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Exploring the practical integration of 4IR technologies in industrial design education in South Africa

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Abstract
The Fourth Industrial Revolution (4IR) is changing the world around us, altering the way we live, work, and engage with one another. Driven by the Internet of Things (IoT), the 4IR and its associated technologies are driving great shifts in manufacturing and production and as such, within the Industrial Design (ID) discipline itself, not only in the products we design but more notably, in the tools and processes we use to do so. The unprecedented speed at which these innovative technologies are progressing and reshaping the industry calls for the urgent restructuring of higher education curricula. To prepare students for the rapidly changing industry, ID programmes must develop appropriate content and integrate these technologies into their teaching and learning to deliver the skills and knowledge needed in this new era. This paper reports on the first cycle of an Action Research study in which ID lecturers and 1st-year students explored the utilization of 4IR technologies in undergraduate teaching. This project aimed to identify the opportunities and challenges of such technologies to determine the most effective and appropriate way to incorporate new technologies into the curriculum. The purpose of this paper is to present and discuss the implementation of these technologies through the assessment of the efficacy of the project outcomes through examples provide, and the students' individual experiences and reflections, and finally, to present key findings and recommendations for further study.

Keywords: 4IR, IoT, Virtual Reality, 3D Printing, Laser Cutting, Handmade, Digital Fabrication, Pedagogy.

1. Introduction

Industrial Design (ID) can be defined as the process of designing manufactured products. The manufacturing and industrial sectors have been subject to great shifts and change through the three preceding industrial revolutions and the 4IR has been no different (Mukwawaya et al., 2018). Historically, ID as a discipline has placed great emphasis on traditional hand-based skills such as drawing and model making, however, emerging technologies are rapidly reshaping and unlocking new potentials in the design process (Petrov, 2018). The exponential speed at which technology is progressing is unprecedented and is noticeably transforming all industries (Schwab, 2016). According to Adelabu and Campbell (2020), the 4IR calls for restructuring higher education curricula, providing students with the skills and knowledge necessary for successful contributions to the new world of work. To prepare students for this new era, ID programmes must not only integrate such technologies into their teaching and learning but must continually re-evaluate, reflect, and update their methods of doing so to keep up with and remain relevant in the fast-changing industry.

This paper reports on the first cycle of an Action Research (AR) project exploring the integration of various digital fabrication technologies in undergraduate teaching in a bid to build capacity and empower students. The purpose of this study was to assess the application of these technologies in the design process through the assessment of the efficacy of the project outcomes and discussion of students' individual experiences and reflections, ultimately to propose instructional changes in their undergraduate practical design modules (O'Connor et al., 2006).

2. Contextualization

The ID discipline is very much practice-based, and as most projects have a physical product outcome, students and practitioners must rely on their making skills to create these prototypes. The tools and methods used in the prototyping process have evolved significantly over the years, greatly influenced by the advancements in the technology of preceding industrial revolutions. In the not-so-distant past, prototypes were typically made through handmade crafting processes using simple tools. Additive processes like sculpting, build objects up by adding material layer by layer. Subtractive processes involve the removal/carving away of material to create/ leave behind the desired part. Moving into the digital era, these processes have been largely replaced by more efficient digital fabrication techniques.

Computer-Aided Design (CAD) has already become a common tool used for the ideation and prototyping processes in ID. CAD software can be used to create accurately dimensioned two-dimensional (2D) drawings or virtual three-dimensional (3D) models. These tools allow designers to ideate and develop their designs digitally on a computer and then export files suitable for rapid prototyping processes, enabling the quick, cost-effective production of to-scale prototypes (Penprase, 2018). Additive Manufacturing (AM) is commonly used as an interchangeable term for 3D printing, a process of producing a physical product directly from a 3D CAD model. Like additive handmade methods, 3D printing is a process whereby material is deposited in thin layers representing the thin sections of the 3D model until it is built up to the full 3D CAD model design (Gibson et al., 2021). The inverse of this is the subtractive manufacturing process such as CNC milling and laser cutting (Dzogbewu, Afrifa Jnr, Amoah, Fianko, & de Beer, 2022: 296), where full blocks and/or sheets of material are cut down to reveal and produce the final artefact. The digital file preparation for the subtractive process differs depending on the specific manufacturing process. For laser cutting, 2D plans and outlines are designed in vector processing applications such as Adobe Illustrator or open-source software like Inkscape, whereas CNC milling would use a 3D CAD file. The above-mentioned tools and processes although considered to be innovative and new, have been around for decades, but the materials used, speed, accuracy and size capabilities have and continue to evolve significantly.

