Integration of additive manufacturing and augmented reality in early design phases: a way to foster remote creativity

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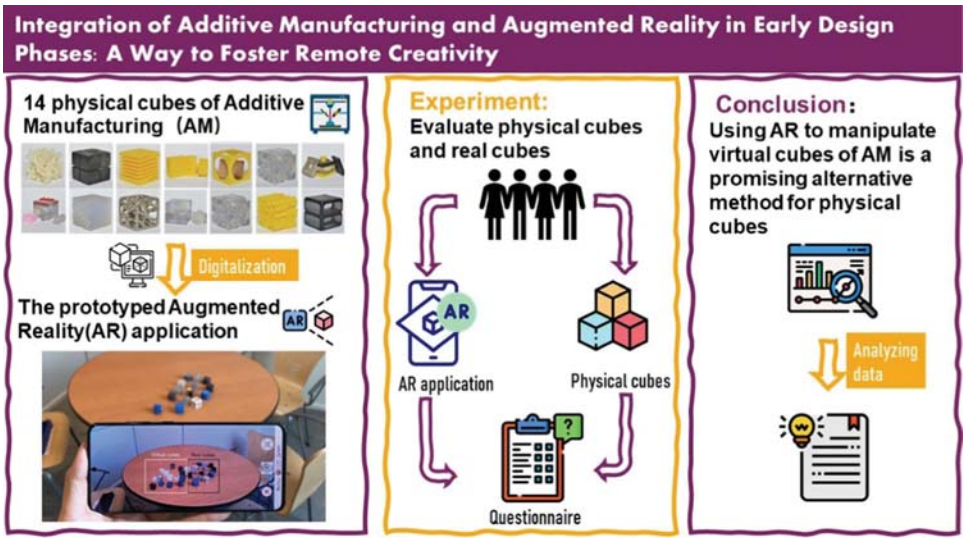
Abstract
Additive Manufacturing (AM) has known a substantial growth in recent years. More and more designers are interested in using AM during the early design stages, and are not familiar with the opportunities provided by AM. Augmented Design with AM Methodology (ADAM^2) is a methodology which can help the designer to understand and exploit the potential of AM. This methodology can be explained through inspirational objects to represent the opportunities of AM. However, due to the substantial manufacturing expenses incurred in producing multiple sets of physical cubes of ADAM^2 during the product design process, this paper exploring the implementation of Augmented Reality (AR) technology as a cost-effective means to showcase and demonstrate these cubes. This paper presents the integration of 14 cubes and AR and evaluates whether virtual cubes could have similar performance as real cubes in terms of usability and AM potential. The digitalization of these inspirational objects and their inter-action through AR is proposed to overcome the limits of physical objects during early product design. Through a mobile device (e.g., smartphone) the user can interact through screen with virtual inspirational objects. An AR application is developed to let users have interaction with 14 virtual cubes as similar with manipulating with real cubes. Users could manipulate cubes and change their material with the markerless AR application. Then the prototyped AR application is tested by experiment. The result shows the virtual cubes can achieved promising performance as similar as the real cubes in the usability and demonstrating the potential of AM. In future work, experiments will be conducted to examine the impact of early design on creativity.

Graphical abstract



Keywords Additive manufacturing · Augmented design with AM methodology · Augmented reality · Product design

1 Introduction

The world is experiencing the fourth industrial revolution and the digital transformation of business, commonly referred to as Industry 4.0 [1]. The technologies associated with Industry 4.0 include AM, Artificial Intelligence, Big Data and Analytics, Blockchains, Cloud Computing, industrial Internet of Things, and simulations, among others [2].

AM is the industrial term for the manufacturing of functional ready to use end pasts [3]. In the Standard NF E 67-001 [4], AM is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Compared to traditional manufacturing, AM allows for some limitations to be exceeded [5]. AM prospects new opportunities and offers many possibilities for those companies that try to improve manufacturing efficiency.

Using AM, the complexity inherent to traditional manufacturing can be eliminated; it is possible to enhance existing products or even manufacture objects. A thorough understanding of the specific manufacturing capabilities and constraints of AM processes is required in order to take advantage of these processes [6]. Lang [7] presented a method called ADAM^2, to assist designers in capturing the creative potential of AM during the early stages of product design. The author proposed 14 inspirational objects, known as opportunities, aimed at introducing AM to a design session so that creativity can be stimulated.

Product design is a core activity in product development [8]. Whether or not a product design has been successful will have an impact on the development and production of the final product. Any errors or potential dangers not anticipated in the product design may result in a product redesign or higher costs [9]. Therefore early stages of design are very important as the design decisions can influence the incurred cost [10]. With the digitalization of design information, new technologies can be integrated so that designers can review their designs more realistically [11]. This integration allows design team to collaborate in an interactive environment. Interactive design is especially developed to support the knowledge modelling in preliminary design. In interactive design, the creation of a product is considered to be constrained by three factors: the expert's knowledge, the end-user satisfaction and the realization of functions [11].

ADAM^2 is a methodology to promote the generation of creative solution and the exploitation of the potential of AM during the early stages of design.

The AM opportunities offered by ADAM^2 could assist designers in developing a deeper understanding of AM during the early stages of design. However, during the design process, it is important to keep in mind that the production of 14 inspirational objects requires a considerable amount of time and money and is geographically limited during the early stages of design.

The purpose of this paper is to propose a solution to overcome the challenges, which would enable the 14 inspirational objects of ADAM^2 to be displayed through an AR application, rather than the 14 physical objects. The contributions of this work are summarized as follows:

- This paper presents a general framework for exploring AM opportunities through AR in early design phase. A combination of AM, AR, and early design is proposed in this framework.
- Based on the framework outlined above, the 14 opportunities in ADAM^2 are digitized using AR technology. We developed an AR application that allows manipulating 14 cubes and changing the materials of the cubes. Using this application, designers manipulate virtual cubes to obtain knowledge about AM.
- An experiment is presented to test the prototyped AR application. In the experiment, the usability and utility of virtual cubes and real cubes are evaluated through questionnaires. According to the results, virtual cubes provide a good alternative to real cubes in terms of usability and potential for AM.

The remaining parts of this paper are organized as follows. Section 2 introduces the state of art to analyze the use of AM in product design and the research on the combination of AR with AM. Section 3 describes proposed approaches, including a general framework for exploring AM opportunity cubes through AR, a prototype AR application, and the application's function. Section 4 presents an experiment to evaluate the virtual cubes and real cubes and analyze the results of experiment. Finally, conclusion and recommendation for future work are given in Sect. 5.

2 State of the art

The paper illustrates the potential for AM to be used at the early stages of product development by recurring to AR technology. The purpose of this section is to analyze the application of AM to product design as well as the combination of AR and AM in order to examine the advantages of this combination and the reasons for adopting markerless AR.

2.1 AR for product design

Since 1960, AR has been demonstrated, but has not been used effectively [12]. With the development of related technologies, AR has once again become accessible to the industrials. If combined with human abilities, AR could provide efficient and complementary tools which can prove useful to assist manufacturing tasks [13]. AR could support concurrent collaborative product design among the members of a multi-disciplinary team [14]. AR has been used in many fields, including gaming [15–19], education [20–23], medical [24–26] and industry [27–31]. AR applications have been considered significantly helpful to improve efficiency.

AR offers the digital environment to designer. It supports designer to interact with virtual designed product to simulate its usage. Kim et al. [32] designed an application to assist designers in the early design stages. This paper provided an architectural design ideation platform in handheld devices with AR. In Mourtzis et al. [11] AR technology was used to advance visualization in product design. Engineers through the AR supported design evaluation process, design errors that could potentially lead to delays or even failure in the final assembly of the radio-controlled car can be early diagnosed and corrected. They modify the model based on the information obtained from AR, and then use AR for evaluation. In this way, by using the AR-supported design evaluation process, it is likely to identify and correct any design errors prior to the final assembly of the radio-controlled car.

2.2 AR for AM

Eiriksson explored by using AR system in an manufacturing environment [33]. In addition to providing users with an overview of the production floor, the AR interface can also be used to control the thermal state of the nozzle that extrudes liquid plastic, preview available models and choose which should be printed, as well as control the carriage by using an AR interface.

Kutej presented a smartphone application based on AR to support the workflow of producing special components based on AM. Based on virtual three-dimensional (3D)-computer-aided design (CAD) models projected to the intended installation site, the application facilitates evaluation of individually engineered parts. In this way, problems caused by inaccessible raw measurements or difficulty anticipating movement of the produced parts can be detected, and the number of time-consuming 3D print iterations can be reduced [34].

The Design for Additive Manufacturing (DfAM) methodology has been developed to enable consideration of the specificities of AM during the design phase [35]. According to Laverne et al. [36], Design with Additive Manufacturing is an adaptation of Design with X. DfAM provides designers with access to AM knowledge for them to consider the specificities of AM in their design process [37].

In Lang et al. [10] a method is presented to assist designers in capturing the creative potential of AM during the early stages of product design. This method is referred to as ADAM^2. ADAM^2 proposed 14 inspirational objects also called opportunities (Fig. 1) aiming at introducing the potential of AM to a design session in order to stimulate creativity [7]. Gibson et al. [3] defined the complexities of AM, which encompass shape complexity, hierarchical complexity, functional complexity, and material complexity.

