

**AI-POWERED MOBILE AUGMENTED REALITY
EDUCATIONAL SYSTEM FOR PRIMARY SCHOOL
STUDENTS:
GEOMETRY AND ENGLISH LITERACY LEARNING
INDIVIDUAL THESIS**

Individual component: 2D-to-3D Geometry Validation

Research Project: R26-IM-005 | Product: GeoLex AR

Himsara M.K.D.L (IT22274298)

Report submitted in partial fulfilment of the requirements for the

B.Sc. (Hons) Degree in Information Technology

Specializing in Interactive Media

Department of Information Technology

Sri Lanka Institute of Information Technology

Sri Lanka

October 2026

DECLARATION AND SUPERVISOR CERTIFICATION

Candidate declaration. I declare that this thesis is my own work and does not incorporate, without acknowledgement, material previously submitted for a degree or diploma at any university or institute of higher learning. To the best of my knowledge, it contains no material previously published or written by another person except where acknowledgement is made in the text. I grant the Sri Lanka Institute of Information Technology the non-exclusive right to reproduce and distribute this thesis, in whole or in part, in print, electronic, or other media, while retaining the right to use the content in future work.

Academic integrity and AI disclosure. I used ChatGPT as an assistive tool during software-development troubleshooting, explanation, drafting, language refinement, and document preparation. All technical descriptions in this thesis were checked against the final source code, the finalized research paper, the project proposal, the Topic Assessment Form, and the available evaluation records. I remain responsible for the accuracy, originality, citations, code, data, analyses, and conclusions presented in this thesis.

Student name: Himsara M.K.D.L

Student ID: IT22274298

Signature: _____ Date: _____

Supervisor certification. The above candidate carried out this research for the bachelor's degree thesis under my supervision.

Role and name	Signature	Date
Supervisor: Mr. Aruna Ishara Gamage		
Co-supervisor: Mr. Nushkan Nisme		

ABSTRACT

Primary-school geometry requires learners to coordinate two-dimensional nets with the three-dimensional solids they form, yet static textbook representations provide limited support for testing whether a learner-created net is structurally correct. This thesis presents the 2D-to-3D Geometry Validation component of the AR Educational Suite for Primary Students' Geometry and Literacy. The component was developed in Unity 2022.3 LTS for Android and uses deterministic, shape-specific validation rather than the CNN-based geometry-recognition approach proposed at the beginning of the project. Cube, Cuboid, Triangular Prism, Tetrahedron, and Cylinder activities evaluate faces, dimensions, connectivity, adjacency, orientation, and folding compatibility before permitting 3D reinforcement. Valid constructions are converted into animated three-dimensional forms and then placed in the physical environment through AR Foundation and the ARCore XR Plugin; invalid constructions are blocked and can be routed to the correction pathway. A Design Science Research approach guided iterative design, implementation, technical verification, and learner evaluation. The pilot evaluation involved 25 learners aged 9–12 and 25 geometry cases, with four valid and one invalid case per supported solid. All 25 validity decisions matched the expected labels; all 20 valid cases progressed to 3D/AR and all five invalid cases were blocked. Mean task time was 12.65 s, with shape-specific means ranging from 6.55 s for Cuboid to 24.14 s for Tetrahedron. The C1 group mean increased from 5/10 in the pre-test to 9/10 in the post-test. These results provide descriptive evidence that validation-first, learner-generated geometry can form a practical bridge between 2D construction and AR-based spatial reinforcement, while the small sample and aggregate learning scores limit inferential claims.

Keywords: augmented reality, geometric net validation, spatial visualization, 2D-to-3D transformation, primary geometry

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor, Mr. Aruna Ishara Gamage, and my co-supervisor, Mr. Nushkan Nisme, for their guidance, critical feedback, and encouragement throughout the research and development process. Their advice was valuable in refining the research problem, narrowing the individual contribution, and aligning the implementation and evaluation with the requirements of the research project.

I also acknowledge the academic staff of the Department of Information Technology at the Sri Lanka Institute of Information Technology for providing the academic foundation, facilities, and research guidance required to complete this work. I am grateful to my research group members for their collaboration during system integration, especially where the geometry-validation component exchanges states with the 2D Net Correction and Virtual Slicing component and shares navigation and AR presentation with the wider educational suite.

My appreciation is extended to the learners, parents or guardians, and educational personnel who supported the pilot evaluation in a Sri Lankan school or educational setting. Their participation made it possible to observe the component in an age-appropriate learning context. Finally, I thank my family and friends for their continued support during the design, implementation, testing, and documentation stages of the project.

TABLE OF CONTENTS

Declaration and Supervisor Certification	i
Abstract	ii
Acknowledgements	iii
Table of Contents	iv
List of Figures	vi
List of Tables	vii
List of Abbreviations	viii
1 INTRODUCTION	1
1.1 Overall project context	1
1.2 Individual component context	1
1.3 Problem statement	1
1.4 Research gap	1
1.5 Aim and objectives	2
1.6 Research questions or hypotheses	2
1.7 Scope limitations and assumptions	2
1.8 Individual contribution	3
1.9 Thesis structure	3
2 LITERATURE REVIEW AND RELATED WORK	4
2.1 Review method and scope	4
2.2 Domain and theoretical foundations	4
2.3 Related research	4
2.4 Existing systems products and techniques	5
2.5 Gap synthesis and conceptual framework	5
3 RESEARCH METHODOLOGY	7
3.1 Research design	7
3.2 Data participants or study materials	8
3.3 Experimental or study procedure	8
3.4 Measures and evaluation metrics	8
3.5 Data analysis	9
3.6 Ethics privacy security and responsible AI	9
3.7 Reproducibility and research artefacts	9
4 PRODUCT AND SOLUTION DESIGN	10
4.1 Requirements	10
4.2 Component architecture within the complete solution	10
4.3 Design alternatives and decisions	11
4.4 Detailed design	12
4.5 Standards and professional practice	12
5 IMPLEMENTATION INTEGRATION AND TESTING	13

5.1 Development environment and technology stack	13
5.2 Component implementation	13
5.3 Integration with the other components	14
5.4 Verification and software testing	15
5.5 Deployment and operation	15
6 RESULTS AND VALIDATION	16
6.1 Research results	16
6.2 Product and technical results	16
6.3 User or stakeholder validation	17
6.4 Integration results	17
6.5 Summary of findings	18
7 DISCUSSION	19
7.1 Interpretation of findings	19
7.2 Comparison with literature baselines and existing solutions	19
7.3 Research contribution	19
7.4 Product contribution	19
7.5 Limitations and threats to validity	20
7.6 Implications	20
8 COMMERCIALISATION AND SUSTAINABILITY	21
8.1 Value proposition and target users	21
8.2 Market and competitive position	21
8.3 Business or sustainability model	21
8.4 Scalability intellectual property and compliance	21
8.5 Contribution to the Sustainable Development Goals	21
9 CONCLUSION AND FUTURE DIRECTIONS	22
9.1 Conclusion	22
9.2 Achievement of objectives	22
9.3 Individual research and product contributions	22
9.4 Future directions	22
REFERENCES	23
APPENDICES	25