The term Internet of Things (IoT) refers to the interconnectivity between computers, sensors and everyday items allowing these devices to generate, exchange and consume data with minimal human intervention (Rose et al., 2015). The IoT is powering the exponential growth in technological advancements in manufacturing, data processing, robotics and more, thereby having a dramatic effect on the way the 4IR continues to evolve (Burkhalter, 2022). The IoT has also given rise to new processes and methods of prototyping in the design process, most notably, Virtual Reality (VR). VR refers to the computer-generated simulated 360-degree 3D environment which can be explored and interacted with in a seemingly real way (Jerald, 2016). In the design space, VR serves as the "ultimate medium for design conception" and can significantly optimise the design process by merging several of the design development phases into one (Bordegoni & Caterina, 2011).

Disadvantages associated with current 3D CAD modelling methods include the lack of full integration meaning that it is usually necessary to build a physical mock-up of any ID object to fully understand scale, fitting, and usability (Petrov, 2018). Unlike traditional interfaces, VR provides a fully immersive experience using electronic equipment, such as headsets/goggles and hand-held sensors/controls. The direct input allowed in VR through the incorporation of joysticks allows the designer to use their hands directly in the creation process mimicking the multi-axial rotation of the human hand (Petrov, 2018: 65). VR has redefined the interaction between designer and product by enabling designers to interact intuitively with their sketches and 3D models, developing a greater understanding of proportion, scale, and form. The integration of VR in product development phases allows for sketching, scaling, material testing and prototyping to be done in the virtual environment without having to build costly mock-ups, thus ensuring cost-effectiveness (Bordegoni & Caterina, 2011). Conversely, there are challenges faced when using existing VR design tools. Firstly, the limited precision and lack of measuring abilities of the free-form modes means that models need to be re-exported to more accurate CAD programs for measurements (Petrov, 2018). Secondly, modelling in VR requires a large amount of data processing to achieve a realistic, immersive environment pointing to the need for better-equipped machines to keep up with these heavy requirements (Ruan & Dongliang, 2021: 167; Petrov, 2018) resulting in the need for more capital investment meaning it is a costly approach to implement. Furthermore, the overuse of the technology can result in negative side effects such as 'Cybersickness', a visually induced motion sickness from being immersed in a virtual world seen through headaches, physical fatigue, and repetitive strain injuries (Jerald, 2016).

Recent white papers describe how the 4IR will "shape the future of education, gender and work" (World Economic Forum, 2017a) and will require "accelerating workforce reskilling" (World Economic Forum, 2017b). However, one must acknowledge and consider the potential barriers to the implementation of 4IR technologies in developing or underdeveloped countries (Markowitz, 2019).

The digital divide is significant in Africa, with only 24% of the continent's population accessing the internet, compared to the 51% global average. Considering that the majority of 4IR technologies are driven/supported by the IoT, this highlights the need to improve IT infrastructure to take full advantage of such advancements (Markowitz, 2019; Mukwawaya, Bruno, & Sibusiso, 2018: 1598; Olaitan, Moshood, & Ntombovuyo, 2021). Acknowledgement of these necessary changes and rooting them in relevant contexts could turn into opportunities for successful implementation that are both appropriate and equitable. In South Africa, it's important to acknowledge the income disparity and divide (StatsSA, 2017) and acknowledge that for new technologies to be equitably accessed, reform and change are necessary for its systems. There is limited funding that is normally directed towards physical infrastructure and the development of already underserved areas of computing (Mukwawaya, Bruno, & Sibusiso, 2018: 1598) without even first considering the 'luxurious' purchases of VR, Augmented Reality (AR) and Artificial Intelligence (AI) hardware. Some of these are also only accessible with stable internet and power connectivity; both of which have disrupted services, especially in South Africa (Olaitan, Moshood, & Ntombovuyo, 2021: 8). High implementation costs are also related to the running cost of the equipment i.e., maintenance, proprietary software, internet, and electricity costs. South Africa is currently experiencing disrupted power connectivity through the implemented load shedding and electricity is necessary to run equipment and charge equipment (Olaitan et al., 2021), therefore needing disruptions to be catered for and considered in the process workflow.