The 14 inspirational objects (opportunities) of ADAM^2 could stimulate designers' understanding of the potential of AM. However, producing them is a complex process, which requires a certain amount of time and money. In addition, for

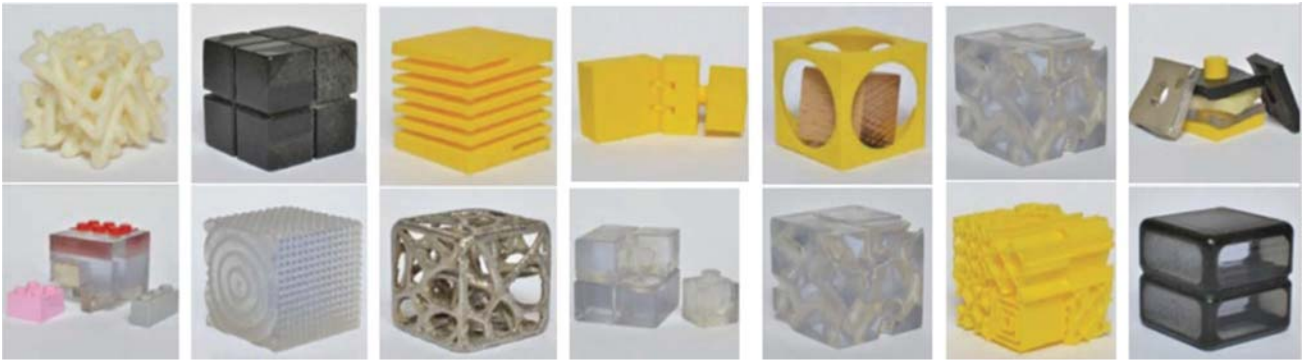


Fig. 1 14 opportunities of ADAM^2 [7]

online sessions of remote design creativity workshops the exploitation of physical inspirational objects becomes difficult. All the online participants may not have these physical inspirational objects and the interaction with the physical objects cannot be shared, understood and synchronized among all participants. Therefore, the use of digital copies for these inspirational objects seems crucial and unavoidable. The digital mockups of these objects exist and it is necessary to have computer aided design tools for manipulating them. This may not be accessible for all participants due to the lack of software or even skills of using them. Therefore, the use of AR technologies seems obvious to let user interact intuitively with the digital inspirational objects that are naturally embedded in the real world.

AR seems to be one of the key technologies for digital transformation, being not only confined to the industrial areas but applicable in the non-industrial areas [27]. According to Azuma, there is a variation between AR and Virtual reality (VR). VR completely immerses a user inside a synthetic environment [38]. While immersed, the user cannot see the real world around him [39]. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it [40]. Two types of AR can be distinguished- one is called marker-based AR, the other is called markerless AR [41]. For marker-based AR, the marker can be 2D image or natural objects in the real environment [39, 40]. Markerless can be achieved by many different types of sensors, including GPS, gyroscopes, cameras, hybrid vision, accelerometers and many others [40, 43].

Marker AR would affect the user's sense of immersion to some extent. And marker AR is limited by the maker. Markerless AR is likely to expand the applicability range being less intrusive and usually requiring minimum or zero setup effort of the final user [44]. Markerless AR could promote the realistic of the 14 virtual cubes. This paper proposes makerless AR to present the 14 opportunities, in order to overcome the limitation that exists in marker AR.

The trend in AR libraries points towards increased use of markerless AR [45]. Occlusion can also happen when used tools and user hands block the line of sight from the camera viewpoint to the markers, potentially causing tracking failures. Thus, a clear concern by researchers and industry arises to provide markerless AR solutions [44, 45]. Usually, markerless AR require little or no setup effort from the final user, increasing their applicability range [44].

In this paper a markerless AR application is designed and prototyped for designers that can introduce virtual inspirational objects and put them related to real environment such as on the table, on the wall, etc. User can freely interact with them such as change the size, orientation, and move them from one place (e.g., Table) to another place (e.g., Wall).

Gerbeau et al. used an AR application to present inspirational objects. In this study designers could view and interact with 14 virtual opportunities [48]. The application utilized marker-based tracking technology, employing 14 cards (as shown in Fig. 2) featuring the image, name, and description of each opportunity as image targets to facilitate the presentation of these 14 opportunities.

A series of 14 cards was created by Kaufmann to serve as image targets for the application. The cards provide a short explanation as well as the opportunity's name [48]. The application could move the 14 opportunities in all 3 directions (translation and rotation) by moving the card, visualize up to 2 cubes simultaneously, change the material of the cube, monitor the cube's size and opacity, as well as enter inside the cube (internal structure not available yet).

In the state of the art, AR is more commonly used after production and AM manufacturing processes. However, despite its immense potential, AR remains somewhat underutilized in the crucial early stages of product design. Most research focuses on post-production and manufacturing applications, neglecting the creative potential of AR in the initial design phases. This paper addresses this gap by exploring the 14 AM opportunities introduced by ADAM^2, aiming to empower designers with a more profound understanding of AM technology from the outset. This paper leverages the

Fig. 2 The application made by Gerbeau [48]. **a** the marker-based tracking cards **b** the interface of the application

virtualization of these 14 cubes as a means to manipulate design elements without the constraints of physical space.

And the interaction functions are limited in the AR application for learning the AM knowledge. This paper aims to provide an effective method to better demonstrate the potential of AM technology. Gerbeau's application integrates AR and AM to displays 14 ADAM^2 cubes. However, there are limitations in interacting with the real environment and only 2 cubes can be displayed simultaneously. In terms of user experience, we expect the 14 cubes virtualized with AR technology to be closer to the real cubes. This paper presented an innovative application that enables the manipulation of virtual cubes, free from numerical restrictions. Let the virtual cubes approach the experience of the real cubes, to a certain extent, can replace the real cubes.

3 Proposed approaches

This paper addressed the development process of the proposed approach as follows:

- Visualization of CAD Models: This paper initiated the process by visualizing the CAD models of AM opportunities within an AR environment, ensuring they closely resemble real objects.
- Enhanced Realism through markerless AR: To improve the virtual objects' similarity to real objects in both manipulation and visual appearance, the application utilizes markerless AR technology.
- Integration of Functions: Building upon the CAD models, this paper integrated the necessary functions into the AR application, enhancing the user experience and interaction.
- Development Using Unity: The AR application was developed using the Unity platform, which provided the tools and framework necessary for creating a seamless AR experience.
- ARCore for Android Devices: Leveraging Google's ARCore, the application delivers AR experiences on Android devices, ensuring accessibility and usability for a broad range of users.

3.1 General framework for exploring AM opportunity cubes through AR

Figure 3 shows the general framework for exploring AM opportunity cubes through AR. First, the real environment is scanned and reconstructed. Then, in the virtual environment the exact geometry or approximate geometry (e.g., planes) as same as real environment can be reached. Generally, AR application through ARCore or ARKit to detect feature points and planes in the real environment, continually improves its understanding of the environment. Google's AR platform ARCore is designed so that a user's smartphone can navigate the real world, interpret it, and interact with it through various APIs (Application Programming Interface). The ARCore app works primarily on Android phones running Android 7.0 or later [49]. The AR application development kit (ARKit) was launched by Apple around June 2017 [50]. The iOS-specific kit allows users to develop AR applications for iPhones and iPads running iOS 11 or later. Apple's ARKit SDK is available to all iOS developers with an Apple developer account. The most recent version, Apple ARKit 6, was introduced at the Apple Worldwide Developers Conference (WWDC) in 2022 [51].AR application through ARCore or ARKit to detect feature points and planes in the real environment, continually improves its understanding of the environment. By looking for clusters of feature points on common horizontal or vertical surfaces, such as tables and walls, ARCore or ARKit makes these surfaces available to your app as geometric planes.

The CAD models of AM opportunities (e.g., cubes) are digitalized and become the mock-ups. Mock-ups related AM are visualization by Unity, achieving the realistic embedding and physical simulation. Based on the mock-ups related AM, some interactions are added in the application.