LIST OF FIGURES

Figure 2.1 Conceptual framework of the 2D-to-3D Geometry Validation component	6
Figure 3.1 Design Science Research cycle applied to the component	8
Figure 4.1 Final C1 component architecture within the integrated solution	11
Figure 5.1 Runtime progression from learner construction to AR placement	14
Figure 6.1 Mean C1 task time by supported solid	17
Figure 6.3 C1 pre-test and post-test group means	17

LIST OF TABLES

Table 2.1 Positioning of related approaches against final C1	5
Table 3.2 C1 evaluation measures	8
Table 4.1 Functional and non-functional requirements	10
Table 4.2 Shape-specific validation conditions	12
Table 5.1 Development environment and technology stack	13
Table 6.1 C1 technical validation results	16
Table 6.2 Mean task time by solid	17
Table B.1 AI-use disclosure	28

LIST OF ABBREVIATIONS

Abbreviation	Meaning
AR	Augmented Reality
ARCore	Google platform for Android augmented reality
C1	Component 1 - 2D-to-3D Geometry Validation
C2	Component 2 - 2D Net Correction and Virtual Slicing
CSV	Comma-Separated Values
DSR	Design Science Research
FPS	Frames Per Second
JSON	JavaScript Object Notation
MR	Mixed Reality
SDG	Sustainable Development Goal
UI	User Interface
UX	User Experience
XR	Extended Reality

1 INTRODUCTION

1.1 Overall project context

AR can make abstract geometric relations inspectable in the learner's physical environment, but its educational value depends on interaction design rather than 3D visualization alone. Meta-analytic and K-12 reviews report positive potential while emphasizing task design and usability [1], [2]. The wider project contains four components - C1 geometry validation, C2 correction and slicing, C3 air-writing, and C4 sketch-driven vocabulary - connected by a shared learner-input, analysis, feedback, and reinforcement architecture. This thesis addresses C1 only.

1.2 Individual component context

C1 acts as the validation gate between learner-created 2D geometry and 3D/AR reinforcement. The final implementation supports Cube, Cuboid, Triangular Prism, Tetrahedron, and Cylinder through square-grid, triangular-grid, or guided face-arrangement interfaces. Unlike the proposal-stage camera/CNN concept, the final C1 uses deterministic rules over structured digital input. Valid nets progress to visible 3D folding and AR; invalid nets are blocked and may be routed to C2 correction.

1.3 Problem statement

Primary learners can experience difficulty when they are asked to infer a three-dimensional solid from a flat net. The challenge is not merely recognizing that a diagram contains squares, rectangles, triangles, or circles; the learner must understand whether the faces form one connected structure, whether matching dimensions are compatible, whether orientations are appropriate, and whether folding would cause incompatible face assignments. If educational software bypasses these conditions and simply displays a correct 3D object after any input, it risks reinforcing an incorrect construction.

1.4 Research gap

Existing AR geometry research establishes that interactive 3D representations can support spatial learning, but the closest systems commonly start from predefined

valid content [3]-[7]. This means that the learner may manipulate a cube, prism, or other solid without demonstrating that a corresponding learner-created net is itself mathematically foldable. In parallel, sketch-to-3D research demonstrates that freehand sketches can be reconstructed into three-dimensional geometry [8], and sketch-recognition methods show that hand-drawn forms can be computationally classified [9], [10]. These capabilities are valuable, but recognition or reconstruction alone does not establish the foldability of a constrained geometric net.

1.5 Aim and objectives

The aim of this individual research component is to design, develop, and evaluate a mobile 2D-to-3D geometry validation framework that verifies learner-generated geometric nets before converting valid constructions into interactive 3D and AR representations for primary-school geometry learning.

1.6 Research questions or hypotheses

The study follows a research-question approach. The principal question is RQ1: How accurately and reliably does the 2D-to-3D Geometry Validation component distinguish valid and invalid learner-created nets and progress valid nets to the intended 3D/AR state? A secondary educational question is RQ2: To what extent does interaction with the validation-first geometry workflow correspond with a change in learners' understanding of the relationship between 2D nets and 3D solids? RQ2 is interpreted descriptively because the finalized evaluation retained aggregate group means rather than participant-level paired scores suitable for inferential testing.

1.7 Scope limitations and assumptions

The scope is limited to C1 within the wider research suite. The thesis therefore does not claim ownership of C2's fault-specific correction and Virtual Slicing, C3's camera-based air-writing recognition, or C4's sketch-driven vocabulary pipeline. C1 integrates with C2 by producing valid or invalid geometry states, and it shares broader navigation and AR presentation conventions with the integrated application.

1.8 Individual contribution

The individual contribution is the design and implementation of the validation-controlled geometry pathway. It includes the structured drawing and guided-arrangement interfaces, shape-specific validation logic, 2D-to-3D generation and folding behavior, progression control, AR handoff, and research logging required to evaluate the component. The central novelty is not the existence of a 3D shape by itself; it is the rule that the learner's own construction must satisfy explicit geometric constraints before that 3D/AR reinforcement becomes available.

1.9 Thesis structure

Chapter 2 reviews AR geometry learning, spatial visualization, learner-generated input, sketch-based modeling, and the distinction between recognition and geometric validity. Chapter 3 describes the Design Science Research methodology, participants, evaluation procedure, metrics, ethics, data handling, and reproducibility. Chapter 4 presents requirements, architecture, design alternatives, and the detailed validation strategy. Chapter 5 documents the Unity implementation, integration, software verification, deployment, and research instrumentation. Chapter 6 presents the technical and learner-validation results. Chapter 7 interprets the findings against the literature and research questions. Chapter 8 discusses commercialisation, sustainability, scalability, intellectual property, and SDG alignment. Chapter 9 concludes the thesis and identifies future directions.

2 LITERATURE REVIEW AND RELATED WORK

2.1 Review method and scope

The review was scoped around the knowledge required to justify C1 rather than around every function of the integrated suite. Sources were selected from the finalized research-paper literature and grouped into four themes: AR in education and geometry learning; spatial visualization and child-computer interaction; learner-generated sketch or net interpretation; and computational methods that reconstruct or classify sketches. Design Science Research literature was reviewed separately in Chapter 3 because it supports the research method rather than the domain problem.

The review gives priority to recent systematic reviews and primary studies that are directly relevant to K-12 or geometry contexts. Chang et al. synthesize a decade of AR educational research and show generally positive effects while cautioning that outcomes depend on study design and educational context [1]. Law and Heintz focus specifically on K-12 AR applications from usability and user-experience perspectives [2]. These sources provide the broad evidence base for using AR with young learners without assuming that AR is automatically effective.