While 4IR is driving a huge shift the in industry and emerging technologies are redefining the design process, there is an insufficient assessment of their impact on the current teaching and learning processes and quality (Oke & Fernandes, 2020; Adelabu & Campbell, 2020). Lines of enquiry need to focus on how education could be transformed through digitalization and embracing of 4IR and there is a need to expand on knowledge of processes and approaches that the education sector, especially in Africa could adopt to fully appreciate the benefits of 4IR (Oke & Fernandes, 2020).

3. Methodology

Action research (AR) is a practical and iterative research methodology and tool used by educators to conduct research in classrooms to identify strategies to examine, and ultimately improve, their pedagogy and teaching practice (O'Connor et al., 2006; Swann, 2002). This project aimed to explore the opportunities and challenges associated with integrating 4IR-related technologies into undergraduate ID education in the South African context to identify the most effective and appropriate methods to incorporate such technologies into the curriculum. The researchers conducting this study worked collaboratively across two practical modules and used the results to propose instructional changes and/or follow-up iterations in their undergraduate modules (O'Connor et al., 2006). AR is an inquiry where participants and researchers cogenerate knowledge through collaborative and communicative processes in which all participants' contributions are taken seriously (Clark et al., n.d.). Therefore, staff and student participation, engagement and reflection were key aspects of the process and findings. Data were analysed using qualitative methods and the findings of this pilot project were placed into two categories. Firstly, lecturer observations throughout the project and final assessment of project outcomes, and secondly, student reflections/experiences of the respective methods used and how they believed the method affected the design outcome. 1st-year was chosen because, at that level, students have a minimal foundation and formative skills related to specific technologies/tools. It was assumed that they would therefore be more receptive to the experimentative and exploratory methods. Furthermore, the lack of experience across the year group in any of the methods allowed for a relatively "even playing field". This would then serve as an effective benchmark to outline the suitability and feasibility of incorporating emerging technology into the ideation process from the foundation phase upwards.

This study followed the four-phase AR process (Figure 1) namely, *Plan, Act, Observe* and *Reflect* (Swann, 2002). This paper discusses the first cycle of these 4 phases. The remaining sections of this paper are structured according to these 4 phases as outlined below:

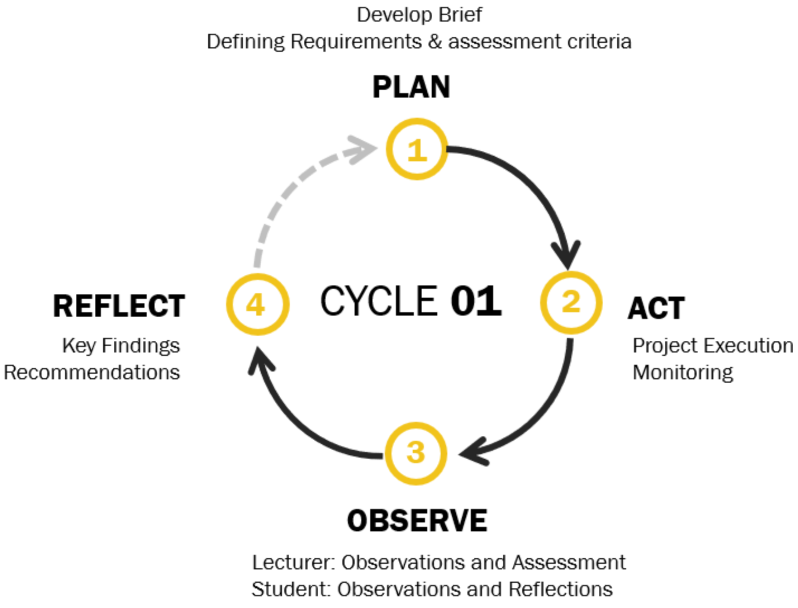

Figure 1 - Four Phase Action Research Cycle

I. Plan: The first phase involved the identification of research questions and goals, preparation of the project brief and learning material, definition of requirements and assessment criteria. In this paper, the "Plan" phase is presented through a description of the project brief and requirements in section 4.
II. Act: Phase two involved project execution. In this paper, the "Act" phase is presented through the discussion of examples of student work created during the project in section 5.