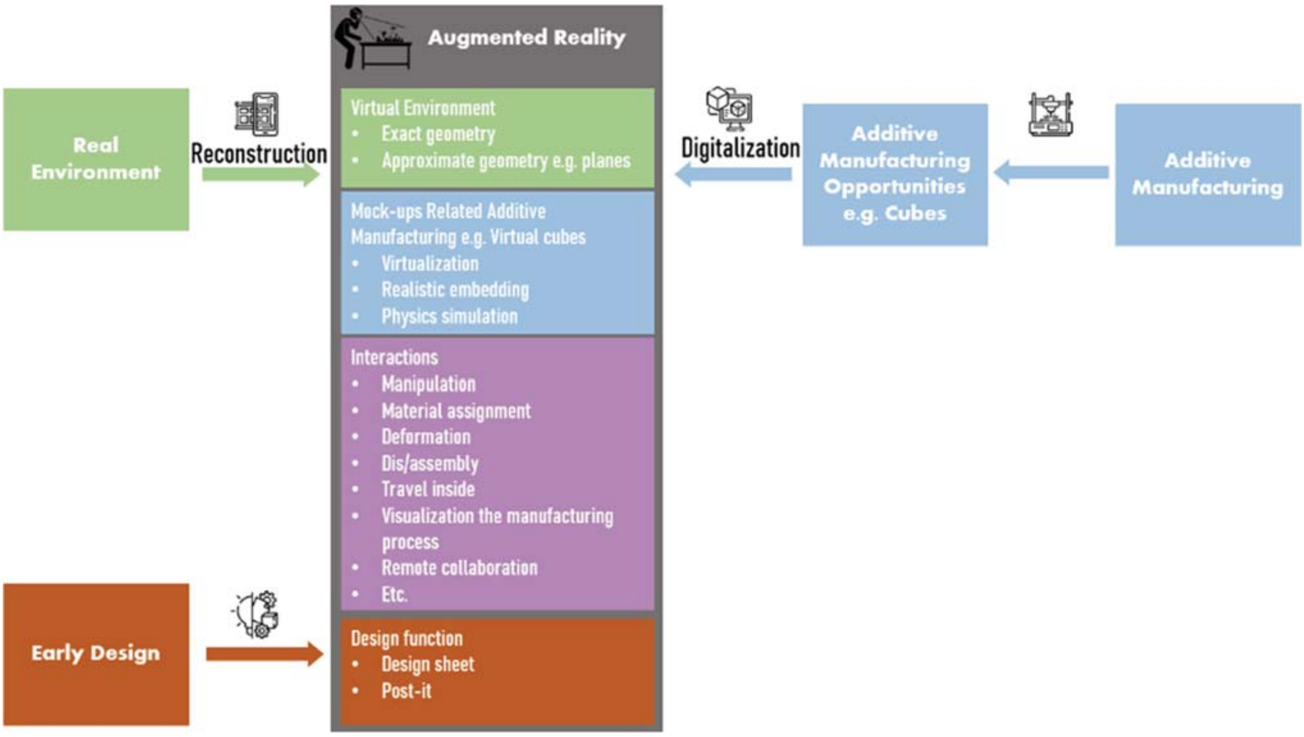


Fig. 3 General framework for exploring AM opportunity cubes through AR

- *Manipulation* Users can manipulate the cubes. For example, moving the cubes from one plane to another plane and rotating the cubes.
- *Material assignment* It is difficult to change cubes' materials in the real world, while in the AR, users can change the materials easily. Even, users can set different components of a cube to different materials
- *Deformation* Set animation when grabbing Cubes, so that users feel that cubes have deformation. Cubes present a different amount of deformation when the user grabs them, depending on the material. This feature makes cubes more realistic.
- *Dis/assembly* Some cubes can be disassembled, and the application allows users to disassemble and assemble cubes in the software. This is similar to an assembly game that will prompt when the user assembly is wrong. If the user needs it, it can provide disassembly guidelines.
- *Travel inside* For cubes with complex structure, it is difficult to observe the internal structure in reality. In AR, the size of the cubes can be enlarged, and the user can enter the inside of the cubes to see their internal structure.
- Visualization the manufacturing process: Application can display the production.
- *Remote collaboration* The application allows designers to collaborate remotely, enabling design communication to be unrestricted by distance. Application can add synchronization function, assuring a real-time communication among designers.

3.2 Prototyped AR application under the framework

Physical 14 opportunities require a certain amount of production time and expense, and they are difficult to collaborate remotely. Gerbeau [48] proposed to integrate AR and AM to virtualize 14 cubes; however, some limitations were evident such as: unable to enter the interior of the cubes to observe the internal structure, a limited number of cubes to be placed, and limited user interaction with cubes.

As opposed to Gerbeau's [48] AR application with marker (14 cards), this paper utilizes markerless AR. In this way, remote display will be easier and more convenient.

Several limits presented in the Gerbeau's solution have been overcome in the new AR solution presented in this paper. The limit of instances for each inspirational object (let's call them cubes) that can be visualized simultaneously was removed. At the same time, this application enhances the interaction with cube. These changes facilitate a greater immersion by designers in the cubes and enhance their understanding of AM's potential in the early design stages.

3.3 Framework for AR application

The application is developed using a game engine Unity [52] for 3D interactive virtual scene and the library of AR Foundation for markerless AR tracking function. Package ARCore, AR Foundation and XR Plugin Management in Unity are used to achieve AR effects. AR Foundation allows users

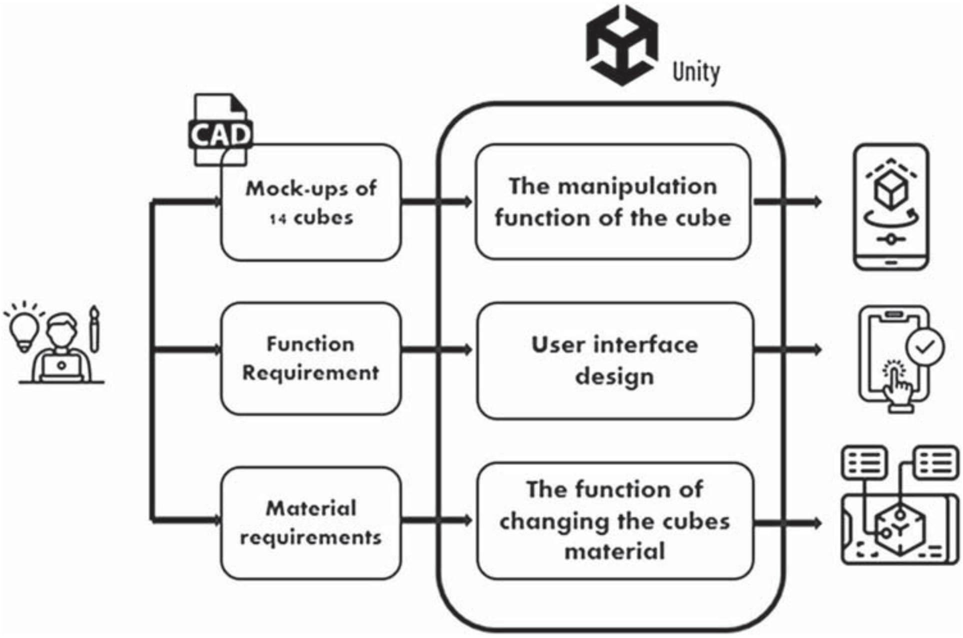


Fig. 4 Framework for AR application

to design and develop AR platforms compatible for multi-platform within Unity. This application contains selecting cubes, moving and rotating cubes, and changing materials for cubes.

Within this application, users can perform essential functions such as cube selection, manipulation encompassing movement and rotation, as well as material adjustments for cubes. It's important to note that not all functions outlined in the general framework have been fully implemented in the current application. The primary contribution lies in evaluating that the existing virtual cubes offer a compelling alternative to their physical counterparts, particularly in terms of usability and their potential applications in the field of AM.

Figure 4 shows the development structure of application. After digitizing the 14 cubes models, import 14 cubes CAD models into Unity. In Unity, design the manipulation of cubes.

Design the user interface and the development of AR interactive functions according to the functional requirements. The application has the function of changing the cubes material.

3.3.1 Cube selection from the cube's library

In Fig. 5a, the cube's library is illustrated, and users can select the cube by adopting this interface. Each option includes a description, information, and a picture of the cubes. Once a cube is selected, it will appear in the plane in the middle of the screen as in Fig. 5b. Press and hold the cube to move it. Click the blue confirm button, the cube will be placed on the plane, and click the red delete button, the cube will be deleted. The default material for the cube is Gray white, and clicking the yellow button in the middle will display the replaceable materials for the cube.

3.3.2 Manipulation of virtual cubes

The application allows users to move and rotate cubes on the plane, as showed in Fig. 6a. Press and hold the cube to move it. Hold the cube with one finger and slide the other finger on the screen to rotate it on the z-axis, as shown in Fig. 6b.

3.3.3 Material changes

Figure 7 is the interface of the material's library. The cube will change to that material once the user clicks on the card of material. By using this software, it is possible to easily alter the cubes' materials. Figure 7b is setting the materials to cubes. Figure 7c is changing the materials.

A comparison of the virtual cubes and the real cubes is shown in Fig. 8. As can be seen, the virtual cubes closely resemble the real cubes. The white box contains virtual cubes, whereas the black box contains real cubes.