2.2 Domain and theoretical foundations

C1 is grounded in three related ideas: spatial visualization requires learners to coordinate flat and volumetric representations; learner-generated construction should occur before reinforcement; and a geometric net is a constrained face-and-edge structure rather than merely an image. AR studies support spatial learning [3]-[7], while the final design uses AR only after the learner-created structure has been validated.

2.3 Related research

Related AR geometry studies mainly begin with predefined valid content [3]-[7]. Sketch2Model demonstrates 3D reconstruction from freehand input [8], and sketch-recognition research shows that hand-drawn forms can be classified [9], [10]. C1 differs by treating the learner's net as a constrained mathematical structure and checking foldability before 3D output rather than optimizing visual reconstruction or category recognition.

2.4 Existing systems products and techniques

Existing approaches can be grouped by what they treat as the authoritative input. AR geometry viewers use predefined 3D assets; intelligent tutors add guidance around predefined content; sketch-to-3D systems use freehand appearance to reconstruct geometry; sketch classifiers predict a category from visual input; and the final C1 uses structured learner input to evaluate geometric validity. The differences are summarized in Table 2.1.

Table 2.1 Positioning of related approaches against final C1

Approach	Primary capability	Limitation for the C1 problem	Final C1 distinction
AR geometry learning	Interactive spatial visualization.	Usually begins from predefined valid objects.	Learner-created nets must pass a validity gate before 3D.
Intelligent AR tutoring	Guidance and adaptive instructional support.	Tutoring may occur around system-provided geometry.	Instructional state originates from the learner-created net.
Sketch-to-3D modeling	Reconstructs 3D form from freehand input.	Visual reconstruction does not guarantee foldability.	Uses explicit shape constraints and fold relations.
Sketch recognition	Classifies hand-drawn forms.	Category prediction does not prove net validity.	Validates faces, dimensions, adjacency, orientation, and connectivity.
Final C1	Construction + mathematical validation + folding + AR.	Limited to five explicitly supported solids.	Combines validation-first progression with learner-generated input.

2.5 Gap synthesis and conceptual framework

The reviewed literature demonstrates the value of AR, the feasibility of learner-generated sketch input, and the potential of intelligent educational feedback. The unresolved space for this research lies in combining these ideas around a strict validation gate. The learner must be able to create or arrange a net, the system must reason about that exact structure, invalid constructions must remain invalid until corrected, and only valid constructions should be transformed and reinforced through 3D/AR.

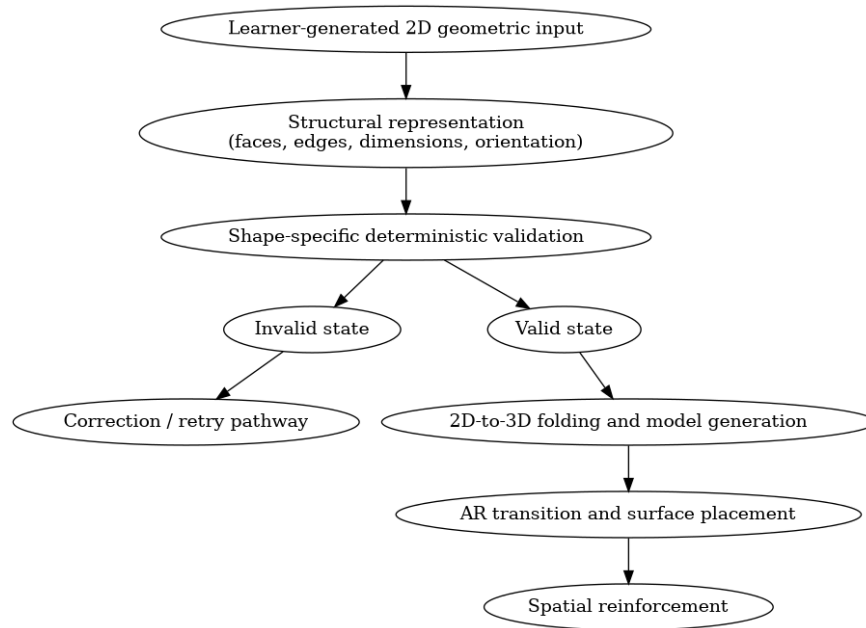


Figure 2.1 Conceptual framework of the 2D-to-3D Geometry Validation component

Figure 2.1 captures the conceptual framework used throughout the thesis. The structural representation is intentionally placed between raw interaction and validation. This reflects the final implementation: the application does not need to classify a screenshot of a cube net when it already knows which grid cells or guided faces the learner has produced. The framework also separates invalid and valid states before 3D generation. This separation is the basis of the evaluation reported in Chapter 6, where expected validity is compared with the system decision and progression behavior.

3 RESEARCH METHODOLOGY

3.1 Research design

The study follows Design Science Research (DSR), treating C1 as an artifact iteratively designed, implemented, and evaluated to address the 2D-to-3D representation gap [11], [12]. Early requirements proposed camera-based recognition of paper nets, but prototyping showed that structured digital input exposed exact faces, edges, dimensions, and orientations. The research therefore retained the original validation problem while refining the artifact toward deterministic geometry rules. Technical correctness and learner outcomes were evaluated separately.

