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Designing Learning Trajectories for Nets of Polyhedrons through Simulation-Based PBL

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ABSTRACT

Students frequently experience difficulties in learning nets of polyhedrons because they must coordinate two-dimensional representations with three-dimensional objects and mentally anticipate folding processes. This study aimed to develop and refine an empirically grounded learning trajectory for nets of polyhedrons by integrating Problem-Based Learning (PBL), contextual simulation, animated videos, and student worksheets. A design research approach was employed through three phases: preliminary design, teaching experiment, and retrospective analysis. The pilot teaching experiment involved six ninth-grade students representing high, moderate, and low levels of mathematical achievement, while the large-scale implementation involved 28 ninth-grade students in a regular classroom. Data were collected through classroom observations, semi-structured interviews, students' written work, worksheets, learning outcome tasks, and instructional documentation, and were analyzed by comparing predicted responses in the Hypothetical Learning Trajectory with students' actual learning processes. The findings showed a progressive development from recognizing familiar packaging patterns to visualizing folding processes, distinguishing valid and invalid nets, analyzing relationships among faces and edges, constructing alternative nets, and communicating mathematical justifications. Animated visualization and contextual simulation helped students connect informal experiences with formal geometric concepts, while collaborative investigation and reflection supported the transition from perceptual judgments to structural reasoning. Retrospective analysis produced a refined eight-stage learning trajectory: gift-shop simulation, activation of prior knowledge, animated visualization, identification of valid and invalid nets, collaborative investigation, alternative net construction, presentation and mathematical justification, and reflection and generalization. The trajectory offers a practical and theoretically informed design for supporting conceptual understanding and spatial visualization, although further scaffolding is needed to strengthen students' written mathematical communication.

ABSTRAK

Peserta didik sering mengalami kesulitan dalam mempelajari jaring-jaring bangun ruang karena mereka harus mengoordinasikan representasi dua dimensi dengan objek tiga dimensi serta membayangkan proses pelipatan secara mental. Penelitian ini bertujuan mengembangkan dan menyempurnakan lintasan belajar yang berbasis bukti empiris pada materi jaring-jaring bangun ruang melalui integrasi Problem-Based Learning (PBL), simulasi kontekstual, video animasi, dan lembar kerja peserta didik. Penelitian menggunakan pendekatan design research yang meliputi tiga tahap, yaitu preliminary design, teaching experiment, dan retrospective analysis. Uji coba awal melibatkan enam peserta didik kelas IX yang mewakili tingkat kemampuan matematika tinggi, sedang, dan rendah, sedangkan implementasi skala besar melibatkan 28 peserta didik kelas IX dalam pembelajaran reguler. Data dikumpulkan melalui observasi kelas, wawancara semi-terstruktur, hasil kerja tertulis, lembar kerja, tugas hasil belajar, dan dokumentasi pembelajaran. Analisis dilakukan dengan membandingkan respons yang diprediksi dalam Hypothetical Learning Trajectory dengan proses belajar aktual peserta didik. Hasil penelitian menunjukkan perkembangan pemahaman secara bertahap, mulai dari mengenali pola kemasan yang familiar, memvisualisasikan proses pelipatan, membedakan jaring-jaring yang valid dan tidak valid, menganalisis hubungan antarsisi dan rusuk, mengonstruksi alternatif jaring-jaring, hingga mengomunikasikan justifikasi matematis. Visualisasi animasi dan simulasi kontekstual membantu peserta didik menghubungkan pengalaman informal dengan konsep geometri formal, sedangkan investigasi kolaboratif dan refleksi mendukung peralihan dari pertimbangan visual menuju penalaran struktural. Analisis retrospektif menghasilkan lintasan belajar delapan tahap, yaitu simulasi toko kado, aktivasi pengetahuan awal, visualisasi animasi, identifikasi jaring-jaring valid dan tidak valid, investigasi kolaboratif, konstruksi alternatif jaring-jaring, presentasi dan justifikasi matematis, serta refleksi dan generalisasi. Lintasan ini dapat digunakan sebagai desain pembelajaran yang praktis dan berlandaskan teori untuk mendukung pemahaman konseptual serta visualisasi spasial, meskipun scaffolding tambahan masih diperlukan untuk memperkuat komunikasi matematis tertulis peserta didik.