4 Experiment

The aim of the experiment was to evaluate the similarity of virtual cubes and real cubes in the process of selecting,

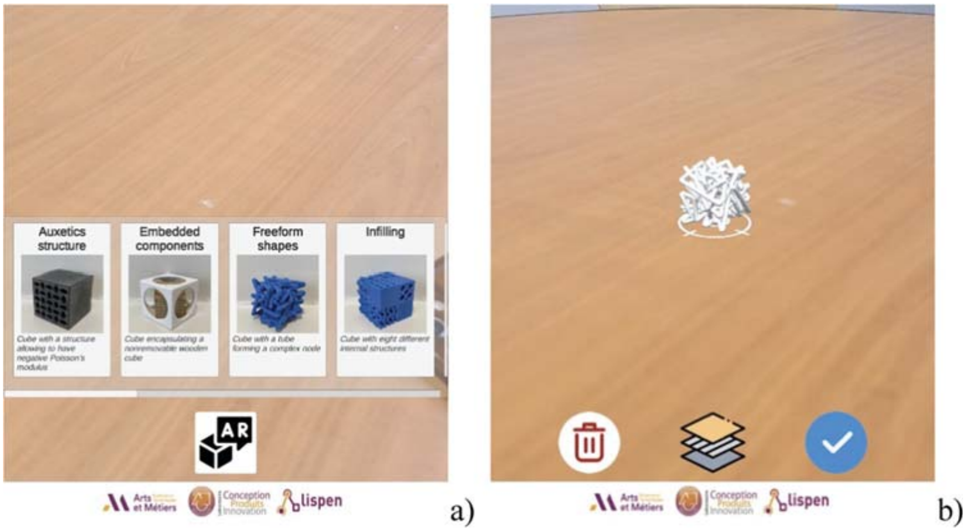


Fig. 5 Cube selection from the cube's library. **a** cube's library **b** select one cube

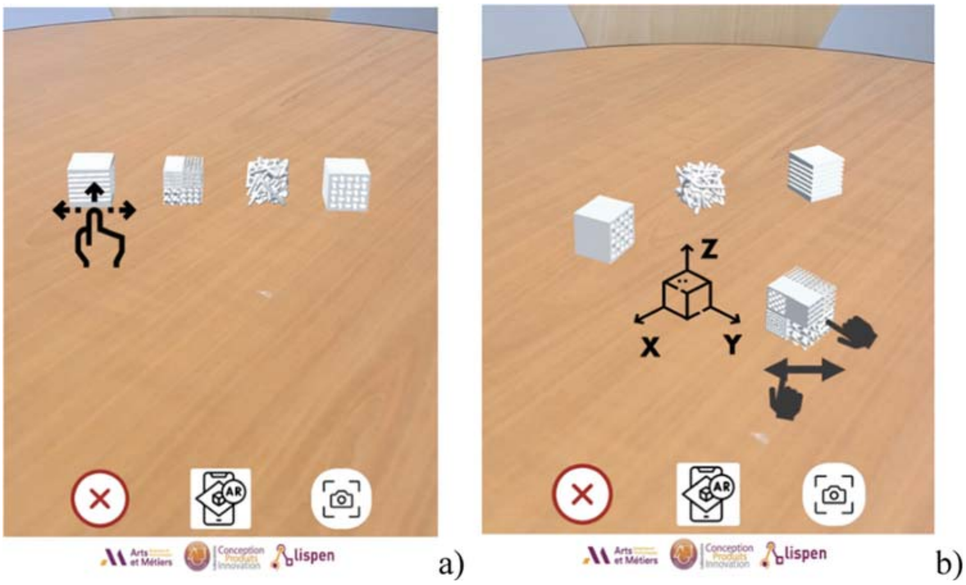


Fig. 6 Manipulate cubes. **a** move the cube **b** rotate the cube

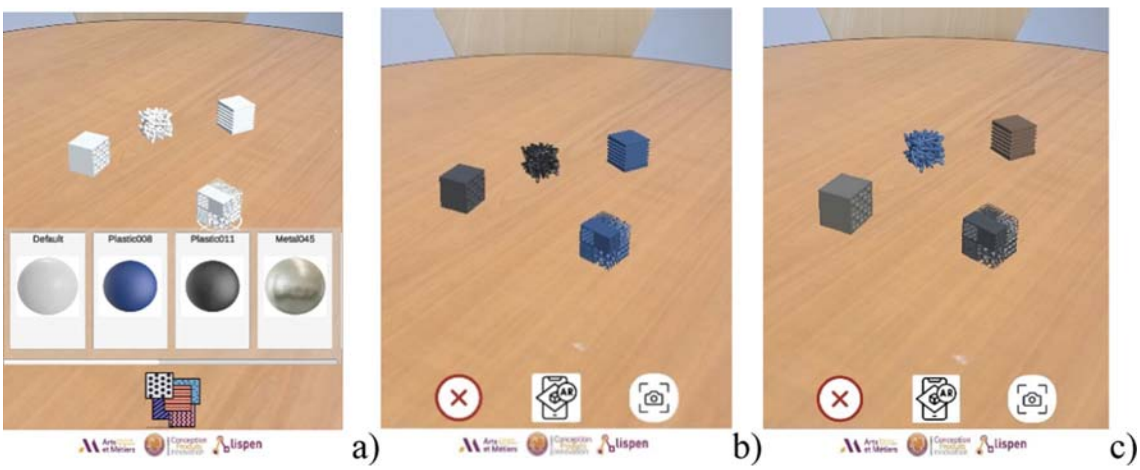


Fig. 7 Material changes. **a** material's library **b** setting the materials to cubes **c** changing the materials

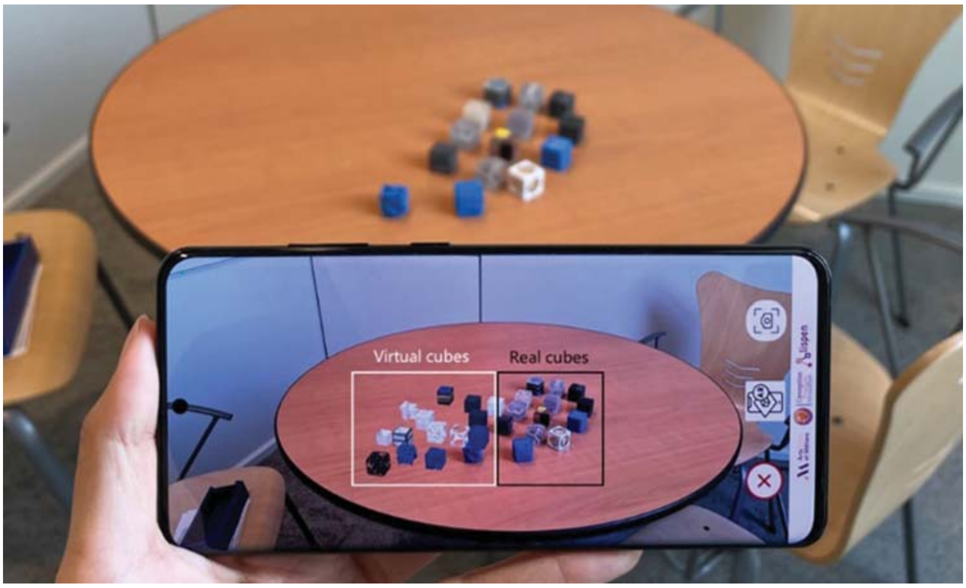


Fig. 8 A comparison of the virtual cubes and the real cubes

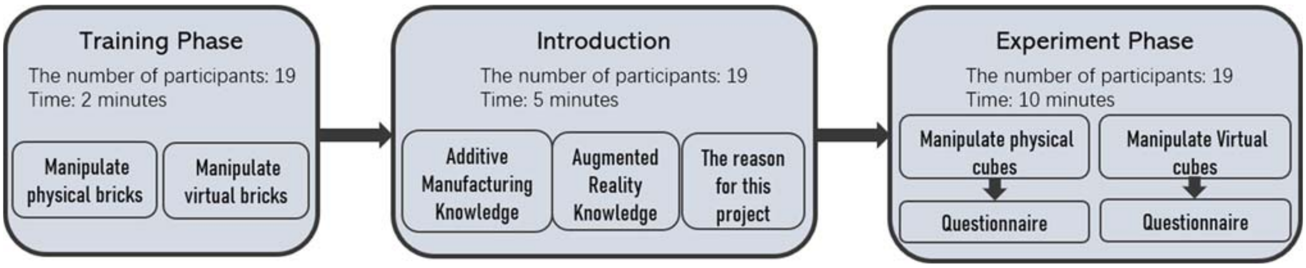


Fig. 9 The structure of the experiment

Fig. 10 Training phase—the first task is to manipulate physical bricks

moving and rotation. This experiment comprised 3 components: Training phase, Introduction, and Experiment phase. The structure of the experiment is depicted in Fig. 9.

4.1 Training phase

The purpose of training phase was to make testers familiar with the experiment process.

1. The first task was to manipulate physical bricks (see Fig. 10).

- According to the pictures of left side, the participants selected 3 bricks from the 6 bricks and putted them on the pictures.
- Moved the 3 bricks to the pictures of the right side.
- Rotated each brick and observed the details.

2. The second task was to manipulate virtual bricks (see Fig. 11).

- According to the pictures of left side, the participants selected 3 bricks from the 6 bricks and putted them on the pictures.
- Moved the 3 bricks to the pictures of the right side.
- Rotated each brick and observed the details.

4.2 Experimental phase

A brief introduction to AM and AR was provided.

Fig. 11 Training phase—the second task is to manipulate virtual bricks

Fig. 12 Experimental phase—the first task is to manipulate real cubes

Fig. 13 Experimental phase—the second task is to manipulate virtual cubes

1. The first task was to Manipulate real cubes (time = 7 min) (see Fig. 12).
- Selected 6 real cubes from the 14 cubes and putted them on the pictures.
- Moved real cubes to the pictures of the right side.
- Introduced the AM opportunities represented by each cube. Let users observed the details of cubes.
- Answered the questionnaire.
2. The second task was to Manipulate virtual cubes (time = 3 min) (see Fig. 13).
- Selected 6 virtual cubes from the 14 cubes library and putted them on the pictures.
- Moved real cubes to the pictures of the right side.
- Answered the questionnaire.