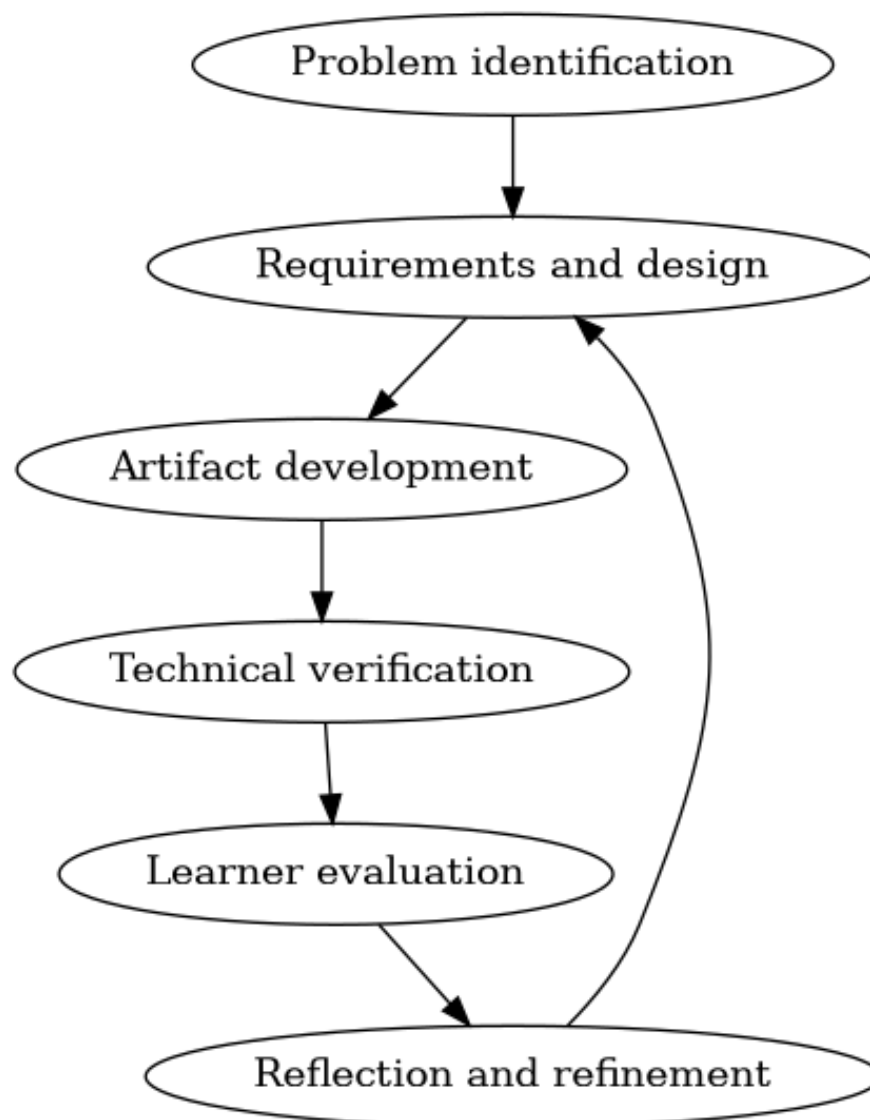


Figure 3.1 Design Science Research cycle applied to the component

3.2 Data participants or study materials

The C1 pilot involved 25 learners aged 9-12 in a Sri Lankan school or educational setting. Evaluation covered all five supported solids with four expected-valid and one expected-invalid case per solid. Materials included the Android application, expected validity labels, task-time records, and a 10-mark pre-test/post-test. The original test photographs will be inserted in Appendix A. The supplied CSV export is a smaller implementation/logging subset and is used to verify instrumentation fields rather than to replace the finalized 25-case results.

3.3 Experimental or study procedure

Learners constructed or arranged the required net and selected Validate. The shape-specific validator produced a valid/invalid state and message. Expected labels were compared with system decisions; valid cases were checked for 3D and AR progression, while invalid cases were checked for blocking before reinforcement. Task time was recorded. A pre-test preceded the activity and a post-test followed it. Because the final analysis retained aggregate group means rather than paired individual scores, learning change is reported descriptively.

3.4 Measures and evaluation metrics

Table 3.2 C1 evaluation measures

Measure	Definition	Interpretation
Validity agreement	Number of test cases where system valid/invalid decision equals the expected label.	Primary technical correctness measure for RQ1.
Valid progression	Number of expected-valid cases that generated a 3D model and reached AR placement.	Checks that a correct decision leads to intended reinforcement.
Invalid blocking	Number of expected-invalid cases prevented from reaching 3D/AR.	Checks that incorrect geometry is not positively reinforced.
Task time	Elapsed time recorded for the geometry attempt.	Descriptive efficiency/usability indicator; reported overall and by shape.
Pre-/post-test mean	Average score out of 10 before and after interaction.	Descriptive learner-outcome indicator; not used for inferential claims.
Runtime interaction flags	Help, correction viewed, retry, 3D generated, and AR placed.	Instrumentation for richer future behavioral analysis.

3.5 Data analysis

Analysis used counts, proportions, means, and standard deviations from the finalized evaluation. Validity agreement compared expected and system labels. Shape-

specific task times were summarized descriptively, and the learning result was reported as the difference between pre-test and post-test group means. No inferential significance or participant-level effect size is claimed because paired individual scores were not retained.

3.6 Ethics privacy security and responsible AI

The study involved minors; parental/guardian consent and learner assent were obtained, and the institution is anonymized as a Sri Lankan school or educational setting. Analytical records use ST identifiers. C1 validation and AR run locally, and session JSON is written under `Application.persistentDataPath/ResearchData` with a 24-hour session-folder expiry mechanism. A local student-profile file maps the entered name to an ST identifier; aligning its cleanup with session expiry is identified as a future privacy improvement. ChatGPT was used only as an assistive development/documentation tool and all technical/result claims were verified against project artefacts.

3.7 Reproducibility and research artefacts

Reproducibility is supported by the final C# source, Unity version, explicit shape rules, JSON/CSV logging schema, and reported pilot metrics. The supplied export contains fields for StudentID, activity, attempts, validation result/message, faces, time, help/correction/retry, 3D generation, and AR placement. It contains a subset of current logged activities, so headline five-shape results in Chapter 6 are taken from the finalized pilot evaluation rather than recomputed from that partial export.

4 PRODUCT AND SOLUTION DESIGN

4.1 Requirements

The final requirements preserve the original research objective while reflecting the implemented artifact: learners must be able to construct nets for five solids; validators must evaluate shape-specific structural constraints; invalid states must block 3D/AR; valid states must visibly transform into 3D and support AR placement; research events must be logged locally; and the portrait Android UI must remain child-oriented and usable at the 1080 x 1920 reference resolution.

Table 4.1 Functional and non-functional requirements

ID	Requirement	Type
FR1	Allow learners to construct or arrange nets for Cube, Cuboid, Triangular Prism, Tetrahedron, and Cylinder.	Functional
FR2	Validate shape-specific face counts, connectivity, dimensions, adjacency, orientation, and folding compatibility as applicable.	Functional
FR3	Block invalid nets from 3D/AR progression and expose a correction/retry state.	Functional
FR4	Generate and visibly transform a valid 2D net into a corresponding 3D solid.	Functional
FR5	Support AR plane detection, raycasting, placement, and inspection for the generated solid.	Functional
FR6	Record validation, timing, interaction flags, 3D generation, and successful AR placement for research.	Functional
NFR1	Operate on-device on an ARCore-compatible Android device without cloud dependency for C1.	Non-functional
NFR2	Use a child-friendly portrait UI designed around a 1080 x 1920 reference resolution.	Non-functional
NFR3	Keep validation logic deterministic and explainable for the five supported solids.	Non-functional
NFR4	Preserve privacy by using analytical student IDs and local storage.	Non-functional

4.2 Component architecture within the complete solution

C1 is layered into input managers, validators, model/folding controllers, shared AR services, and research logging. Shape-specific managers maintain the structural representation; validators produce the instructional state; valid states reach ModelSpawner and NetTo*Folder classes; ARModeManager and ARPlacedModelManager handle the physical placement stage; and SessionDataLogger records key events. This shared pipeline allows each solid to keep an appropriate algorithm without duplicating the complete application infrastructure.

