education. It is in consideration of these issues alongside proposed benefits that we base our critical appraisal.

2.3 Mixed Reality Design Tools

As outlined in the introduction, the availability of mixed reality tools has significant potential to change and improve the design process. To understand the breadth of mixed reality tools and their

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value within the design process, we draw heavily on the systematic review and framework of potential value that MR prototyping tools can bring to practicing designers and engineers in Kent et al. (2021). To date this is the most comprehensive review of mixed reality design tools, and thus also the most comprehensive in distilling the underlying value tools can offer to engineers and designers. Table 1 adapted from Cox et al. (2022) is used to provide an overview of state of the art MR prototyping tools. Notable in Cox et al. (2022) is the wide array of tools spanning physical and virtual, but also the range of fidelity that some tools support, while others tend toward higher or lower fidelity.

Table 1 Overview of new and emerging MR prototyping tools derived from Cox et al., 2022)

Virtuality/Physicality	MR Prototyping technology	Example(s)
Virtuality	Mixed Reality Headset	Microsoft HoloLens, MagicLeap, etc.
Virtuality	Virtual Reality Headset	Valve Index, Oculus Rift, etc.
Virtuality	Screen-Based Augmented Reality	Vuforia, Adobe Aero, Echo3D, etc.
Physicality	Haptic Gloves	HaptX, Dexmo, etc.
Physicality	Robotic Arm (Force Feedback)	Mantis Force Feedback, Kuka, etc.
Physicality	Motion Tracking and Capture	Kinect, Leapmotion, Fiducials, etc.
Physicality	Physical Substitute Model	Rapid prototype, Junk prototype

At the highest level, the promise of MR prototyping tools is to blend levels of fidelity and virtuality physicality present in current tools. Blending thus presents opportunities to save time and resources when transitioning between tools, referred to as “transition time”. This overall value proposition is highly compelling in the constrained context of design education. Specific dimensions of value of MR prototyping tools that are appraised in this paper are Creation and Configuration, Visualisation, Knowledge Management, Integrated Analysis, and Collaboration. Definitions of each dimension are provided within the critical appraisal (sections 3.1 – 3.6)

3 CRITICAL APPRAISAL OF MR PROTOTYPING TOOLS FOR IMPLEMENTATION IN STUDIO DESIGN EDUCATION

The critical appraisal seeks to understand the possible implications of new MR prototyping tools prior to implementation. The appraisal assesses the extent that dimensions of value offer opportunities, or present challenges to educators considering the factors outlined in 2.1 and 2.2. For the purpose of this article, we define opportunities as; opportunities to harness the purported value of MR prototyping tools in support of reflective design thinking and to mitigate some of the negative factors that compromise reflective design thinking outlined in 2.2. Correspondingly challenges are defined as; challenges in harnessing the proposed value that may arise through either MR prototyping tools suitability in light of constraints in the educational setting or exacerbating known issues. The appraisal is conducted via systematically assessing for each dimension of value how the factors can lead to possible opportunities and challenges. Each assessment is rationalised via the addressing the following questions for each dimension of value:

Which factors of the educational setting might impact the value being achieved? (thus, presenting challenges),
To what extent do the dimensions of value present opportunities to resolve/improve the factors/concerns with teaching design/engineering?

The following sub-sections present results of the appraisal, split by each dimension of value.

3.1 Creation and configuration

The Creation and Configuration dimension of value is summarised as the ability to create or reconfigure geometry in a mixed reality environment, either via modifying geometry in the virtual space via tangible interactions, or by tangible modifications being reflected in updated virtual representations. Hence the overarching benefit lies in saving time invested in affecting changes in designs between virtual and physical domains, i.e saving transition time.

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Opportunities
The proposed value presents an opportunity for educators in terms of a faster transition time enabling greater frequency prototype iterations within the constrained timeline of a university project. This in turn supports reflective design thinking through the ease and number of opportunities to use prototypes to develop ideas towards a resolved outcome. At the same time, we can view reduced transition time as a means to reduce sunk cost effects and fixation that arise through the efforts usually involved iterating prototypes, especially at higher fidelities towards the end of the project's design process. The concept of tangible interaction to update the virtual model may offer gains in terms of lower threshold skills and resulting creativity. A tangible intuitive manipulation being reflected in the digital model has the potential to mitigate challenges that a student with limited CAD competency might face when updating (transitioning) from physical to virtual domains.