INTRODUCTION

Mathematics education plays a crucial role in fostering students' logical, critical, systematic, and creative thinking skills. However, geometry, particularly the topic of nets of polyhedrons, remains challenging for many students because it requires strong spatial visualization abilities. Classroom observations revealed that students often had difficulty visualizing three-dimensional objects from given net representations and identifying appropriate nets for constructing specific polyhedrons. These challenges were closely associated with limited spatial visualization skills, which hindered students' ability to interpret and mentally manipulate three-dimensional forms. Therefore, the integration of instructional media that supports the visualization of geometric concepts is essential for facilitating students' understanding of spatial relationships and geometric structures (Octaviani, Indrawatiningsih, & Afifah, 2021; Arhalifi, Witarsa, & Nurmalina, 2023; Niryan & Habibi, 2024; Maghfiroh & Qothrunnada, 2024).

In addition, classroom observations indicated that students' engagement during mathematics lessons remained relatively low. Teacher-centered instructional practices and the limited use of visual learning media tended to position students as passive recipients of information rather than active participants in the learning process. Consequently, students had fewer opportunities to explore mathematical concepts independently, which may have contributed to lower levels of interest and attention during classroom activities (Rizqiyani et al., 2024). Furthermore, the lack of diverse and innovative instructional media may restrict students' conceptual understanding of the material being studied because abstract mathematical ideas are more difficult to comprehend without adequate visual and interactive support (Widiastawan, Werang, & Ujianti, 2023; Purnama et al., 2025).

These challenges highlight the need for a learning design that enables students to develop a more concrete understanding of nets of polyhedrons while promoting active participation throughout the learning process. One instructional approach that has considerable potential for addressing this issue is Problem-Based Learning (PBL). This approach encourages students to engage in problem-solving activities, develop critical thinking skills, and construct knowledge through meaningful learning experiences. Previous studies have reported that the implementation of PBL can enhance students' mathematical understanding, critical thinking, and problem-solving abilities, making it a promising strategy for supporting geometry learning (Dwita & Hidayati, 2022; Putri, Hidayah, & Yuwono, 2023; Zetriuslita, Suripah, Ariawan, & Hidayat, 2023; Wahyuni, 2023).

This study adopted a contextual approach in which mathematical concepts were connected to situations familiar to students' daily lives. Through this approach, students were expected to relate mathematical concepts to their everyday experiences, thereby making learning more meaningful and easier to understand (Dianartasi & Sthephani, 2021; Amalia, Makmuri, & El Hakim, 2022; Azzahra & Hartono, 2026).

To support the implementation of the contextual approach, simulation was employed as the primary instructional strategy. Simulation-based learning was selected because it provides students with opportunities to engage in situations that closely resemble real-world problems, enabling them to apply mathematical concepts in more authentic contexts. Furthermore, simulations can help students develop a more concrete understanding of mathematical concepts through interactive and meaningful learning experiences (Fitri & Putri, 2021). Simulations involving visual representations and object manipulation also have the potential to enhance students' spatial visualization skills, which are essential for learning geometry (Betts et al., 2023). Through activities that require students to observe, imagine, and connect two-dimensional representations with three-dimensional objects, students can develop a deeper understanding of abstract geometric concepts (Octaviani, Indrawatiningsih, & Afifah, 2021; Ahmar, Azzajjad, & Ahmar, 2023; Maghfiroh & Qothrunnada, 2024). Therefore, the integration of a contextual approach and simulation-based learning was expected to support students' understanding of nets of polyhedrons while simultaneously promoting greater engagement throughout the learning process.

The instructional media employed in this study consisted of animated videos on nets of polyhedrons and student worksheets. The animated videos were designed to help students visualize the transformation of two-dimensional nets into three-dimensional objects in an engaging and interactive manner. Visual representations presented through animation can facilitate students' understanding of geometric structures that are often difficult to comprehend through static images alone (Oktavianah, 2022). Furthermore, previous studies have reported that the integration of animated videos within a Problem-Based Learning (PBL) environment contributes positively to students' conceptual understanding of mathematics and supports more effective learning experiences (Krisnayanti & Wiarta, 2022; Primadewi & Agustika, 2022; Nasution et al., 2023; Lestari et al., 2026). Student worksheets were used to support learning activities by providing structured opportunities for exploration, discussion, and problem-solving. Previous studies have also shown that PBL-oriented worksheets can support students' problem-solving abilities and facilitate meaningful mathematical learning (Pratiwi & Hiltrimartin, 2024). Through these worksheets, students were encouraged to actively investigate mathematical concepts, collaborate with their peers, and develop solutions to the problems presented during the learning process.