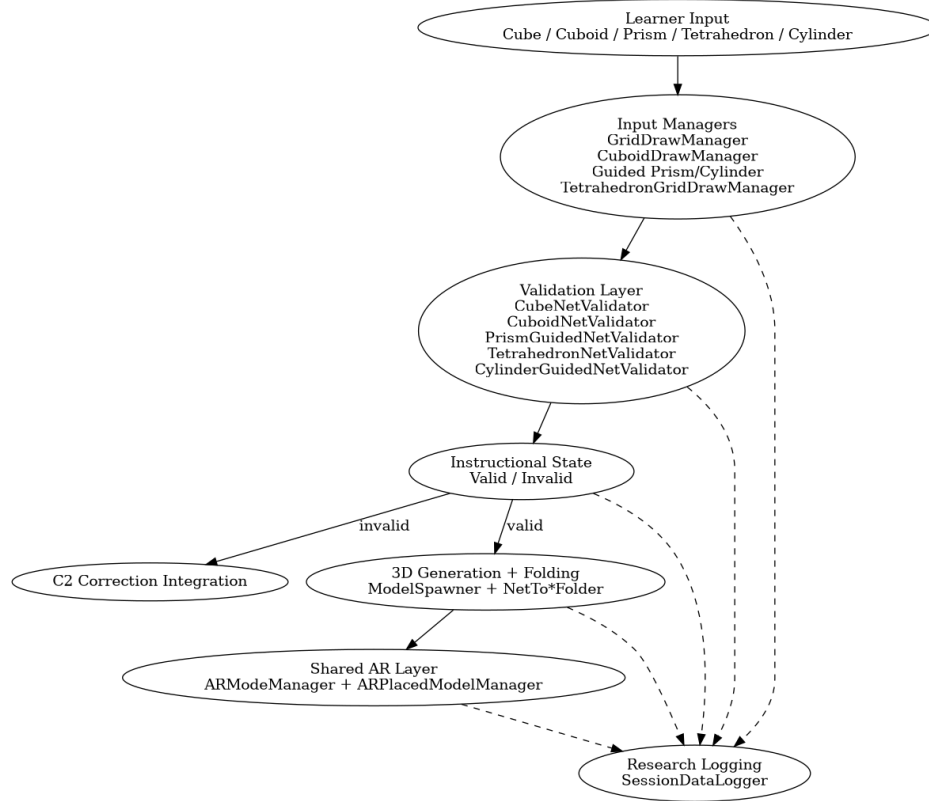


Figure 4.1 Final C1 component architecture within the integrated solution

4.3 Design alternatives and decisions

Three design choices shaped the final component. Structured in-app input replaced proposal-stage camera recognition because exact grid/face data were already available; shape-specific validators were preferred over one generic classifier because the five solids have different geometric constraints; and Cube, Cuboid, and Cylinder were refined to use a learner-controlled Go To AR action after folding, while Tetrahedron and Triangular Prism currently retain timed transitions.

4.4 Detailed design

The final validators implement explicit rules appropriate to each solid. Cube propagates discrete fold bases across six connected cells; Cuboid infers dimensions and simulates a connected five-hinge fold tree; Triangular Prism checks a three-rectangle strip and two correctly oriented end caps; Tetrahedron checks four connected triangles with exactly three shared fold edges; and Cylinder checks two equal circles against a compatible lateral rectangle. Table 4.2 summarizes these conditions.

Table 4.2 Shape-specific validation conditions

Solid	Core validity conditions in final source
Cube	Exactly six square cells; all cells connected; simulated fold-basis propagation must assign six consistent and unique face normals, equivalent to one of the 11 valid cube nets.
Cuboid	Exactly six rectangles; dimensions inferred from face-size pairs; no interior overlap; adjacency graph with five fold connections; graph connected; 90-degree folding simulation consistent with inferred dimensions.
Triangular Prism	Exactly two triangles and three rectangles; exactly four hinge connections; rectangle strip connected; each triangle has one hinge; triangles point outward, occupy opposite ends, and have corresponding orientation.
Tetrahedron	Exactly four detected triangles; face graph connected; exactly three shared folding edges; no isolated face.
Cylinder	Exactly two circles and one rectangle; both circles snapped on opposite sides; equal radii; circle radius matches configuration; rectangle length matches $2\pi r$ and rectangle height matches selected cylinder height.

4.5 Standards and professional practice

Professional practice was addressed through local processing, explainable deterministic rules, child-oriented UI design, traceable requirements, and explicit separation between proposal-stage ideas and implemented features. AR uses AR Foundation/ARCore rather than a cloud service, and the thesis distinguishes the full pilot results from the smaller exported logging subset. These choices improve auditability and reduce the risk of reporting features or measurements that the final artefact does not support.

5 IMPLEMENTATION INTEGRATION AND TESTING

5.1 Development environment and technology stack

The final component was implemented in Unity 2022.3.62f3 LTS using C# for Android. uGUI/TMP provide the portrait learning interface, AR Foundation and the Google ARCore XR Plugin provide plane detection and raycasting, and JSON files under Application.persistentDataPath store research sessions for CSV export. C1 does not require a cloud inference service.

Table 5.1 Development environment and technology stack

Technology / artefact	Role in C1
Unity 2022.3.62f3 LTS	Scene management, rendering, UI, animation, and C# runtime.
C#	Drawing logic, validators, fold simulation, procedural geometry, AR control, and logging.
uGUI / Text / TMP	Child-facing construction interfaces, status messages, buttons, and student entry.
AR Foundation	Cross-platform AR abstractions used for planes, raycasting, and AR session management.
Google ARCore XR Plugin	Android AR provider used for physical environment tracking.
JSON local files	Attempt-level session persistence under Application.persistentDataPath/ResearchData.
CSV export	Research analysis/export format containing attempt and progression fields.

5.2 Component implementation

The implementation separates input capture, validation, 3D generation, AR placement, and logging. GridDrawManager, CuboidDrawManager, TetrahedronGridDrawManager, and the guided Prism/Cylinder managers maintain structured learner input. Dedicated validators produce the valid/invalid state. ModelSpawner and NetTo*Folder classes recreate and fold the learner's net in world space, after which ARModeManager and ARPlacedModelManager provide shared plane detection and placement. SessionDataLogger records research events independently of the rendering logic.