4.3 Questionnaire

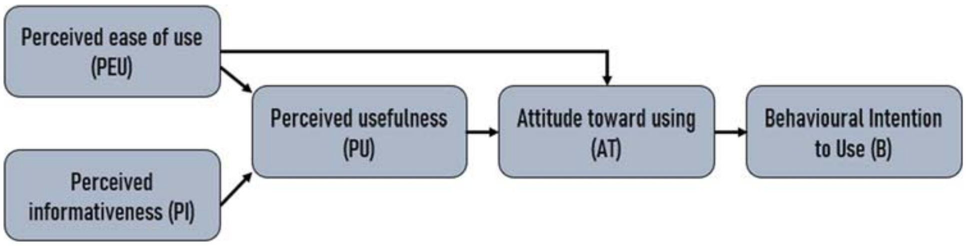
Regarding measuring the acceptance of new technologies, the Technology Acceptance Model (TAM) is a widely used tool for this purpose [53, 54]. Mikropoulos presented the utilization of an AR system for simulating sensory overload, a phenomenon commonly experienced by children with Autism Spectrum Disorders (ASD). Subsequently, an evaluation of the AR system's acceptance was conducted using a variant of the TAM [54]. Rese used TAM to assess the level of acceptance exhibited by users towards the mobile IKEA catalogue application, which incorporates AR functionalities, thereby providing an enhanced and interactive shopping experience [55]. Hence, the utilization of the TAM as a tool for the assessment of applications developed by AR technology is feasible.

According to the basic TAM model, perceived ease of use (PEU) and perceived usefulness (PU) of a technological innovation are related to attitudes (AT) and behavioural Intention to Use (B) toward utilizing the technology. It is additionally proposed that PEU has an indirect positive impact on PU [53, 54]. User acceptance has been measured by the intention to use an innovation or available system. Studies have confirmed that there is a positive relationship between the five constructs and the usefulness of the TAM model in predicting usage in general [55].

The basic TAM model is therefore useful in predicting the application's usage intention. The following is an explanation of each TAM structure:

- Perceived ease of use (PEU): The degree to which a person believes that using a particular system would be free of effort [57].

Fig. 14 Research model of TAM



- Perceived informativeness (PI): Perceived informativeness can affect the perceived usefulness [58].
- Perceived usefulness (PU): The degree to which person believes that using a particular system would enhance his or her job performance [57].
- Attitude toward using (AT): Attitude can also be defined by the positive or negative feelings felt by individuals in performing behaviour [59].
- Behavioural Intention to Use (B): Behavioural intention to use is a trend of behaviour that continues to apply technology [59].
- The Fig. 14 flowed is research model of TAM.

The questionnaire included some questions about the Geometric Complexity (GC) of AM to evaluate the role of the application in learning AM knowledge. All item scales were measured on a 7-point Likert scale (with "1" = "strongly disagree" to "7" = "strongly agree") (see Table 1).

4.4 Results of the experiment

There were 19 participants in the experiment, ranging in age from 21 to 51 (Mean = 27.9, SD = 7.3), as shown in Fig. 15.

As Fig. 16 shows, the questionnaire asks two questions about the participants' knowledge about AM and AR. 42.1% of participants don't know about the AM, 15.8% know it, but never use it, 26.3% know it and have used it, and 15.8% are experts. There are 10.5% don't know about the AR, 10.5% know it, but never use it, 68.5% know it and have used it, and 10.5%are experts.

The questions are summarized in Table 1. The table shows the mean and standard deviation of scores for each question in two sets of questionnaires. The questionnaire consists of 6 parts, perceived ease of use (PEU), Perceived informativeness (PI), perceived usefulness (PU), attitudes toward using (AT), behavioral intention to use (B) and Geometric Complexity (GC) of AM.

The following is the mathematical calculation of the experimental results. M_{Rj} is the Mean of the jth question for real cubes. M_{Vj} is the Mean of the jth question for virtual cubes.

$$M_{Rj} = \frac{\sum_{i=0}^{18} S_{Ri,j}}{18} \tag{1}$$

$$M_{Vj} = \frac{\sum_{i=0}^{18} S_{Vi,j}}{18} \tag{2}$$

where $S_{Ri,j}$ is ith participant's score on the jth question for real cubes. $S_{Vi,j}$ is ith participant's score on the jth question for virtual cubes.

σ_{Rj} is the Standard Deviation (SD) of jth question for real cubes. σ_{Vj} is the Standard Deviation (SD) of jth question for virtual cubes.

$$\sigma_{Rj} = \sqrt{\frac{1}{18}\sum_{i=0}^{18}(S_{Rij} - M_{Rj})^2} \tag{3}$$

$$\sigma_{Vj} = \sqrt{\frac{1}{18}\sum_{i=0}^{18}(S_{Vij} - M_{Vj})^2} \tag{4}$$

In order to compare the scores of real cubes and virtual cubes in 6 parts, the Mean and SD of all questions under each part are averaged to get the Mean and SD of each part. $\{M_{R-6}\}$ represents the Mean value of the 6 parts of the real cubes. $\{M_{V-6}\}$ represents the Mean value of the 6 parts of the virtual cubes. $\{\sigma_{R-6}\}$ represents the SD value of the 6 parts of the real cubes. $\{\sigma_{V-6}\}$ represents the SD value of the 6 parts of the virtual cubes.

$$\{M_{R-6}\} = \begin{pmatrix} M_{R-PEU} = \frac{\sum_{j=0}^{2} M_{Rj}}{3} \\ M_{R-PI} = \frac{\sum_{j=3}^{4} M_{Rj}}{2} \\ M_{R-PU} = \frac{\sum_{j=5}^{6} M_{Rj}}{2} \\ M_{R-AT} = \frac{\sum_{j=7}^{9} M_{Rj}}{3} \\ M_{R-B} = \frac{\sum_{j=10}^{11} M_{Rj}}{2} \\ M_{R-GC} = \frac{\sum_{j=12}^{16} M_{Rj}}{5} \end{pmatrix}, \{M_{V-6}\} = \begin{pmatrix} M_{V-PEU} = \frac{\sum_{j=0}^{2} M_{Vj}}{3} \\ M_{V-PI} = \frac{\sum_{j=3}^{4} M_{Vj}}{2} \\ M_{V-PU} = \frac{\sum_{j=5}^{6} M_{Vj}}{2} \\ M_{V-AT} = \frac{\sum_{j=7}^{9} M_{Vj}}{3} \\ M_{V-B} = \frac{\sum_{j=10}^{11} M_{Vj}}{2} \\ M_{V-GC} = \frac{\sum_{j=12}^{16} M_{Vj}}{5} \end{pmatrix} \tag{5}$$

Table 1 Summary of the questions

Questions	Mean		SD	
	Real cubes	Virtual cubes	Real cubes	Virtual cubes
Perceived ease of use (PEU)	6.96	6.49	0.19	0.89
I think the cube is easy to take	7.00	6.58	0.00	0.84
I think the cube is easy to move	7.00	6.79	0.00	0.54
I think the cube is easy to rotate	6.89	6.11	0.32	1.10
Perceived informativeness (PI)	6.53	6.00	0.80	1.45
I could observe the number of levels of cubes easily	6.68	5.95	0.58	1.47
I could observe the number of holes of cubes easily	6.37	6.05	0.96	1.47
Perceived usefulness (PU)	6.32	6.37	0.74	0.88
For me, the system has great value	6.26	6.53	0.81	0.61
Using the system would facilitate observing the details of cubes	6.37	6.21	0.68	1.08
Attitude toward using (AT)	6.26	6.46	0.94	0.76
I am positive about the system	6.32	6.32	0.95	0.82
The use of the system makes learning more interesting	6.11	6.47	1.10	0.77
I believe that using such a system in the product design is a good idea	6.37	6.58	0.76	0.69
Behavioral Intention to Use (B)	5.92	6.26	1.08	0.83
If 1 were to learn Additive Manufaturing in the future, I would use the system immediately	5.79	6.21	1.18	0.92
I will recommend using the system to others	6.05	6.32	0.97	0.75
Geometrical complexity (GC)	5.55	5.81	1.13	0.93
I feel able to explain the opportunities of AM under GC to someone else	5.68	5.89	1.06	0.81
I feel able to give example of objects that take advantage of AM opportunities that are relevant to GC	5.79	6.11	1.08	0.81
I feel capable of proposi ng ideas of innovative object exploiting the opportunities of the AM relevant to GC	5.53	5.84	1.26	1.07
I feel able to recognize objects exploiting the AM opportunities related to GC	5.53	6.00	1.17	0.82
I think I have mastered the AM opportunities related to GC	5.21	5.21	1.08	0.92

Questions	Mean		SD	
	$M_{\text{R-6}}$	$M_{\text{V-6}}$	$\sigma_{\text{R-6}}$	$\sigma_{\text{V-6}}$
Perceived ease of use (PBJ)	6.96	6.49	0.19	0.89
Perceived informativeness (PI)	6.53	6.00	0.80	1.45
Perceived usefulness (PU)	6.32	6.37	0.74	0.88
Attitude toward using (AT)	6.26	6.46	0.94	0.76
Behavioral intention to use (B)	5.92	6.26	1.08	0.83
Geometrical complexity (GC)	5.55	5.81	1.13	0.93

$$\{\sigma_{R-6}\} = \begin{pmatrix} \sigma_{R-PEU} = \frac{\sum_{j=0}^{2} \sigma_{Rj}}{3} \\ \sigma_{R-PI} = \frac{\sum_{j=3}^{4} \sigma_{Rj}}{2} \\ \sigma_{R-PU} = \frac{\sum_{j=5}^{6} \sigma_{Rj}}{2} \\ \sigma_{R-AT} = \frac{\sum_{j=7}^{9} \sigma_{Rj}}{3} \\ \sigma_{R-B} = \frac{\sum_{j=10}^{11} \sigma_{Rj}}{2} \\ \sigma_{R-GC} = \frac{\sum_{j=12}^{16} \sigma_{Rj}}{5} \end{pmatrix}, \qquad \{\sigma_{V-6}\} = \begin{pmatrix} \sigma_{V-PEU} = \frac{\sum_{j=0}^{2} \sigma_{Vj}}{3} \\ \sigma_{V-PI} = \frac{\sum_{j=3}^{4} \sigma_{Vj}}{2} \\ \sigma_{V-PU} = \frac{\sum_{j=5}^{6} \sigma_{Vj}}{2} \\ \sigma_{V-AT} = \frac{\sum_{j=7}^{9} \sigma_{Vj}}{3} \\ \sigma_{V-B} = \frac{\sum_{j=10}^{11} \sigma_{Vj}}{2} \\ \sigma_{V-GC} = \frac{\sum_{j=12}^{16} \sigma_{Vj}}{5} \end{pmatrix} \tag{6}$$