Although previous studies have demonstrated that Problem-Based Learning, contextual learning, simulation activities, and animated videos can support students' conceptual understanding and spatial visualization in geometry learning, most have focused primarily on evaluating the effectiveness of particular instructional models or learning media. Limited attention has been given to the systematic development and refinement of students' learning trajectories in learning nets of polyhedrons through iterative design research cycles. As a result, there is still insufficient knowledge of how students' understanding of nets of polyhedrons develops progressively through carefully designed learning activities that integrate contextual problems, simulations, and visual representations. Therefore, research is needed not only to examine learning outcomes but also to investigate and refine the learning process through the development of a Hypothetical Learning Trajectory (HLT) that can guide students' conceptual development and describe how their understanding evolves throughout instructional activities (Firmasari et al., 2023; Thohari et al., 2024).

In contrast to previous studies, which have primarily examined the effects of Problem-Based Learning (PBL), contextual learning, simulations, or animated videos on students' learning outcomes, the present study emphasizes the development and refinement of a learning trajectory through a design research approach. The proposed learning trajectory was constructed by comparing the Hypothetical Learning Trajectory (HLT) with students' actual learning processes, resulting in an empirically grounded learning trajectory that provides evidence of students' conceptual development in understanding three-dimensional geometric nets.

Within design research, a learning trajectory serves as both a theoretical and practical tool for describing how students' understanding may develop through a sequence of instructional activities. A learning trajectory is commonly represented through a Hypothetical Learning Trajectory (HLT), which includes learning goals, a sequence of instructional activities, predictions of students' responses, and anticipated instructional interventions designed to support conceptual development (Pramesti et al., 2025; Thohari et al., 2024; Muhammad et al., 2026). Through iterative cycles of implementation, evaluation, and revision, the HLT can be progressively refined to generate an empirically grounded learning trajectory that reflects students' actual learning processes. Consequently, the development of an HLT is a central component of design research because it enables researchers to compare hypothetical and actual learning processes, refine instructional designs, and generate empirically grounded learning trajectories that support students' conceptual growth (Firmasari et al., 2023; Pinasthi & Amir, 2025).

Based on these considerations, this study aimed to develop and evaluate a learning trajectory for learning nets of polyhedrons through the integration of Problem-Based Learning (PBL), a contextual approach, simulation-based learning, animated videos, and student worksheets. Using a design research approach, the study sought to develop and refine a Hypothetical Learning Trajectory (HLT) that describes how students' understanding of nets of polyhedrons evolved through a sequence of meaningful learning activities. The resulting learning trajectory is expected to provide an empirically grounded instructional design that can support students' conceptual understanding, spatial visualization, and active participation in geometry learning while also contributing to the development of a Local Instructional Theory for teaching nets of polyhedrons.

METHOD

This study employed a qualitative educational design research approach to develop and refine a learning trajectory for nets of polyhedrons through iterative cycles of analysis, design, implementation, evaluation, and revision. Educational design research combines the systematic development of an instructional intervention with empirical investigation in an authentic learning setting, allowing practical solutions and theoretical understanding to be developed simultaneously (Bakker, 2018; Cobb et al., 2003; McKenney & Reeves, 2018). Accordingly, the study consisted of three interrelated phases: (1) preliminary design, (2) teaching experiment, and (3) retrospective analysis. Throughout these phases, the hypothetical learning process was continuously compared with students' actual classroom responses so that the learning trajectory could be revised on the basis of empirical evidence (Pujiani & Effendi, 2025).

The study was conducted at SMP IT Attaubah Karawang during the 2025/2026 academic year. The participants were ninth-grade students. The pilot teaching experiment involved six ninth-grade students representing high, medium, and low levels of mathematical achievement, while the subsequent teaching experiment was conducted in one ninth-grade classroom consisting of 28 students. The latter was implemented in a regular classroom setting to investigate students' learning processes during the implementation of the revised learning trajectory. The six students in the pilot teaching experiment were selected purposively based on recommendations from the mathematics teacher, academic achievement, and classroom performance. Purposive selection was used to obtain information-rich cases that represented meaningful variation in students' mathematical ability (Palinkas et al., 2015). Both the pilot teaching experiment and the teaching experiment were conducted in a single session, each lasting 2 × 40 minutes. All instructional activities were carried out by the researcher, while the mathematics teacher served as an observer who monitored implementation and provided feedback. The learning design focused on nets of polyhedrons and integrated PBL, a contextual approach, simulation-based activities, animated videos, and student worksheets.

The first phase was the preliminary design. At this stage, the researchers conducted classroom observations, interviews with mathematics teachers, curriculum analysis, student characteristics analysis, and a review of relevant literature. Classroom observations revealed that students had difficulty visualizing three-dimensional objects from two-dimensional net representations and tended to be passive during mathematics lessons. Interviews with teachers also indicated that students often relied on memorization rather than conceptual understanding when learning geometry.