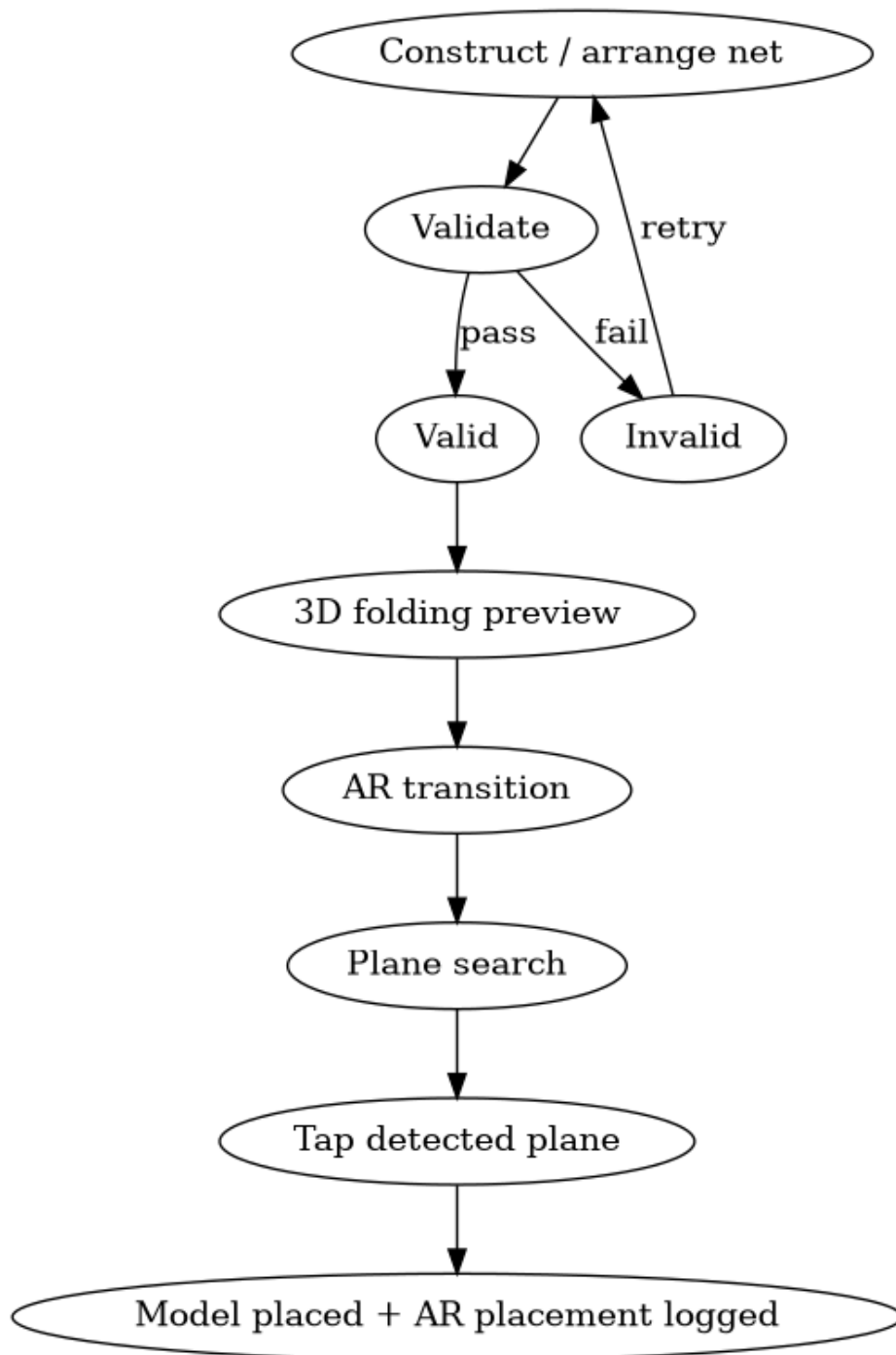


Figure 5.1 Runtime progression from learner construction to AR placement

5.3 Integration with the other components

C1 integrates most directly with C2: invalid geometry can route to C2 correction, while valid geometry progresses to 3D/AR. C1 shares menu/navigation and AR presentation services with the wider suite but does not depend on the AI models used

by C3 or C4. This keeps geometry validation technically independent while preserving a coherent application experience.

5.4 Verification and software testing

Developer verification covered representative valid and invalid nets for all five solids, undo/reset invalidation, folding completion, progression control, AR surface guidance, and research-event logging. Particular regression checks confirmed continuous Tetrahedron drag drawing, the 6 x 6 Cube grid, manual Go To AR behavior for Cube/Cuboid/Cylinder, and the requirement that ARPlaced is written only after a successful plane raycast positions and activates the model.

5.5 Deployment and operation

The learner enters a name, receives a local ST identifier, selects a geometry activity, constructs the net, validates it, and progresses according to the decision. The UI uses a 1080 x 1920 portrait reference. AR requires an ARCore-compatible Android device and sufficient surface features for horizontal-plane tracking. Core C1 validation and logging are local, so the geometry workflow does not require continuous internet access.

6 RESULTS AND VALIDATION

6.1 Research results

The finalized C1 pilot contained 25 labeled cases across five solids, with four valid and one invalid case per solid. System decisions matched all 25 expected labels. All 20 expected-valid cases generated a 3D model and reached AR placement, while all five expected-invalid cases were blocked before 3D/AR. The overall mean task time was 12.65 s (SD = 6.81 s). The 100% agreement is limited to this prepared pilot set and is not claimed as universal accuracy for arbitrary geometry.

Table 6.1 C1 technical validation results

Outcome	Observed result
Correct validity decisions	25/25 (100% agreement with expected labels)
Expected-valid cases	20/20 progressed to 3D and AR placement
Expected-invalid cases	5/5 blocked before 3D/AR
Overall mean task time	12.65 s (SD = 6.81 s)

6.2 Product and technical results

Mean task time varied by solid: Cube 6.77 s, Cuboid 6.55 s, Triangular Prism 11.55 s, Cylinder 14.23 s, and Tetrahedron 24.14 s. The final product achieved the intended sequence from validation to visible 3D construction and AR placement. Cube, Cuboid, and Cylinder additionally use a learner-controlled Go To AR transition after fold completion, whereas Tetrahedron and Triangular Prism retain timed transitions in the supplied source.