Challenges
Creating designs in a mixed reality environment requires the use technology and tools beyond those typically used in design education. This arises from the need to create and/or visualise digital 3d geometry alongside sensing and/or computer vision systems that unite the physical and virtual interactions. As such the process to create designs would be more involved technology than the tools currently used by students and practitioners alike (CAD software and manual prototyping methods). This presents challenges in terms of reduced competency with a complex MR tool leading to issues of bounded creativity, sunk cost and fixation that occur already with digital prototyping tools.
Ultimately the extent of opportunity or challenges will depend heavily on the complexity of operating the tool and the time and resources available to train students on a given tool. This finding aligns with (Kent et al., 2021) who indicate how substantial value can be achieved via the use of MR, however technological challenges must first be addressed before it can be realised.

3.2 Visualisation

This dimension of value is summarised as higher fidelity visualisation of designs within their intended context and heightened ability to inspect complex and/or obscured geometry. The value arises via both flexibility of visualisation that is possible, and the heightened fidelity both in terms of proposed product context but also integration of essential parts or subsystems. Thus, an elevated level of information can be embodied and communicated within visualisations leading to design teams being more informed about various qualities of design when making decisions on how to proceed.

Opportunities
We contend the improved information sharing and reasoning offers substantial support for reflective design thinking. The main contributing factor to this opportunity is that the MR prototyping tools offer higher fidelity visualisation but don't necessarily require higher fidelity in terms of the design created. For example, a low fidelity digital model can be visualised in the use context. Thus, the overall fidelity is greater in terms of communicating environmental qualities of the product, while fidelity in the design, e.g. geometry or smaller details, can remain ambiguous. This offers value to educators in terms of supporting quicker iteration and reflection while fidelity of the design remains low, and thus avoiding fixation and sunk cost. At the same time higher fidelity visualisation presents value via educators being able to give richer feedback based on an improved shared understanding that arises from the higher fidelity visualisation.

Challenges
Compared to the creation and configuration dimension, the visualisation dimension presents fewer challenges in harnessing the value. This relates to the way that visualisation in MR can be achieved with screen-based AR and pre-existing digital modelling packages. In other words, the Visualisation dimension of value is much less reliant on haptic and computer vision systems required for real-time creation and configuration in mixed reality. Not so much a challenge, but a consideration, is how this approach could lead students to using digital tools (with capacity for higher fidelity) when a low fidelity physical model would be of equal or more value in reflective design thinking. Doing so runs the risk of encouraging students towards tools that could exacerbate sunk cost effects or limit creativity.

3.3 Knowledge management

The principal value proposition in the dimension of knowledge management is the capture of information linked to the use of prototypes for testing a design. Thus, this value feeds into the value of prototypes in learning about and communicating a design and its merits.

Opportunities

This value proposition is beneficial in design education in terms of supporting reflective practice. Specifically, how knowledge embodying reflections on the prototype can be more explicitly and seamlessly captured. This is helpful in supporting students to document the test and subsequent finding that would support a design iteration. Hence, it could enable more explicit communication of the pros and cons of the design with teaching staff. Presently documentation of prototyping occurs via photographing physical prototypes annotated to describe the test and finding. This approach to knowledge management requires transitioning the design into the physical domain (from CAD or sketch) where it is tested, then transition back to virtual domain via photograph where knowledge is captured. In the mixed reality visualisation, the physical and virtual can be captured/recorded together, and thus the prototype can be more readily annotated and shared. Thus, we contend this dimension of value means knowledge pertaining to reflections in reflective design thinking can be more readily and explicitly captured with reduced transition time between physical and virtual domains.

Challenges

It is worth noting that greater value can be harnessed in scenarios of greater complexity. This is explained in the complexity of designs is connected to the number of subsystems and assemblies, and thus the repercussions of any modifications are also greater. While there is an opportunity to support reflective practice through annotation, the level of benefit is proportional to the design complexity. It follows that the time and resources to create such prototypes is greater and so is the possibility of sunk cost effects and fixation. Thus, the extent of benefit will be a trade-off with the level of fidelity where higher fidelity comes with increased risk of sunk cost effects. As such the value may not necessarily mitigate known issues with factors, however the improved ease of capturing knowledge presents an undeniable opportunity to support reflective practice through reduced transition time in documentation of prototypes.

3.4 Integrated analysis

Integrated analysis offers value in terms of using the mixed reality environment to add/augment information about the prototype. In this instance it is the opportunity to embed and visualise analysis of the prototype. As such the value arises from the seamlessness with which analysis can be layered onto the mixed reality environment. In other words, there is less expense of time and resources to move the prototype into different platforms, to run analysis, and subsequently visualise the outcome.

Opportunity

The integrated analysis value proposition in design education is also to more seamlessly support reflection and communication of relative pros and cons of a prototype using analyses of designs to rationalise design iterations. However, we also note that the value of integrated analysis does not directly mitigate known issues.