The curriculum analysis was conducted to identify learning objectives, indicators, and content related to nets of polyhedrons in junior high school mathematics. The analysis of student characteristics focused on identifying students' prior knowledge, learning difficulties, and levels of classroom participation. In addition, a literature review was conducted on Problem-Based Learning, contextual learning, simulation methods, animated learning videos, student worksheets, spatial visualization skills, and learning trajectory theory.

Based on the results of these analyses, a Hypothetical Learning Trajectory (HLT) was developed. The HLT consisted of learning objectives, a sequence of learning activities, predictions of students' responses, and anticipated teacher interventions. The initial HLT was organized into five main learning activities: (1) identifying and evaluating gift-wrapping patterns through a contextual simulation, (2) visualizing the relationship between two-dimensional nets and three-dimensional solids through animated videos, (3) analyzing valid and invalid net configurations through collaborative investigation, (4) constructing and presenting alternative net designs, and (5) engaging in presentation and reflection. Each activity was designed to progressively support students' conceptual understanding of nets of polyhedrons while developing spatial visualization and mathematical reasoning skills.

To support the implementation of the HLT, several learning materials were developed, including a teaching module, animated videos illustrating the transformation of nets into three-dimensional solids, contextual simulation activities using a gift shop scenario, and student worksheets (LKPD). As presented in Table 1, the initial HLT consisted of learning objectives, a sequence of learning activities, predictions of students' responses, and anticipated teacher interventions..

Table 1. Initial Hypothetical Learning Trajectory for Learning Nets of Polyhedrons

Learning Activity	Learning Goal	Predicted Student Responses	Anticipated Teacher Interventions
Contextual simulation: selecting gift-wrapping patterns for packaging boxes	Students identify the relationships between package shapes and wrapping patterns (nets)	Students recognize some patterns based on visual appearance but may not yet accurately distinguish valid and invalid nets	Ask guiding questions about how the package would look when folded and encourage students to justify their choices
Observing animated videos of the folding and unfolding of polyhedrons	Students visualize the connection between two-dimensional nets and three-dimensional solids	Students begin to understand the folding process but may still confuse face positions and orientations	Replay critical parts of the animation and encourage students to predict folding outcomes
Group investigation of valid and invalid net configurations using worksheets	Students analyze the characteristics of valid and invalid nets of polyhedrons	Students identify several valid nets but may still have misconceptions about overlapping faces or incorrect face arrangements	Facilitate group discussions and prompt students to compare different net configurations
Designing alternative nets for a given polyhedron	Students construct multiple valid nets and explain their reasoning	Students create alternative nets with varying levels of accuracy and reasoning quality	Provide scaffolding questions and encourage students to test and justify their designs
Presentation and reflection	Students communicate mathematical reasoning and evaluate different solutions	Students compare solutions, defend arguments, and refine their understanding through discussion	Guide whole-class reflection and summarize key mathematical ideas about nets of polyhedrons

The second phase was the teaching experiment, which consisted of a pilot teaching experiment (small-scale trial) and a teaching experiment (large-scale trial). The small-scale trial was conducted to examine the feasibility of the initial learning design, identify students' difficulties, and evaluate the suitability of the learning materials. Consistent with the iterative character of design experiments, evidence from this stage was used to revise the HLT, improve worksheet instructions, refine contextual tasks, and adjust classroom procedures before the large-scale implementation (Cobb et al., 2003).

The large-scale teaching experiment implemented the revised learning design in a classroom setting. Learning activities were organized according to the stages of Problem-Based Learning. In the problem orientation stage, students were introduced to a contextual simulation in which they acted as gift shop owners who needed to select suitable gift-wrapping patterns for various package shapes. To support students' visualization of geometric concepts, an animated video showing the unfolding and folding processes of nets of polyhedrons was presented.

During the stage of organizing students for learning, students were divided into small groups and provided with worksheets to guide their investigations. In the guided investigation stage, students analyzed different wrapping patterns, identified valid and invalid nets, justified their reasoning, and created alternative net designs. The teacher facilitated discussions by providing guiding questions and encouraging students to compare various net configurations.

In the stage of developing and presenting work, students presented their findings and explained the reasoning behind their decisions. Class discussions were then conducted to compare different solutions and address misconceptions. Finally, in the stage of analyzing and evaluating the problem-solving process, students reflected on their learning experiences, evaluated the validity of various net patterns, and completed evaluation tasks designed to assess their conceptual understanding.