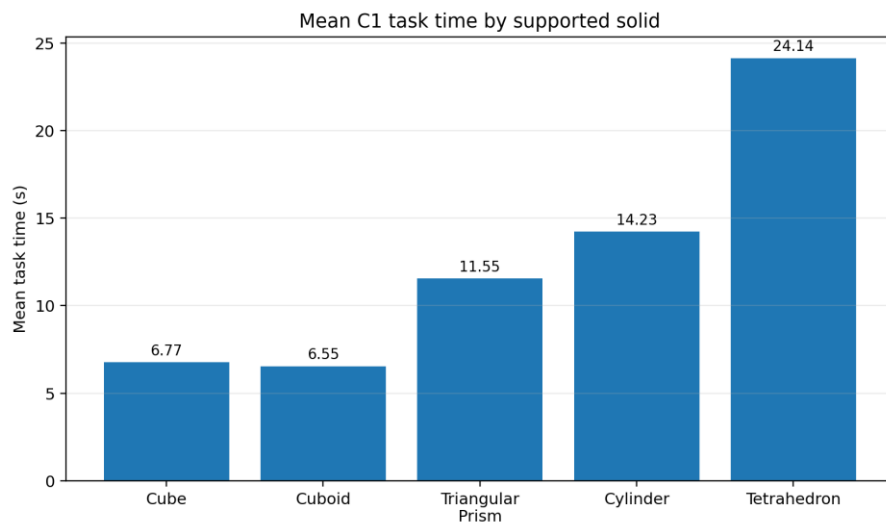


Figure 6.1 Mean C1 task time by supported solid

Table 6.2 Mean task time by solid

Solid	Mean task time (s)
Cube	6.77
Cuboid	6.55
Triangular Prism	11.55
Cylinder	14.23
Tetrahedron	24.14

6.3 User or stakeholder validation

The C1 group mean increased from 5/10 in the pre-test to 9/10 in the post-test, an absolute increase of four marks. This is reported as descriptive pilot evidence only. The available aggregate means do not establish statistical significance and cannot isolate whether the change resulted from validation, folding animation, AR inspection, repeated exposure, or other contextual factors.

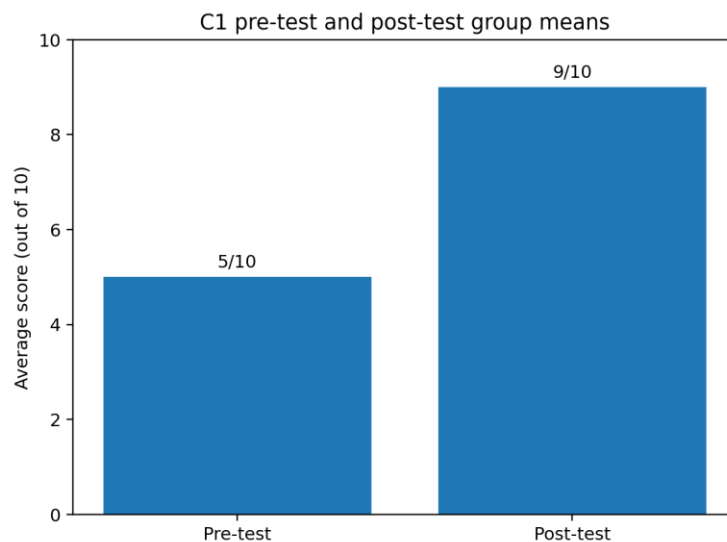


Figure 6.3 C1 pre-test and post-test group means

6.4 Integration results

Integration testing confirmed that C1 can provide valid/invalid states to the wider geometry pathway, generate 3D models through shape-specific spawners, and use the shared AR managers. Invalid Cube and Cuboid flows can invoke correction interfaces belonging to C2. The research logger records validation and progression events for Cube, Cuboid, Tetrahedron, and Cylinder in the supplied source. The Triangular Prism validator and 3D/AR flow are present, but the supplied Prism source does not call SessionDataLogger in the same way as the other four shapes; the pilot's five-shape

results were therefore retained from the finalized evaluation dataset rather than reconstructed from the current local export.

6.5 Summary of findings

The results support RQ1 within the stated pilot scope: the component matched all 25 expected validity labels, progressed all 20 valid cases, and blocked all five invalid cases. The technical result shows that explicit shape-specific validation is feasible within a mobile Unity workflow. The 5/10 to 9/10 group-mean change provides descriptive support for the educational pathway, while the absence of participant-level paired scores prevents inferential conclusions. The timing data also reveal that interaction complexity differs by shape and should be considered in future UI evaluation.

7 DISCUSSION

7.1 Interpretation of findings

The central technical result is that the validation gate remained aligned with expected labels and progression behavior in all 25 prepared cases. This supports the final decision to use explicit shape-specific rules over structured input: the system can explain why geometry is accepted or rejected and avoids an unnecessary image-classification layer when exact structural data are already available.

7.2 Comparison with literature baselines and existing solutions

AR geometry research supports spatial visualization [3]-[7], while sketch-to-3D and sketch-recognition research demonstrates computational interpretation of learner drawings [8]-[10]. C1 occupies a different point in this space: it requires the learner-created net to satisfy explicit foldability constraints before 3D/AR reinforcement. It therefore complements rather than replaces recognition research; camera recognition would become relevant again if future versions accept unconstrained paper sketches.

7.3 Research contribution

The research contribution is a validation-first mobile interaction framework for learner-generated geometry. The contribution combines five elements: learner construction, explicit shape-specific validation, progression control, visible 2D-to-3D transformation, and AR reinforcement. The implementation demonstrates that these elements can be combined without a general-purpose geometry classifier and that component-specific logic can coexist under a shared application architecture.

7.4 Product contribution

The product contribution is the working Android C1 implementation and its integration artefacts. These include the square and triangular drawing systems, guided face-arrangement systems, validators, fold controllers, shared AR placement mechanism, status/feedback flow, and research instrumentation. The post-paper usability refinements - a 6 by 6 Cube grid, 1080 x 1920 reference resolution, continuous Tetrahedron drag drawing, and manual AR buttons for Cube, Cuboid, and Cylinder - demonstrate the iterative refinement expected in a design-science project.

7.5 Limitations and threats to validity

The study is limited by a small 25-learner pilot, no randomized control condition, no delayed retention test, and aggregate rather than participant-level paired learning scores. Task time mixes interaction complexity with reasoning difficulty. The current implementation is also not fully uniform: Cube/Cuboid/Cylinder use manual AR transition, Tetrahedron/Prism use timed transitions; the current logger is not integrated identically across all five shape flows; and the local name-to-ID profile mapping is not covered by the same automated expiry used for session folders.

7.6 Implications

The findings suggest that AR can be positioned as reinforcement after learner reasoning rather than as the starting content. For software design, a shared progression/AR layer can coexist with specialized validators. For future research, the artifact provides a basis for controlled comparisons against predefined-object AR, non-AR geometry practice, or camera-based paper-net recognition.

8 COMMERCIALISATION AND SUSTAINABILITY

8.1 Value proposition and target users

C1 offers a reusable digital geometry manipulative for schools, teachers, learners aged 9-12, parents, and educational programmes. Its distinguishing value is that a learner-created net must be validated before 3D/AR reinforcement, allowing repeated practice without requiring a physical geometry kit for every activity.

8.2 Market and competitive position

The component competes on validation and progression rather than on 3D display alone. It sits between passive AR viewers and unconstrained sketch-recognition tools, offering explicit geometry rules, visible folding, and local AR placement within one Android learning activity.

8.3 Business or sustainability model

A practical model could combine institutional school licensing with a limited free demonstration tier. Because C1 validates locally, recurring cloud cost is low; ongoing expenditure would mainly involve maintenance, Android/ARCore compatibility, curriculum expansion, testing, and support.