III. Observe: This phase involves the evaluation of the action undertaken through appropriate methods and techniques (Swann, 2002). In this project, the "Observe" phase included two components namely, *lecturer observation* of project outcomes as well as *student reflection* on their experience of using their respective method. The outcomes of each method were analysed by lecturers through the lenses of *Detail, Accuracy, Design Complexity* and *Speed*. Upon project completion, students were asked to complete an online Google Form, reflecting on the project. Students were first asked to reflect on their personal experiences working with their chosen method. Furthermore, they were asked to reflect on their observed differences between the final physical prototypes throughout the class and finally how they felt each of the methods affected their work or project outcomes in terms of detail, accuracy, and complexity. These observations are documented in section 6 below.

IV. Reflect: The final phase of the AR cycle involves reflecting on the entire action and research process leading to the identification of key findings which will inform subsequent cycles (Swann, 2002). In this paper, key findings are outlined in section 7.

4. Project Brief (Plan)

Linked to an industry partner, 1st-year students were required to design a customizable cover plate for a high-end basin/bath mixer (Figure 2) incorporating a unique relief pattern inspired by their individual interpretations of their South African culture or heritage. The cover plates were designed to suit any cast material such as metal, resin, ceramic, etc., incorporating a unique relief pattern. During this project, students were required to prototype their cover plates through a series of steps including master pattern making, mould making, casting, and finishing. This project aimed to explore the opportunities and challenges of integrating 4IR-related technologies in the design process, in comparison to traditional methods. Therefore, this project was specifically designed to incorporate a variety of different methods/processes to create the same product/outcome, specifically the master pattern.

Figure 2 - AXOR MyEdition Mixer with Customisable Cover Plates

Students could choose one of four methods or routes (Figure 3) for the creation of their master pattern, ultimately affecting the aesthetic of the outcome. So as not to disadvantage any of the students, the project outcomes were not marked according to accuracy/neatness, but rather the design intent and message behind the design, as well as the ability to execute the various practical steps. Penprase (2018) cites flexible shorter-term assignments as a key factor to address within 4IR education. Therefore, this project was designed to be fast-paced forcing students to actively engage with the project make decisions and learn about the relevant processes to inform their process accordingly.