The final phase was retrospective analysis. In this phase, the researchers analyzed the implementation of the learning design by systematically comparing the actual learning process with the HLT developed during the preliminary design phase. Retrospective analysis is central to educational design research because it enables researchers to examine how an intervention functioned, identify mechanisms that supported or constrained learning, and refine both the instructional design and the underlying theoretical conjectures (Cobb et al., 2003; McKenney & Reeves, 2018). The analysis focused on similarities and differences between predicted and actual student responses, students' learning strategies, conceptual understanding, misconceptions, and difficulties encountered throughout the learning process.

Particular attention was given to how students responded to each learning activity, how their understanding evolved during the learning process, and how instructional interventions influenced their conceptual development. The findings from this analysis were used to revise the initial HLT and formulate a refined learning trajectory that more accurately reflected students' actual learning processes. The retrospective analysis revealed that several learning stages originally embedded within broader activities emerged as distinct phases of students' conceptual development. Therefore, the refined learning trajectory contained a more detailed sequence than the initial HLT.

The research instruments consisted of observation sheets, interview guidelines, student worksheets, learning documentation, and learning outcome tasks. Observation sheets were used to document students' participation and learning behaviors during classroom activities. Interview guidelines were used to explore students' reasoning, perceptions, and learning experiences. Student worksheets served both as learning materials and as sources of evidence regarding students' conceptual understanding of nets of polyhedrons. Learning outcome tasks were administered to assess students' understanding after the implementation of the learning trajectory.

Data were collected through classroom observations, students' written work, semi-structured interviews, and documentation of learning activities. To enhance the credibility and trustworthiness of the findings, data-source triangulation was employed by comparing evidence obtained from these different sources (Carter et al., 2014). The data were analyzed through data reduction, systematic organization, comparison, and retrospective analysis. Evidence from classroom observations, interviews, students' written work, and documentation was compared with the HLT to identify consistencies and discrepancies between the predicted learning trajectory and students' actual learning processes. Interpretations were then checked across data sources, and the convergent findings were used to formulate an empirically grounded learning trajectory for nets of polyhedrons.

RESULTS AND DISCUSSION

The preliminary analysis revealed that students experienced difficulties in visualizing the relationship between two-dimensional nets and three-dimensional solids. Based on these findings, an initial Hypothetical Learning Trajectory (HLT) was developed by integrating Problem-Based Learning (PBL), contextual simulation, animated videos, and student worksheets. The HLT was designed to support students' progression from recognizing packaging patterns in a real-life context to constructing and evaluating alternative nets of polyhedrons. The following sections describe how this initial HLT was tested, revised, and refined through iterative teaching experiments.

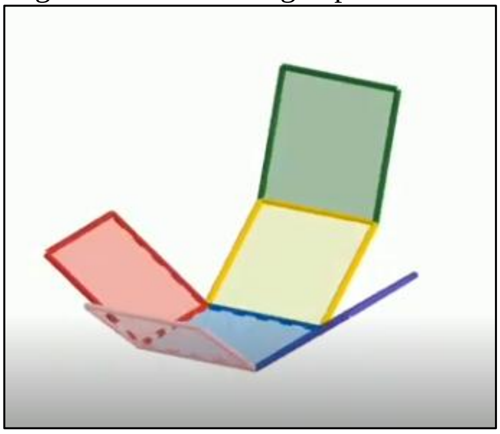
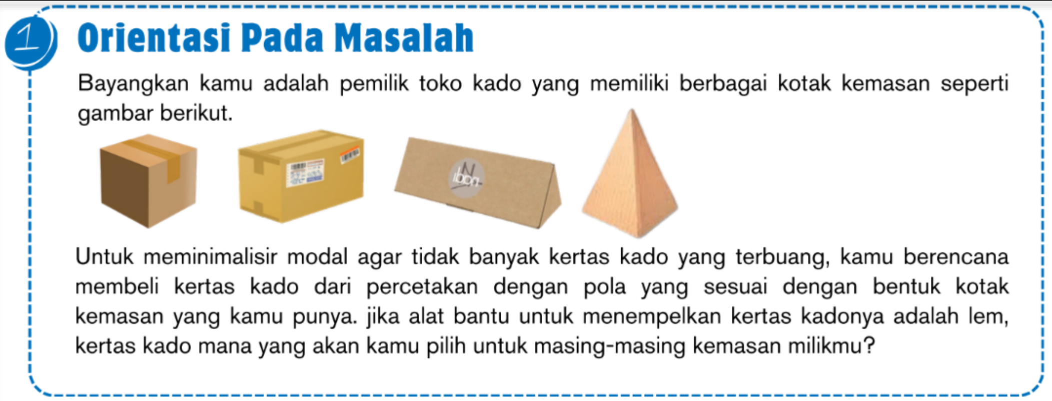


Figure 1. Screenshot of the animated video on nets of polyhedrons



English Version
Imagine that you own a gift shop that uses various types of packaging boxes, as shown in the following figure. To minimize costs by reducing wrapping paper waste, you plan to order wrapping paper printed in the form of nets that match the shapes of your packaging boxes. Assuming glue is used to assemble the wrapping paper, which net would you select for each packaging box?