Challenges

A key consideration in this dimension of value is the extent to which the MR system is bespoke. The systematic review in Kent et al. (2021) provides examples of how mixed reality system can support the overlay of analytical data on a physical model in response to changes in the physical model. A challenge for educators to harness such value is that such systems require bespoke set-up depending on the analyses and the project in question. Neither would be specified in a studio design project as outcomes are undefined at the start of the project. Hence implementation in this way would require significant technical overheads to set up during projects. This would stretch time and budgets for educators, or likely detract from time available for students to develop and resolve their projects.

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3.5 Collaboration

This dimension of value is characterised by supporting remote collaborative design by integrating prototyping with other collaborative and project management tools.

Opportunities

In terms of design education, this represents an exciting opportunity for remote learning and teaching of engineering and design projects. For example, it suggests the possibility of groups of students in distributed teams collaborating on a single shared prototype. Likewise, it offers an opportunity for richer feedback with educators while not being physically co-located.

Challenges

As with the case of creation and configuration, the technology to facilitate this kind of interaction is relatively complex and embryonic in terms of its level of development. Thus, the value proposition advantages can only be harnessed with training and availability of the tool. Without this there is a significant risk of bounded creativity and sunk cost arising, hindering reflective design thinking. Thus, while the potential benefit is significant, the ease of use and readiness of implementation presents a challenge.

3.6 Key findings and recommendations

Following the appraisal, we distil the following key findings in terms of opportunities and challenges to harness value and support reflective design thinking.

Visualisation is most readily implementable with benefits that align but also opportunities to mitigate sunk cost effects by preserving lower fidelity modelling while also supporting reflective design thinking through greater fidelity in visualisation. These opportunities are largely driven by this dimension of value being achievable with existing commercialised products (e.g. virtuality focused prototypes such as screen or headset based augmented reality). Thus, we recommend this dimension of value as most readily harnessed in studio education.

Knowledge management is also recommended as readily implementable working alongside visualisation. The dimension of value presents less opportunity to mitigate existing issues than visualisation. However, it does offer opportunity to support reflective design thinking in terms of making reflections more explicit and shareable with less time investment.

Creation and configuration have great potential but are less readily implementable due to technology requiring higher and/or new threshold skills in students plus high-tech or creation of bespoke MR prototyping systems. This potentially creates more challenges for educators before value can be fully realised. The same can be said for Collaboration and Integrated Analysis. While theoretical value is undeniable, the availability, usability and skills to effectively use MR in these contexts could exacerbate known issues rather than mitigate them. These considerations together lead to a recommendation that these dimensions of value would require review of, and availability of tools combined with ample training with tools and technology prior to students and educators realising the substantial benefits.

4 ILLUSTRATIVE CASE STUDY: APPLIACTION OF MR VISUALISATION WITHIN AN INDUSTRIAL DESIGN STUDIO

The following presents reflections from implementing MR visualisation within a studio design project. The case is presented to illustrate how the appraisal was used in the creation and implementation of an activity within a studio project to scaffold a MR prototyping process.

4.1 Implementation based on recommendations

MR prototyping was implemented within a second-year industrial design studio project that tasked students to design a product for making food or hot drinks. This course builds on the foundational industrial design content on prototyping that features throughout students' first year of their degree. The goal of the course where MR prototyping was trialled is to complete a self-directed brief to design

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a kitchen appliance (e.g. coffee maker). Learning objectives are to cement foundational knowledge within a self-directed brief and to introduce usability and user experience qualities to their design process. As such it presents a scenario where students' threshold skills in prototyping are achieved but expertise is limited, and thus also a scenario that can lead to issues described in 2.2. Hence it presents a suitable scenario to test the opportunities for MR to support prototyping but, also mitigate extant issues. Following the recommendations described in 3.6, MR prototyping focused on the Visualisation and to a lesser extent Knowledge Management dimensions of value.

The use of MR was scaffolded to occur once initial concepts for the product were defined, but overall size and proportion were still being developed. Thus, students used the MR prototype to contextualise a preliminary concept (low fidelity) within their own kitchen (heightened fidelity) to reflect the appropriateness of design. As such we aimed to capitalise on the value of MR visualisation offering a heightened level of fidelity in terms of visualisation prior to developing the fidelity in the design. The specific prototyping 'test' was for students to visualise their concepts at low fidelity alongside the various kitchen products with which their design would be used (e.g. cups or mugs used with a coffee maker) as a basis to test preliminary product dimensions and proportions (e.g. height from which coffee is dispensed into a mug).

Adobe Aero (a screen-based augmented reality platform) was selected as the prototyping tool. The choice was taken due to its widespread availability to students and only requiring a smartphone as hardware (rather than headset) to run the technology saving on teaching resource investment. Moreover, the intuitive user interface makes it suitable in minimising threshold skill to learn and use the tool. This adds to the suitability in terms of mitigating fixation issues associated with more complex visualisation tools, but also reducing the studio time required by educators to introduce and explain the tool.