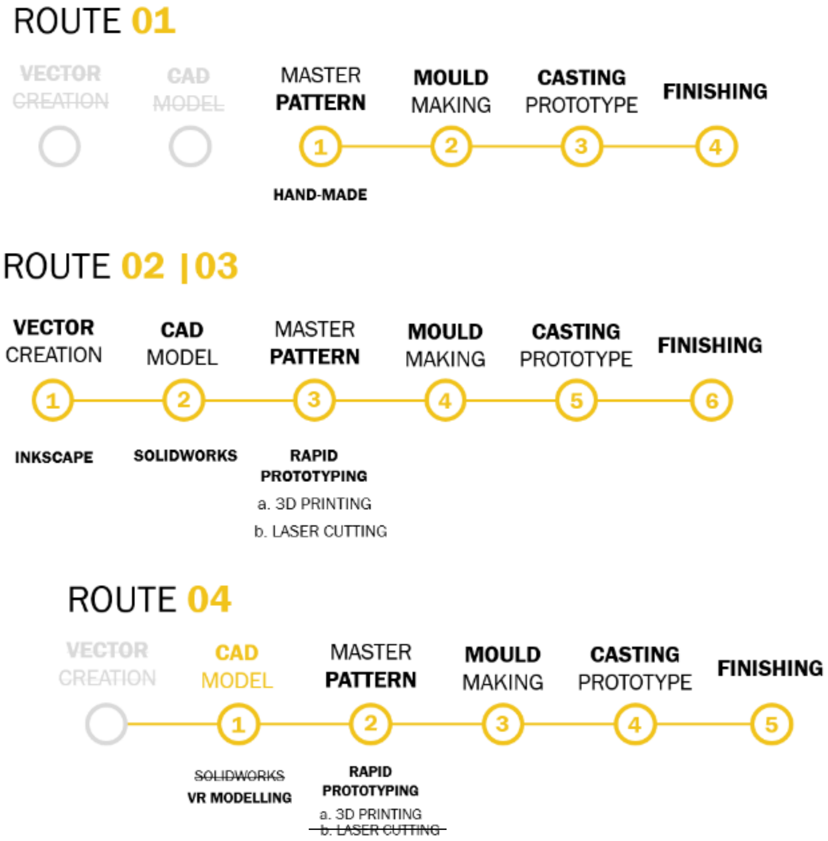

Figure 3 - Four Routes to Manufacture of Final Prototype

Route 1 focused on traditional handmade processes/practices. Students could use additive (sculpting) or subtractive (carving) methods to create their master pattern from materials such as modelling clay, lino etc. Routes 2 and 3 focused on 2D and 3D CAD and rapid prototyping technologies of laser cutting and 3D printing. In these routes, students used 3D modelling software to create their virtual 3D models which were then either 3D printed (Route 2) or laser cut (Route 3). Lastly, Route 4 offered a more experimental approach using newer, unfamiliar technologies namely, VR sketching/modelling. In this route, the 'traditional' 3D CAD modelling was replaced by VR sketching, whereafter students could use 3D printing to create their master pattern, as in Route 2.

5. Project Outcomes (Act)

Figure 4 documents the work of a student who chose Route 1, using Y2-Klay modelling clay and an additive hand sculpting process to create the master pattern. To build their forms, the student used stencils and templates to match the proportions of the envisioned master. Y2-Klay is an air-drying clay that is only pliable under direct heat application, so the process was done using a heat lamp to build up and sculpt the master pattern of the plate by hand. Thereafter, the handmade model was used to create a silicone mould from which a resin prototype could be cast. The mould box was built from MDF, and the master pattern was placed on the bottom. Silicone was poured over and left to set overnight. The resin was then cast into the silicone mould, producing the first cast plate.

Figure 5 - Route 2, 3D Printed Pattern

Figure 4 - Route 1, Handmade Master Pattern and Moulding

Figure 5 documents the work of a student who followed Route 2. Using traditional 2D vector creation in Inkscape, an open-source graphics software, students created linework drawing of their intended relief pattern. Thereafter, the 1:1 scale pattern was exported as a DXF file and imported into SOLIDWORKS, a 3D CAD modelling programme. Using the sketch as reference/template students modelled a 3D version of their cover plate design. This model was exported as an STL file (the file format suited to 3D printing) and imported into Up Studio a programme which then slices the model into individual layers which are then built up into the full 3D printed master pattern. The master pattern took 3,5 hours to print using ABS in a 0,2mm layer height. Thereafter, the same process of mould making and casting as described above was followed to make the final resin prototype.

Figure 6 presents the work of two students who followed Route 3. In this case, students used 2D CAD to create their linework which was then exported as multiple DXFs for the individual laser-cut layers of the master. The first example used engraving to create a finely detailed image, this was achieved by varying the laser power output to create the details in the wood. The second example used two layers of 3mm MDF to create the relief pattern. The individual layers were then glued together and laminated to create the 6mm plate. The same process of mould making and resin casting as described in Routes 1 and 2 was followed.

Figure 6 - Route 3, Laser Cut Master Patterns

Figure 7 shows students engaging with the VR headset and joysticks. Penprase (2018) notes that the shelf life of any skill in the 4IR has become increasingly short and therefore stresses the importance of adaptability and self-directed learning to continuously update their skills and teach themselves about new technologies.