Figure 2. Gift shop simulation context

The animated video and gift shop simulation served as the starting points of students' conceptual development. As shown in figure 1, the video supported students in visualizing how two-dimensional patterns transform into three-dimensional solids, while figure 2 illustrates the gift shop context activated students' prior knowledge about packaging and wrapping materials. Together, these activities were intended to bridge students' informal experiences and formal geometric concepts, forming the foundation of the learning trajectory.

The preliminary teaching experiment was conducted with a small group of students to examine the feasibility of the initial learning design and identify potential difficulties before implementing the design in a larger class. The learning activities began with students watching an animated video showing how nets of polyhedrons could be folded into three-dimensional objects. The contextual simulation was then introduced through a scenario in which students were asked to determine appropriate gift-wrapping patterns for different package shapes.

Analysis of students' responses during the small-scale trial indicated an initial progression in understanding. Most students were able to recognize similarities between packaging patterns and geometric nets after observing the animated video. However, several students still relied solely on visual appearance when determining whether a net was valid. This finding suggested that students required additional opportunities to explore the folding process and compare alternative configurations. Therefore, the initial HLT needed refinement to better support students' transition from intuitive visual judgments to conceptual reasoning about nets of polyhedrons.

Students worked collaboratively using the student worksheets designed according to the Problem-Based Learning framework. During the investigation stage, students analyzed several net patterns and determined whether each pattern could form a cube, cuboid, prism, or pyramid. As shown in Table 2, students' actual responses during each learning activity were compared with the responses predicted during the preliminary design phase.

Table 2. Predicted and Actual Student Responses During the Small-Scale Trial

Learning Activity	Predicted Response	Actual Response
Observing the animated video	Students visualize the transformation from nets to solids	All six students showed curiosity and actively discussed the shapes presented in the animated video throughout the activity.
Analyzing gift-wrapping patterns	Students identify correct and incorrect nets	All six students successfully identified valid and invalid net patterns and were able to justify their responses based on the folding process and the spatial relationships among faces.
Group discussion	Students exchange ideas and justify their answers	The six students actively discussed the tasks during the learning activities, although some still experienced difficulties in clearly explaining the reasoning behind their answers.
Presentation	Students communicate findings confidently	All six students had the opportunity to present their findings. Although some explanations were not yet delivered systematically, the mathematical reasoning underlying their responses was generally correct.

The small-scale trial provided important insights into students' learning processes. Although most students were able to participate actively in the learning activities, difficulties emerged when students were asked to provide written explanations for their answers. In addition, several worksheet instructions were interpreted differently by students, indicating the need for clearer guidance during the investigation stage.

A comparison between the predicted and actual student responses demonstrated that the overall sequence of activities functioned as expected. Students generally followed the intended progression from observing nets to identifying valid configurations. However, two important discrepancies emerged. First, some students had difficulty distinguishing visually similar net patterns. Second, students were able to explain their reasoning orally but struggled to communicate it in written form. These discrepancies became important considerations in refining the HLT before the large-scale implementation.

As summarized in Table 3, several revisions were made before the large-scale implementation. The revisions included simplifying worksheet instructions, providing additional examples of net patterns, and allocating more time for group discussions and reflection.

Table 3. Revisions Based on the Small-Scale Trial

Observation	Follow-up Action
Students had difficulty understanding some worksheet instructions	Instructions were rewritten using simpler language.

Students struggled to justify their answers in writing	Additional guiding questions were added.
Discussion time was insufficient	Time allocation was adjusted.
Some students confused similar net patterns	More visual examples were incorporated.

The findings from the small-scale trial were used to revise the initial Hypothetical Learning Trajectory (HLT). Although most predicted student responses were observed, several discrepancies emerged. Some students required additional support to distinguish visually similar net patterns and communicate their reasoning in written form. Therefore, the revised HLT incorporated clearer worksheet instructions, additional visual examples, and guiding questions intended to support students' mathematical communication and conceptual understanding during the subsequent teaching experiment.