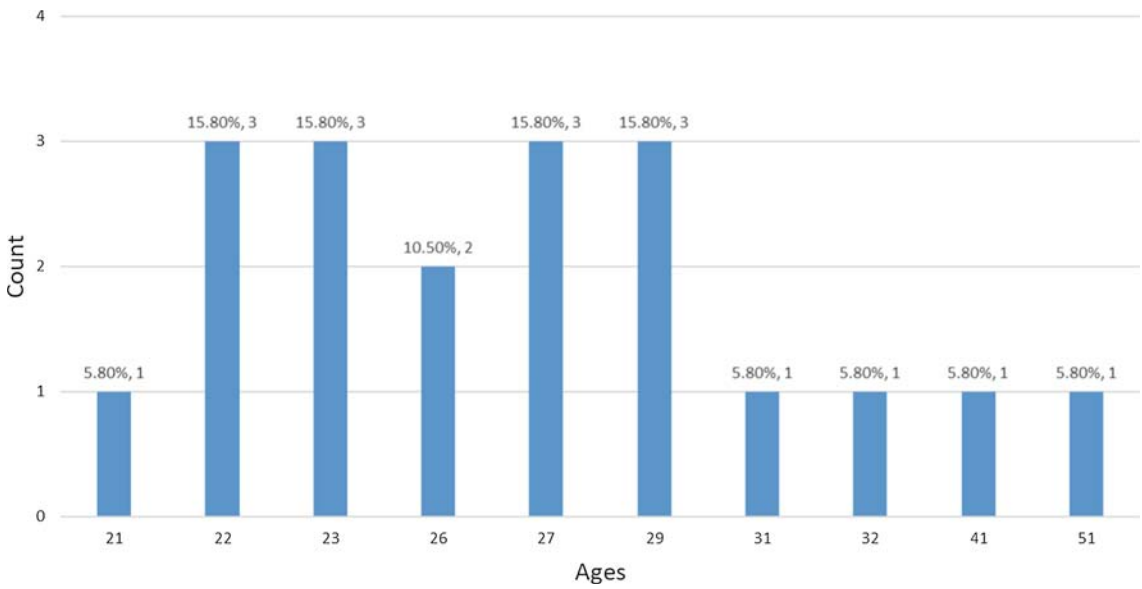


Fig. 15 Ages of the participants

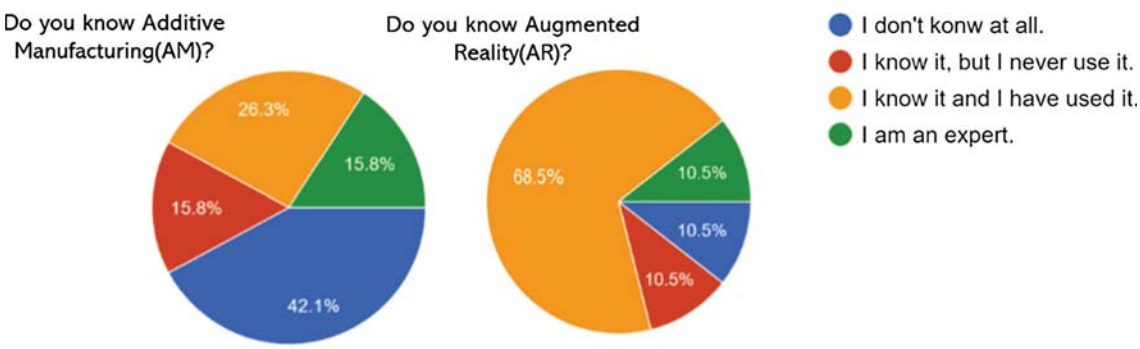


Fig. 16 Participants' knowledge of AM and AR

Fig. 17 is the box plot of the experiment.

Through box plot, it is possible to more intuitively compare the scores of each part of two questionnaires. For each part, this paper calculates the Mean of each participant in each part, and then draw the box plot of this part of the problem based on the data. In the following section, an example will be provided of how to calculate the real cube data in the PEU ($\left\{S_{R-PEU-plot}\right\}$).

$\{S_R\}$ is the data of scores for real cubes, $\{S_V\}$ is the data of scores for virtual cubes.

$$\{S_R\} = \begin{pmatrix} S_{R0,0} & \cdots & S_{R0,16} \\ \vdots & \ddots & \vdots \\ S_{R18,0} & \cdots & S_{R18,16} \end{pmatrix}, \{S_V\} = \begin{pmatrix} S_{V0,0} & \cdots & S_{V0,16} \\ \vdots & \ddots & \vdots \\ S_{V18,0} & \cdots & S_{V18,16} \end{pmatrix} \tag{7}$$

$$\{S_{R-PEU}\} = \begin{pmatrix} S_{R0,0} & \cdots & S_{R0,2} \\ \vdots & \ddots & \vdots \\ S_{R18,0} & \cdots & S_{R18,2} \end{pmatrix} \tag{8}$$

$$\left\{S_{R-PEU-plot}\right\} = \begin{pmatrix} \frac{\sum_{j=0}^{2} S_{R0,j}}{3} \\ \cdots \\ \frac{\sum_{j=0}^{2} S_{R18,j}}{3} \end{pmatrix} \tag{9}$$

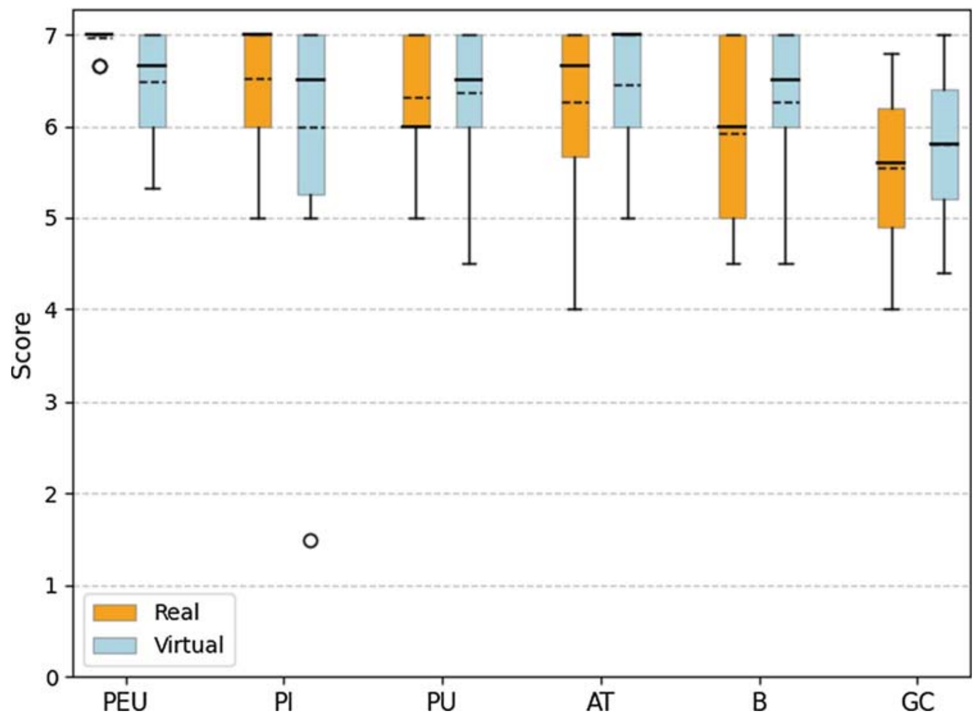
Then use this method to calculate all the scores for real cubes and virtual cubes, and plot the box plot as Fig. 17.

In order to evaluate whether the virtual cubes can achieve similar effects to the real cubes, this paper calculates the score difference between each participant in the same problem in the 2 questionnaires, as the Fig. 18 shows. In the following section, an example will be provided of how to calculate the Score difference in the PEU ($\{\Delta_{R-PEU}\}$).

$$\{\Delta_{R-PEU}\} = \left|\left\{S_{R-PEU-plot}\right\} - \left\{S_{V-PEU-plot}\right\}\right| \tag{10}$$

Then use this method to calculate all score difference between real cubes and virtual cubes, and plot the box plot as Fig. 18.