Following the test, students were tasked with capturing the MR visualisation (via the Adobe Aero app) and followed a series of prompts to demonstrate and reflect on the positives and negatives of their concept with respect to size and proportions. This step was designed to harness value from the Knowledge Management dimension in terms of more seamless documentation and annotation of the prototype. Figure 1presents examples of the AR tests and documentation. The pages within students' project folios documenting the process form the basis for thematic analysis described in the following section.

Figure 1 Examples of MR prototypes produced during the implementation. The 3 Images on the left represent the low fidelity models in context. The 6 Images on the right provide examples of how prototypes were captured, annotated, and used to reflect on design merits. These images also illustrate the documentation used in thematic analysis

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4.2 Reflection on the extent that value was harnessed, and reflective design thinking supported.

Reflections on the application of the critical analysis in the illustrative case study are now given. Reflections are derived from a thematic analysis of each student's documentation of their MR prototyping within their project folio. Analysis is structured by the key value proposition for using MR prototyping, namely, stimulating iteration, reflective design thinking, and mitigating known issues in student prototyping. Analysis and subsequent reflections were undertaken by the staff member responsible for the course.

First, we can reflect that the implementation was successful in terms of adding a design iteration within the design process that would have been otherwise challenging to do due to time constraints. Multiple iterations on scale and proportion were achieved in a short space of time. This is a promising outcome with respect to students engaging in reflective design thinking and in turn avoiding fixation and sunk cost effects. We view this as being facilitated by reduced transition time that MR visualisation facilitates. In our case, students transitioned from an elevation view sketch to low fidelity CAD which could easily be resized and tested in augmented reality. Without AR they would have been tasked to create low fidelity physical prototypes from the sketch, with each subsequent iterations requiring additional time to make from scratch.

While time saving and thus mitigation of sunk cost was consistent across all projects, the value of reflections derived from testing prototypes varied. We contend this variability arose from both the fidelity of models visualised but also the nature of concepts visualised. We found some students with highly simple AR prototypes (e.g. a cylinder representative of the product) could only reflect on overall size and proportion. Other prototypes with greater fidelity, such as including spout and drip tray of a coffee maker, led to richer reflections going beyond overall size to consider size of opening for cups and position of user interface. Thus, a key reflection from the case is on the importance of fidelity with respect to the value that is achieved from the AR prototype. All though it presents variability to the value that can be harnessed from MR visualisation, we contend it also creates a learning opportunity. We argue the reduced time to create the MR prototype mean perception of time wasted was lessened where the prototype gave less rich feedback. Furthermore, it provided a low-stakes opportunity for students to understand how a different level of fidelity would be required to test and resolve other qualities of the design.

While reflection on the implementation was positive, there are still aspects of implementation that should require further testing. First, we acknowledge that the implementation pushes students towards CAD modelling earlier than normal. We assume reduced time and effort required facilitates iteration mitigating sunk cost and fixation. However, it is possible that using CAD for the prototype (even with a simplified model) could still cause sunk cost/fixation. Especially where the nature of the design requires higher fidelity to achieve valuable reflections on the prototype. With respect to knowledge management/communicating insights we reflect that there was no simple means to achieve the immediate understanding and feedback of a comparison of physical models. This was largely caused by the relatively small screen to display visualisations meaning students and educators had to take turns in using the smartphone to review the prototypes. Thus, while the visualisations are easily captured and shared, the screen-based app had limitations in terms of seamless communication between students and staff. We contend however this limitation could be overcome via a more structured AR prototype review class activity, or via more advanced AR headsets that can be used in groups. Ultimately, we find the implementation underscores the value proposition anticipated and helped mitigate issues. While we uncovered some aspects of the implementation that still require development, these are likely resolved via structuring of activities that involve the technology rather than the technology itself.

5 CONCLUSION

Literature on mixed reality prototyping highlights a number of dimensions by which practitioners can improve efficiencies of the prototyping activity during the design process. This paper reports a critical appraisal of these dimension of value to better understand how the value can be harnessed to support practice-based studio design projects. The appraisal highlights how value is most readily harnessed and known issues in student prototyping (sunk cost effects) can be mitigated via the Visualisation dimension of value, and to a lesser extent the Knowledge Management dimension. The appraisal highlights how other dimensions theoretically offer clear value propositions to educators but are less readily harnessed as they are dependent on technologies which require resource investment to set up and use. Thus, at time of writing, Creation and Configuration, Collaboration and Integrated Analysis dimensions are difficult to harness in the context of design studio education. An illustrative case study to implement the MR visualisation within a studio is presented to demonstrate the application of the appraisal. Reflections corroborate the appraisal, but also highlight the need for further research to scaffold and structure the way the MR visualisations can support reflective design thinking in practice-based studio design pedagogy.

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