8.4 Scalability intellectual property and compliance

The modular architecture supports new solids through new input/validator/folding modules behind shared AR services. Commercial deployment would need to protect source/UI assets and comply with child-data, consent, software-licensing, and app-store requirements.

8.5 Contribution to the Sustainable Development Goals

The project aligns with SDG 4: Quality Education by targeting accessible interactive learning on common Android hardware. The pilot does not prove large-scale impact, but local processing, reusable digital manipulatives, and modular content are compatible with deployment in settings where specialized equipment or continuous connectivity is limited.

9 CONCLUSION AND FUTURE DIRECTIONS

9.1 Conclusion

This thesis presented C1, a deterministic validation-first geometry component for five solids. In the 25-case pilot, every expected validity label matched the system decision; all valid cases progressed to 3D/AR and all invalid cases were blocked. The 5/10 to 9/10 pre/post group-mean change provides descriptive educational evidence while remaining subject to the study limitations.

9.2 Achievement of objectives

The prototype achieved the planned functions at pilot level: five learner-input activities, explicit validation, invalid-state blocking, visible 3D transformation, AR placement, and local research instrumentation. The implemented rules and progression behavior are traceable in the supplied source code.

9.3 Individual research and product contributions

The research contribution is the validation-first framing of learner-generated geometry; the product contribution is the working Unity/Android subsystem consisting of structured input, shape-specific validators, folding controllers, shared AR placement, and research logging integrated with the wider suite.

9.4 Future directions

Future work should enlarge the sample, retain paired participant scores, add control/baseline conditions and delayed retention, standardize learner-controlled AR transition across all shapes, unify logging coverage, align profile cleanup with session expiry, and evaluate camera-based paper-net recognition only where unconstrained visual input makes recognition necessary.

REFERENCES

- [1] H.-Y. Chang, T. Binali, J.-C. Liang, G.-L. Chiou, K.-H. Cheng, S. W.-Y. Lee, and C.-C. Tsai, "Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact," *Computers & Education*, vol. 191, Art. no. 104641, 2022, doi: 10.1016/j.compedu.2022.104641.
- [2] E. L.-C. Law and M. Heintz, "Augmented reality applications for K-12 education: A systematic review from the usability and user experience perspective," *International Journal of Child-Computer Interaction*, vol. 30, Art. no. 100321, 2021, doi: 10.1016/j.ijcci.2021.100321.
- [3] M. B. Nadzeri, M. Musa, C. M. Chew, and I. M. Ismail, "The effects of augmented reality geometry learning applications on spatial visualization ability for primary school pupils," *International Journal of Interactive Mobile Technologies*, vol. 18, no. 16, pp. 104-118, 2024, doi: 10.3991/ijim.v18i16.47079.
- [4] W. Tarng, J.-K. Huang, and K.-L. Ou, "Improving elementary students' geometric understanding through augmented reality and its performance evaluation," *Systems*, vol. 12, no. 11, Art. no. 493, 2024, doi: 10.3390/systems12110493.
- [5] J. Wu, H. Jiang, L. Long, and X. Zhang, "Effects of AR mathematical picture books on primary school students' geometric thinking, cognitive load and flow experience," *Education and Information Technologies*, vol. 29, pp. 24627-24652, 2024, doi: 10.1007/s10639-024-12768-y.
- [6] A. Uriarte-Portillo, R. Zatarain-Cabada, M. L. Barrón-Estrada, M. B. Ibáñez, and L.-M. González-Barrón, "Intelligent augmented reality for learning geometry," *Information*, vol. 14, no. 4, Art. no. 245, 2023, doi: 10.3390/info14040245.
- [7] C. Walkington, M. J. Nathan, J. Washington, J. Hunnicutt, T. Darwin, L. Daughrity, and K. Schenck, "Comparing learning geometry using a tablet to head-mounted display augmented reality: How and when dimensionality matters," *Education and Information Technologies*, vol. 30, pp. 5397-5426, 2025, doi: 10.1007/s10639-024-13008-z.
- [8] S.-H. Zhang, Y.-C. Guo, and Q.-W. Gu, "Sketch2Model: View-aware 3D modeling from single free-hand sketches," in *Proc. IEEE/CVF Conf. Computer Vision and Pattern Recognition (CVPR)*, 2021, pp. 6012-6021, doi: 10.1109/CVPR46437.2021.00595.
- [9] L. Zhang, "Hand-drawn sketch recognition with a double-channel convolutional neural network," *EURASIP Journal on Advances in Signal Processing*, vol. 2021, Art. no. 73, 2021, doi: 10.1186/s13634-021-00752-4.

- [10] A. K. Bhunia, P. N. Chowdhury, Y. Yang, T. M. Hospedales, T. Xiang, and Y.-Z. Song, "Vectorization and rasterization: Self-supervised learning for sketch and handwriting," in Proc. IEEE/CVF Conf. Computer Vision and Pattern Recognition (CVPR), 2021, pp. 5672-5681.
- [11] H. Weigand, P. Johannesson, and B. Andersson, "An artifact ontology for design science research," Data & Knowledge Engineering, vol. 133, Art. no. 101878, 2021, doi: 10.1016/j.datak.2021.101878.
- [12] S. G. Sutton, V. Arnold, P. Collier, and S. A. Leech, "Leveraging the synergies between design science and behavioral science research methods," International Journal of Accounting Information Systems, vol. 43, Art. no. 100536, 2021, doi: 10.1016/j.accinf.2021.100536.

APPENDICES

Appendix A Research instruments or extended results

Appendix A is reserved for the original C1 pre-test and post-test question photographs. The study used a 10-mark pre-test and a 10-mark post-test. The final photographs can be inserted in the two reserved pages below without changing the main thesis structure. The thesis reports the finalized group means (5/10 pre-test and 9/10 post-test) but does not reconstruct or invent questions that were not supplied at the time of document generation.

A.1 Pre-test instrument

A.2 Post-test instrume

Appendix B Academic integrity and AI use disclosure

The following disclosure records the use of generative AI during the individual component and thesis preparation. It should be retained or adapted to the final module policy before submission.

Table B.1 AI-use disclosure

Tool	Purpose	Representative use	Verification performed
ChatGPT	Development support and documentation assistance.	Explaining Unity/C# errors, proposing code changes, comparing project documents, drafting and editing thesis prose, and structuring tables/figures.	Final technical descriptions checked against the supplied C# source; research claims checked against the finalized ICAC paper, proposal, TAF, and evaluation artefacts; unsupported claims removed or labelled as future work.

No learner-result values were generated by ChatGPT. The reported 25/25 C1 validity agreement, valid/invalid case counts, task-time statistics, and pre-/post-test means are taken from the finalized project evaluation. The AI tool did not replace ethical consent, participant interaction, coding responsibility, or human verification of the final artefact.