After the learning design was revised based on the findings from the small-scale trial, a large-scale teaching experiment was conducted. The implementation followed the stages of Problem-Based Learning (PBL), namely problem orientation, organizing students for learning, guiding group investigation, developing and presenting work, and analyzing and evaluating the problem-solving process. The learning process began with students observing an animated video showing the transformation of nets into three-dimensional solids, such as cubes, cuboids, prisms, and pyramids. The teacher then introduced a contextual problem through a simulation in which students acted as gift shop owners who needed to select suitable gift-wrapping patterns for different packaging boxes. This problem was designed to encourage students to connect mathematical concepts with real-life situations and stimulate their curiosity about nets of polyhedrons.

At this stage, the learning trajectory began with the activation of students' prior knowledge through a familiar packaging context. Rather than introducing formal definitions of nets directly, students were first encouraged to reason about wrapping patterns and package structures. This activity allowed students to build an initial connection between everyday experiences and geometric representations, which served as the foundation for subsequent conceptual development.

Students' responses during the simulation indicated that the contextual problem successfully activated informal reasoning about geometric structures. Most students initially focused on the visual appearance of the packaging patterns. However, through discussion, they gradually began to consider whether the patterns could actually be folded into three-dimensional objects. This shift suggested an early transition from perceptual reasoning to structural reasoning about nets of polyhedrons. Such conceptual development is consistent with previous studies indicating that contextual learning and problem-based activities support students in constructing mathematical understanding through meaningful experiences and reasoning processes (Dianartasi & Sthephani, 2021; Amalia et al., 2022; Putri et al., 2023). This interpretation was supported by the students' written work and interview data, which showed that students had begun to justify their responses by considering the folding process, the relationships among faces, and the possibility of overlapping faces rather than relying solely on visual resemblance.

To investigate the contextual problem, students worked collaboratively in small groups using worksheets designed according to the Problem-Based Learning framework. The tasks required students to identify valid and invalid net configurations, determine the corresponding solids, and justify their decisions. Through group interaction, students were encouraged to exchange ideas and negotiate different perspectives while solving the given problems. Such collaboration is consistent with the principles of Problem-Based Learning, which emphasize discussion, reasoning, and shared problem-solving (Zetriuslita et al., 2023).

The collaborative investigation stage played an important role in refining students' understanding of nets. Through group discussions, students compared different interpretations of the same net configuration and were required to justify their decisions. As a result, students began to move beyond simple shape recognition and developed a deeper understanding of the relationships among faces, edges, and folding directions. This finding aligns with previous studies suggesting that collaborative problem-solving activities encourage students to negotiate meaning, justify mathematical ideas, and construct conceptual understanding through social interaction (Zetriuslita et al., 2023; Bhari et al., 2023).

Students then analyzed various gift-wrapping patterns presented in the worksheet while repeatedly observing the animated video as a visual reference. They identified which patterns could form cubes, cuboids, prisms, or pyramids and provided reasons for their decisions. Students were also asked to create alternative net designs that differed from the examples provided in the worksheet. During group discussions, students actively exchanged ideas and collaboratively analyzed different wrapping patterns. The classroom atmosphere became more interactive because students were involved in discovering concepts rather than merely receiving information from the teacher.

Analysis of students' worksheet responses showed evidence of conceptual progression. At the beginning of the activity, several students determined the validity of a net based primarily on its visual similarity to examples they had previously encountered. However, after engaging with the animated video and collaborative investigation, students increasingly referred to folding processes, face arrangements, and potential overlaps when justifying their answers. For example, several students initially selected net patterns based solely on visual similarity to familiar examples, whereas later responses included explanations referring to face orientation, folding directions, and possible overlaps between surfaces. This finding indicates that students' reasoning became more conceptually grounded throughout the learning process. The role of visual representations in supporting students' spatial reasoning and understanding of geometric relationships has also been highlighted in previous studies on geometry learning and spatial visualization (Octaviani et al., 2021; Ahmar et al., 2023; Betts et al., 2023).

These findings indicate that the sequence of activities proposed in the initial HLT generally functioned as intended. Students progressed from recognizing packaging patterns in a familiar context to reasoning about the structural properties of nets and constructing alternative configurations. The observed progression suggests that contextual simulation, animated visualization, and collaborative investigation collectively supported the development of students' understanding of nets of polyhedrons.

Figure 3. Students discussing in groups

As shown in figure 3, most groups correctly identified valid net patterns and successfully related them to the corresponding three-dimensional objects. Students demonstrated an improved understanding of the relationship between nets and solids. The animated video helped students visualize how two-dimensional patterns could be folded into three-dimensional shapes, thereby reducing misconceptions about side positions and folding directions. These findings are in line with previous studies showing that animation-based learning media can enhance students' spatial visualization skills and support the understanding of abstract geometric concepts (Ahmar et al., 2023; Lestari & Sari, 2022; Betts et al., 2023).