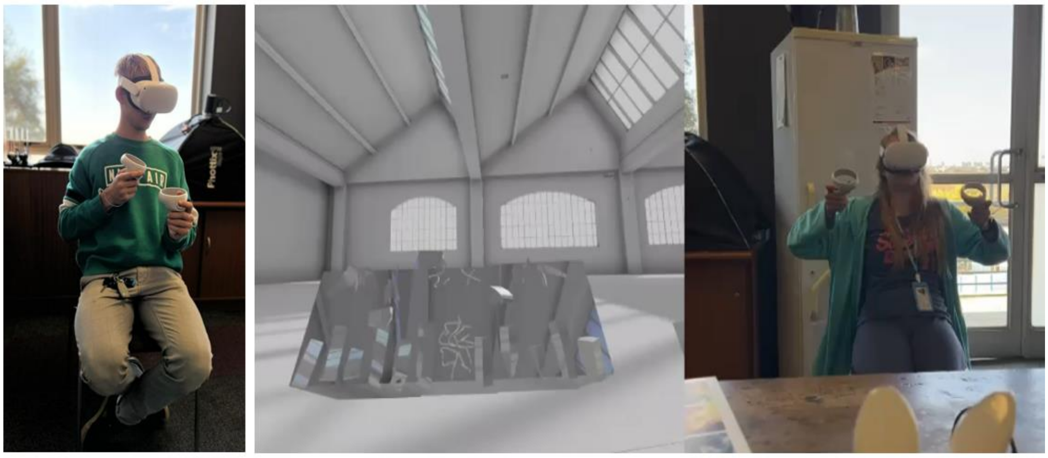

Figure 7 - Route 4, Students Using VR Modelling Software

Therefore, students who chose to use VR in the creation of their 3D models received a brief introduction to the controls and interface but were otherwise self-taught in this experimental process. A VR introductory app, First Steps, was launched for the students to help guide them in the VR environment, where it walked them through being acquainted with the specific controller actions, responses and options (Oculus, 2022). This video also helped the students get comfortable with the feeling of the immersive environment as it might be overwhelming for some. The students then used the Gravity Sketch app on the Oculus headsets to sketch out and 3D model their specific plates. They, through trial and error, had to model their plates to the correct proportion based on their memory of making them by hand. Each student took about 30 to 45 minutes to model their respective designs. The VR 3D model was then exported as a 3D printing-appropriate file and was 3D printed.

6. Observations (Observe)

Figure 8 showcases the variety of master patterns created using the various routes. One can see how the production technique influenced the design according to detail, form-giving, complexity, and the success/failure of these factors was determined by human skill and or machine capabilities.

Figure 8 - Examples of Master Patterns Created Using the Various Routes

Lecturer Observations

Upon reviewing the various master pattern outcomes, some key findings were identified and unpacked below. One student, through their engagement and interest in the process, opted to make a master pattern using three routes – Handmade, CAD to 3D print and VR to 3D print. This example (Figure 9) offered an unexpected but hugely valuable insight into the advantages and disadvantages of each route through a direct comparison of the same design.

Y2-Klay is an effective rapid prototyping medium and is used extensively in the automotive industry for rapid form giving of complex and organic forms. This lends itself well to creating sculptural patterns and masters that are easily achieved in relatively short time frames. Correct use indicates that the Y2-Klay needs to be activated with heat to get (the students used a heating lamp) to get it to the correct malleability point so that it can be manipulated and suitably formed to the desired shape. Once the clay has cooled, it is then suitable to be handled. One drawback of using Y2-Klay is that in relatively thin layers or without supportive substrates, it can be quite brittle and susceptible to breaking and needs to be handled with care. The handmade master was quick to achieve, and the process was most intuitive due to the direct contact with the material. The Y2-Klay material however was difficult to finish/smoothen, and the impressions left on it by the tools used for the sculpting were still present in the final cast item. Some students opted to use air-drying clays and lino for subtractive methods. These were less successful in terms of accuracy and form giving due to the difficulty in working with the material. Students who tried to achieve finer details in their plates using the additive method struggled to achieve the necessary detail/accuracy.

The laser cutting method allowed for significantly finer detail using the etching process, however, the overall form giving was limited due to the process of layering the material (3mm MDF sheets), creating an inherent "stepped" aesthetic. The CAD to 3D print route, with which the student was most familiar, provided the most accurate of the methods. The sketches that had been used to create the vector linework could be imported into the program and extruded to the exact dimensions of the proposed outcome. While the 3D printing method allowed for more options with regards to form giving compared to laser cutting due to the much finer layer tessellations, the downfall is that the master pattern required a lot of hand finishing to remove the tessellation line marks before making the mould. This is a time-consuming process if completed to a good standard.