Fig. 17 Box plot of the experiment



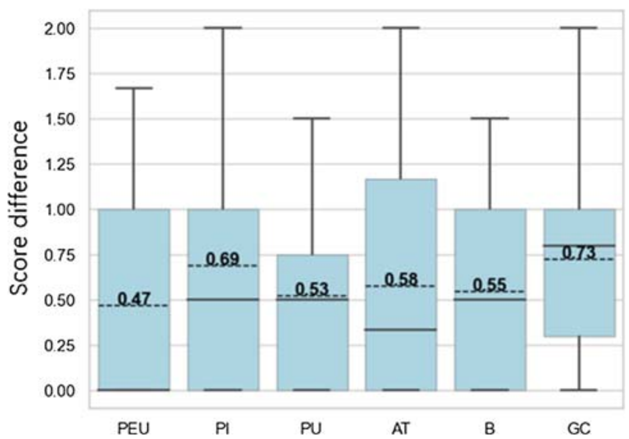


Fig. 18 Score difference between 2 questionnaires

In the parts of PEU and PI, real cubes received higher average scores than virtual cubes, indicating that participants found the real cubes easier to use and more useful. The participants of the experiment also reflected that in the case of selecting, moving, and rotating, the real cubes is better operating. This is also the part that needs to be improved in the future application. The PI score for virtual cubes was slightly lower due to the need for participants to move their phones closer to see details.

Virtual cubes were rated higher in PU, AT, B, and GC, indicating that participants believed that using virtual cubes enhanced job performance, elicited more positive feelings, promoted continued technology use, and effectively conveyed AM-related knowledge. As the score of PU shows that participants believe that using virtual cubes would enhance his or her job performance. The score of AT shows they have more positive feelings by using virtual cubes. The score of B shows a trend of behavior that continues to apply technology, in this respect, virtual cubes perform better. The questions of GC are to focus on the cubes to help users understand AM-related knowledge. Virtual cubes perform better in displaying AM related information. Participants' feedback also indicated that they felt the virtual cubes were more helpful in understanding AM-related knowledge.

To assess whether virtual cubes could achieve similar effects to real cubes, the paper calculated the score difference between participants' responses in the two questionnaires. The result of the score difference is explained that virtual cubes can achieve similar effects to the real cubes.

In summary, the experiment revealed that while real cubes were favored for ease of use and perceived usefulness in some aspects, virtual cubes performed better in conveying AM-related knowledge and eliciting positive attitudes and intentions to use. The findings support the potential effectiveness of virtual cubes in AR applications, with some room for improvement in certain usability aspects.

5 Conclusion and perspectives

This article proposed a combination of AM opportunities and makerless AR to virtualize AM opportunities. In this prototype, the 14 inspirational objects were visualized using

AR. In the application, users could have interactions with the 14 cubes. Additionally, the prototype reduced the amount of time and money that must be invested.

As the results of experiment showed the application had a good performance in each aspect. And, the results showed the virtual cubes could achieve similar effects to the real cubes. In perceived usefulness (PU), attitudes toward using (AT), behavioral intention to use (B) and Geometric Complexity (GC) of Additive Manufacturing, the score of virtual cubes was higher than that of real cubes. Using AR to manipulate virtual cubes of AM is a promising alternative method for physical cubes.

The capabilities of the AR application were presented, including cube selection, manipulation, and material changes. While these functionalities represented a crucial foundation for the project, this paper acknowledged that the application was currently limited in its scope. In the future work, it will expand the application's capabilities to encompass the visualization of the manufacturing process and remote collaboration, which are essential components of the general framework for AM opportunity cubes through AR.

In future, the application will add more interaction to the application, making it more useful in the early design stages. Based on the results of PEU and PI, the average score of real cubes is higher than the score of virtual cubes. The future application will improve the function of manipulation.

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Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. Ghobakhloo, M.: Industry 4.0, digitization, and opportunities for sustainability. J. Clean. Prod. **252**, 119869 (2020). https://doi.org/10.1016/j.jclepro.2019.119869
2. Bai, C., Dallasega, P., Orzes, G., Sarkis, J.: Industry 4.0 technologies assessment: a sustainability perspective. Int. J. Prod. Econ. **229**, 107776 (2020). https://doi.org/10.1016/j.ijpe.2020.107776
3. Gibson, I., Rosen, D., Stucker, B.: Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing. NY: Springer New York, (2015) https://doi.org/10.1007/978-1-4939-2113-3
4. Laverne, F., Segonds, F., Dubois, P.: Fabrication additive—principes généraux. Concept. et Prod. (2016). https://doi.org/10.51257/a-v2-bm7017
5. Attaran, M.: The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing. Bus. Horiz. **60**(5), 677–688 (2017). https://doi.org/10.1016/j.bushor.2017.05.011
6. Van, L.P., Jean, C., Meyrueis, V., Gazo, C., Mantelet, F., Gueguan, J., Segonds, F.: IdeAM running quiz: a digital learning game to enhance additive manufacturing opportunities discovery. Int. J. Emerg. Technol. Learn. **17**(10), 32–50 (2022). https://doi.org/10.3991/ijet.v17i10.25695
7. Lang, A., Segonds, F., Jean, C., Gazo, C., Guegan, J., Buisine, S., Mantelet, F.: Augmented design with additive manufacturing methodology: tangible object-based method to enhance creativity in design for additive manufacturing. 3D Print. Addit. Manuf. **8**(5), 281–292 (2021). https://doi.org/10.1089/3dp.2020.0286
8. Laverne, F., Segonds, F., Anwer, N., Le Coq, M.: Assembly based methods to support product innovation in design for additive manufacturing: an exploratory case study. J. Mech. Des. **137**(12), 121701 (2015). https://doi.org/10.1115/1.4031589
9. Boothroyd, G.: Product design for manufacture and assembly. Comput. Aided Des. **26**(7), 505–520 (1994). https://doi.org/10.1016/0010-4485(94)90082-5
10. Segonds, F., Cohen, G., Véron, P., Peyceré, J.: PLM and early stages collaboration in interactive design, a case study in the glass industry. Int. J. Interact. Des. Manuf. **10**(2), 95–104 (2016). https://doi.org/10.1007/s12008-014-0217-4
11. Mourtzis, D., Zogopoulos, V., Vlachou, E.: Augmented reality supported product design towards industry 4.0: a teaching factory paradigm. Procedia Manuf. **23**, 207–212 (2018). https://doi.org/10.1016/j.promfg.2018.04.018
12. Schmalstieg, D., Langlotz, T., Billinghurst, M.: Augmented Reality 2.0. p. 37. (2008) https://doi.org/10.1007/978-3-211-99178-7_2.
13. Mourtzis, D., Zogopoulos, V., Xanthi, F.: Augmented reality application to support the assembly of highly customized products and to adapt to production re-scheduling. Int. J. Adv. Manuf. Technol. **105**(9), 3899–3910 (2019). https://doi.org/10.1007/s00170-019-03941-6
14. Shen, Y., Ong, S.K., Nee, A.Y.C.: Augmented reality for collaborative product design and development. Des. Stud. **31**(2), 118–145 (2010). https://doi.org/10.1016/j.destud.2009.11.001
15. Kumar, A., Yadav, S. S., Kumar, S., Johri, P.: Augmented reality systems in gaming and multimedia. In: 2021 International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE), Greater Noida, India: IEEE, pp. 333–338. (2021), https://doi.org/10.1109/ICACITE51222.2021.9404682.
16. Pellas, N., Fotaris, P., Kazanidis, I., Wells, D.: Augmenting the learning experience in primary and secondary school education: a systematic review of recent trends in augmented reality game-based learning. Virtual Reality **23**(4), 329–346 (2019). https://doi.org/10.1007/s10055-018-0347-2
17. López-Faican, L., Jaen, J.: EmoFindAR: evaluation of a mobile multiplayer augmented reality game for primary school children. Comput. Educ. **149**, 103814 (2020). https://doi.org/10.1016/j.compedu.2020.103814
18. Rebollo, C., Remolar, I., Rossano, V., Lanzilotti, R.: Multimedia augmented reality game for learning math. Multimed. Tools Appl. **81**(11), 14851–14868 (2022). https://doi.org/10.1007/s11042-021-10821-3
19. Taskiran, A.: The effect of augmented reality games on English as foreign language motivation. E-Learn. Digit. Media **16**(2), 122–135 (2019). https://doi.org/10.1177/2042753018817541
20. Iatsyshyn, A.V., Kovach, V.O., Lyubchak, V.O., Zuban, Y.O., Piven, A.G., Sokolyuk, O.M., Iatsyshyn, A.V., Popov, O.O., Artemchuk, V.O., Shyshkina, M.P.: Application of augmented reality technologies for education projects preparation. CTE Workshop Proc. **7**, 134–160 (2020). https://doi.org/10.55056/cte.318
21. Elmqaddem, N.: Augmented reality and virtual reality in education. Myth or reality?. Int. J. Emerg. Technol. Learn. 14(3). (2019) https://doi.org/10.3991/ijet.v14i03.9289.
22. Wu, H.-K., Lee, S.W.-Y., Chang, H.-Y., Liang, J.-C.: Current status, opportunities and challenges of augmented reality in education. Comput. Educ. **62**, 41–49 (2013). https://doi.org/10.1016/j.compedu.2012.10.024