The experimental VR was the most challenging for the student as it was a newly introduced process. Due to the students' unfamiliarity with the VR modelling tools and equipment, coupled with the relatively early developmental stage of the software interface and devices (controllers/joysticks), the precision students are used to achieving easily with current 3D CAD programs like SOLIDWORKS is not yet available with VR tools. The VR sculpting software can achieve definition and "character lines" as well as give intricate detail to objects, but those cannot be accurately measured. Most VR design tools are still in free-form mode and models need to be exported to CAD programs for measurements. The complexity and accuracy achieved were limited by their knowledge of the VR sketching program and tools. This can be seen in the outcome, not resembling the intended design as accurately as presented in Routes 1 and 2. Both of the 3D printed outcomes required sanding and hand finishing as the tessellations or layers of the 3D printing process were still visible on the final pattern.

South Africa periodically experiences scheduled power outages. During the project, there were numerous interruptions and as a result, internet outages as well. While the students using handmade methods were unaffected, this affected the productivity of the students that relied on laser cutting and 3D printing for the fabrication of their master patterns. This meant that deadlines needed to be extended for the various project deliverables and milestones. This was an important contextual finding and consideration when considering how to implement these technologies into the curriculum full-time, without hindering progress.

HAND MADE – CAST
Time: 2 Hours
Accuracy/Quality: Fair
Complexity: Fair

CAD- 3D PRINT
Time: 5 Hours
Accuracy/Quality: Good
Complexity: Good

VR – 3D PRINT
Time: 3,5 Hours
Accuracy/Quality: Poor
Complexity: Poor-Fair

Figure 9 - Direct Comparison of Routes 1,2 and 4

Student Reflections

Overall, based on the student sample reflections, Routes 2 and 3 using 2D and 3D CAD were most favoured by the students as they produced the most accurate results due to familiarity with the programme and level of control concerning dimensioning, scale, proportions, and detailing. Route 1 was next favoured by the students due to the intuitive nature of the process, as well as the flexibility and malleability of the material. However, the level of detail and accuracy achieved in SOLIDWORKS was not achievable due inherent nature of the handmade process. Finally, while one might expect VR sketching/modelling to have similar characteristics to handmade sculpting, although students enjoyed experiencing the immersive n environment, the unfamiliar interface and controls proved to be a learning curve that restricted the students' control/abilities, resulting in inaccurate if not messy models. Both students commented on the physical strain of the process citing headaches ad eyestrain after using the headset for an extended period.

7. Key Findings (Reflect)

Based on these insights, the authors identified the following key findings:

I. While VR serves as a great conceptualisation tool, the technology is not yet at the point of required accuracy required for current ID outputs, specifically linked to manufacturing requirements more specifically, accurate measurability, tolerancing etc.

II. VR equipment is expensive and limited departmental budgets restrict the number of headsets available to students (currently limited to three). The large investment cost is even less accessible to most of the student group.

III. 3D printing and laser cutting technologies are power and resource-dependent. In a context where such resources are not guaranteed, this can cause project delays affecting scheduling and causing unnecessary project overlaps.

IV. Handmade methods are far more inclusive and accessible to a wider student group from a cost and accessibility point of view. However, they are time-consuming and skill-dependent.

V. The above points (I-IV), due to contextual and curriculum factors the department cannot shift to the 'full' integration of these technologies too quickly, and the Authors suggest a phased hybrid approach, following a parallel learning strategy whereby handmade/traditional methods are used to deliver the necessary learning outcomes, while using newer technologies and processes as a supplementary tool to ensure that students receive the necessary exposure and experience with these tools, developing a familiarity needed when entering the new world of work. As the equipment and resources become more readily available and accessible to students within the department, learning outcomes can be adjusted and these technologies can be phased into the curriculum more seamlessly.

8. Conclusions

It is imperative that in the 4IR we build the capacity to fully take advantage of its benefits, whilst being cognisant of our specific context and its appropriateness to one's context. Therefore, a measured approach for the appropriate and effective integration of these technologies must be followed. This project served as a starting point for identifying a feasible and viable strategy for such integration into the Industrial Design curriculum at a South African Higher education institution. These findings will feed into future projects in the department, where the VR aspect takes a more primary role. To further this Action Research study, two further cycles of this project will be rolled out with the 2nd and 3rd-year cohorts to compare findings and assess if the year of study influences project experiences and practical executions of outcomes. Thereafter, these additional findings will be used to formulate a theoretical framework for further study.

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