23. Videnovik, M., Trajkovik, V., Kiønig, L.V., Vold, T.: Increasing quality of learning experience using augmented reality educational games. Multimed. Tools Appl. **79**(33–34), 23861–23885 (2020). https://doi.org/10.1007/s11042-020-09046-7
24. Sutherland, J., Belec, J., Sheikh, A., Chepelev, L., Althobaity, W., Chow, B.J.W., Mitsouras, D., Christensen, A., Rybicki, F.J., La Russa, D.J.: Applying modern virtual and augmented reality technologies to medical images and models. J. Digit. Imaging **32**(1), 38–53 (2019). https://doi.org/10.1007/s10278-018-0122-7
25. Eckert, M., Volmerg, J.S., Friedrich, C.M.: Augmented reality in medicine: systematic and bibliographic review. JMIR Mhealth Uhealth **7**(4), e10967 (2019). https://doi.org/10.2196/10967
26. Moro, C., Phelps, C., Redmond, P., Stromberga, Z.: HoloLens and mobile augmented reality in medical and health science education: a randomised controlled trial. Br. J. Educ. Technol. **52**(2), 680–694 (2021). https://doi.org/10.1111/bjet.13049
27. Bellalouna, F.: Digitization of industrial engineering processes using the augmented reality technology: industrial case studies. Procedia CIRP **100**, 554–559 (2021). https://doi.org/10.1016/j.procir.2021.05.120
28. Oke, A.E., Arowoiya, V.A.: An analysis of the application areas of augmented reality technology in the construction industry. SASBE **11**(4), 1081–1098 (2022). https://doi.org/10.1108/SASBE-11-2020-0162
29. Zhang, Z., Wen, F., Sun, Z., Guo, X., He, T., Lee, C.: Artificial intelligence-enabled sensing technologies in the 5g/internet of things era: from virtual reality/augmented reality to the digital twin. Adv. Intell. Syst. **4**(7), 2100228 (2022). https://doi.org/10.1002/aisy.202100228
30. Fite-Georgel, P.: Is there a reality in industrial augmented reality?.
31. Laviola, E., Gattullo, M., Manghisi, V.M., Fiorentino, M., Uva, A.E.: Minimal AR: visual asset optimization for the authoring of augmented reality work instructions in manufacturing. Int. J. Adv. Manuf. Technol. **119**(3), 1769–1784 (2022). https://doi.org/10.1007/s00170-021-08449-6
32. Kim, T., Guida, G., Kim, D.: VitruviAR: interactive augmented reality for early design stage applications. In: Blucher Design Proceedings, online: Editora Blucher, pp. 1101–1114. (2021) https://doi.org/10.5151/sigradi2021-83.
33. Eiriksson, E.R., Pedersen, D.B., Frisvad, J.R., Skovmand, L., Heun, V., Maes, P., Aanæs, H.: Augmented reality interfaces for additive manufacturing. In: Image Analysis, P. Sharma, F.M. Bianchi, (eds.), in Lecture Notes in Computer Science, vol. 10269. Cham: Springer International Publishing, pp. 515–525. (2017) https://doi.org/10.1007/978-3-319-59126-1_43.
34. Kutej, D., Vorraber, W.: Fostering additive manufacturing of special parts with augmented-reality on-site visualization. Procedia Manuf. **39**, 13–21 (2019). https://doi.org/10.1016/j.promfg.2020.01.223
35. Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R.I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., Martina, F.: Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP Ann. **65**(2), 737–760 (2016). https://doi.org/10.1016/j.cirp.2016.05.004
36. Laverne, F., Segonds, F., D'Antonio, G., Le Coq, M.: Enriching design with X through tailored additive manufacturing knowledge: a methodological proposal. Int. J. Interact. Des. Manuf. **11**(2), 279–288 (2017). https://doi.org/10.1007/s12008-016-0314-7
37. Gross, J., Park, K., Kremer, G.: Design for additive manufacturing inspired by TRIZ. (2018) https://doi.org/10.1115/DETC2018-85761
38. Raimbaud, P., Lou, R., Danglade, F., Figueroa, P., Hernandez, J.T., Merienne, F.: A task-centred methodology to evaluate the design of virtual reality user interactions: a case study on hazard identification. Buildings, vol. 11, no. 7, (2021). https://doi.org/10.3390/buildings11070277
39. Faliu, B., Siarheyeva, A., Lou, R., Merienne, F.: Design and prototyping of an interactive virtual environment to foster citizen participation and creativity in urban design. In: Advances in Information Systems Development. B. Andersson, B. Johansson, C. Barry, M. Lang, H. Linger, and C. Schneider, (eds.), in Lecture Notes in Information Systems and Organisation. Cham: Springer International Publishing, pp. 55–78. (2019) https://doi.org/10.1007/978-3-030-22993-1_4.
40. Azuma, R.T.: A survey of augmented reality.
41. Cheng, J., Chen, K., Chen, W.: Comparison of marker-based AR and markerless AR: a case study on indoor decoration system. (2017) https://doi.org/10.24928/JC3-2017/0231
42. Kato, H., Billinghurst, M.: Marker tracking and HMD calibration for a video-based augmented reality conferencing system. In: Proceedings 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR'99), San Francisco, CA, USA: IEEE Comput. Soc, pp. 85–94. (1999) https://doi.org/10.1109/IWAR.1999.803809.
43. Comport, A.I., Marchand, E., Pressigout, M., Chaumette, F.: Real-time markerless tracking for augmented reality: the virtual visual servoing framework. IEEE Trans. Vis. Comput. Graph. **12**(4), 615–628 (2006). https://doi.org/10.1109/TVCG.2006.78
44. Paulo Lima, J., Roberto, R., Simões, F., Almeida, M., Figueiredo, L., Marcelo Teixeira, J., Teichrieb, V.: Markerless tracking system for augmented reality in the automotive industry. Expert Systems with Applications, vol. 82, pp. 100–114, (2017) https://doi.org/10.1016/j.eswa.2017.03.060.
45. Lee, T., Hollerer, T.: Handy AR: markerless inspection of augmented reality objects using fingertip tracking. In: 2007 11th IEEE International Symposium on Wearable Computers, Boston, MA, USA: IEEE, pp 1–8. (2007) https://doi.org/10.1109/ISWC.2007.4373785.
46. Frandsen, J., Tenny, J., Frandsen, W., Hovanski, Y.: An augmented reality maintenance assistant with real-time quality inspection on handheld mobile devices. Int. J. Adv. Manuf. Technol. (2023). https://doi.org/10.1007/s00170-023-10978-1
47. Stanimirovic, D., Damasky, N., Webel, S., Koriath, D., Spillner, A., Kurz, D.: [Poster] A Mobile Augmented reality system to assist auto mechanics. In: 2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), Munich, Germany: IEEE, pp. 305–306. (2014), https://doi.org/10.1109/ISMAR.2014.6948462.
48. Gerbeau, V., Segonds, F., Meyrueis, V., Buisine, S.: ACDC: augmented creativity for design collaboration.
49. ARCore. Google AR & VR. https://arvr.google.com/arcore/ (Accessed Mar. 08, 2023)
50. Devagiri, J.S., Paheding, S., Niyaz, Q., Yang, X., Smith, S.: Augmented reality and artificial intelligence in industry: trends, tools, and future challenges. Exp. Syst. Appl. **207**, 118002 (2022). https://doi.org/10.1016/j.eswa.2022.118002
51. Inc, A.: Discover ARKit 6 - WWDC22 - Videos. Apple Developer. https://developer.apple.com/videos/play/wwdc2022/10126/ (Accessed Mar. 08, 2023)
52. Technologies, U.: Unity real-time development platform | 3D, 2D, VR & AR Engine. https://unity.com/ (Accessed Mar. 08, 2023)
53. Beckmann, J., Knauf, K.M., Weber, P.: Holistic evaluation of AR/VR-trainings in the ARSuL-project. p 4327. (2019) https://doi.org/10.21125/inted.2019.1079.
54. Mikropoulos, T.A., Delimitros, M., Gaintatzis, P., Iatraki, G., Stergiouli, A., Tsiara, A., Kalyvioti, K.: Acceptance and user experience of an augmented reality system for the simulation of sensory overload in children with Autism. In: 2020 6th International Conference of the Immersive Learning Research Network (iLRN), 86–92 Jun. 2020, https://doi.org/10.23919/iLRN47897.2020.9155113.

55. Rese, A., Schreiber, S., Baier, D.: Technology acceptance modeling of augmented reality at the point of sale: can surveys be replaced by an analysis of online reviews? J. Retail. Consum. Serv. **21**(5), 869–876 (2014). https://doi.org/10.1016/j.jretconser.2014.02.011
56. Davis, F.D., Bagozzi, R.P., Warshaw, P.R.: User acceptance of computer technology: a comparison of two theoretical models. Manage. Sci. **35**(8), 982–1003 (1989)
57. Davis, F.D.: Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Q. **13**(3), 319–340 (1989). https://doi.org/10.2307/249008
58. Olsson, T., Lagerstam, E., Kärkkäinen, T., Väänänen, K.: Expected user experience of mobile augmented reality services: a user study in the context of shopping centres. Pers. Ubiquitous Comput. (2011). https://doi.org/10.1007/s00779-011-0494-x
59. Natasia, S.R., Wiranti, Y.T., Parastika, A.: Acceptance analysis of NUADU as e-learning platform using the technology acceptance model (TAM) approach. Procedia Comput. Sci. **197**, 512–520 (2022). https://doi.org/10.1016/j.procs.2021.12.168