Nevertheless, some students still experienced difficulties when asked to provide written justifications for their answers. Interestingly, when questioned orally, these students were able to explain their reasoning appropriately. This finding suggests that although students had developed conceptual understanding, they still required support in expressing mathematical reasoning through written communication. Similar findings were reported by Nurbaiti and Rezeki (2021), who argued that students often require additional scaffolding to transform intuitive understanding into formal mathematical communication.

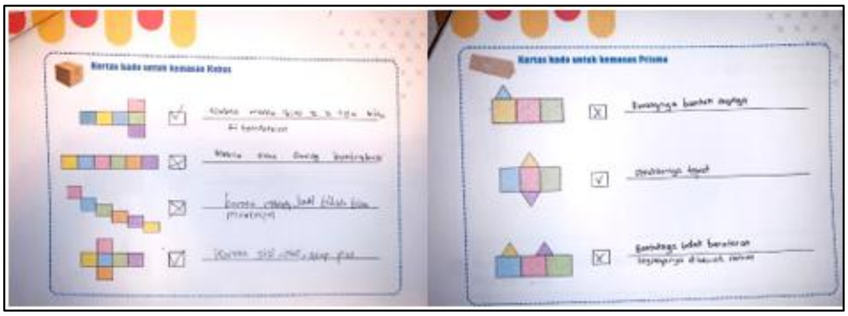


Figure 4. Example of students' worksheet responses

Translation:

- *Because both blue faces can be attached*
- *Because they will overlap each other*
- *Because it is slanted, so it cannot be attached.*
  Because the base and the top fit perfectly
- *Because it lacks a triangular shape*
- *Because the structure is correct*
- *Because the shape is irregular, and all the triangles are on the bottom*

Although the student's written response shown in figure 4, "Both blue faces can be attached," was brief, the interview revealed a more sophisticated understanding. The student explained, "The blue faces will become opposite faces after folding. The yellow face will be opposite the green face, and the pink face will be opposite the purple face." This response indicates that the student was able to reason about opposite-face relationships within the cube, even though such reasoning was not fully reflected in the written worksheet response.

Similarly, a student who initially wrote, "It lacks a triangular shape," later explained during the interview that a valid triangular prism net requires two congruent triangular faces positioned on opposite sides of the net. This explanation suggests that the student's understanding of prism structure was more advanced than what was reflected in the written response.

The interview findings revealed an important discrepancy between students' conceptual understanding and their written mathematical communication. Although students were often able to explain their reasoning verbally using concepts such as opposite faces, folding processes, and face arrangements, they tended to record only short and incomplete explanations in their worksheets. This finding suggests that students' spatial reasoning developed more rapidly than their ability to express mathematical ideas in written form. Similar findings have been reported in previous studies indicating that students may demonstrate conceptual understanding verbally while experiencing difficulties in expressing mathematical reasoning through formal written communication. Therefore, additional scaffolding may be needed to support students in translating conceptual understanding into formal mathematical communication (Nurbaiti & Rezeki, 2021).

After completing the investigation, each group presented its findings to the class and explained the reasoning behind its answers. Students described why certain gift-wrapping patterns could form specific solids and justified their decisions using observations from the animated video and worksheet activities.

During the presentation stage, students were required to articulate and defend their reasoning regarding the validity of different net configurations. Classroom discussions revealed that students increasingly referred to mathematical considerations, such as face arrangement, folding direction, and potential overlap, rather than relying solely on visual appearance. This finding suggests that students' reasoning became more explicit and mathematically justified throughout the learning process.

These findings support previous studies suggesting that Problem-Based Learning promotes mathematical communication and argumentation through collaborative discussions and presentations (Zetriuslita et al., 2023). Presentation activities also enabled students to clarify misconceptions and strengthen conceptual understanding through peer interaction and reflective discussion.

Figure 5. Group presentation and classroom discussion

Based on figure 5, students compared different solutions presented by their peers and reflected on the validity of various net configurations. The teacher facilitated a whole-class discussion to emphasize important concepts related to side arrangements, folding processes, and the possibility of multiple valid nets for the same solid. Students subsequently completed evaluation tasks and formulated conclusions based on the learning activities.

The reflection and evaluation process helped students consolidate their understanding of nets of polyhedrons and recognize that a single solid may have several different valid net patterns. This stage also encouraged students to review and refine their previous reasoning, thereby strengthening their conceptual understanding. Such reflective activities are considered essential in Problem-Based Learning because they allow students to evaluate their problem-solving strategies and construct more robust mathematical knowledge (Putri et al., 2023; Wahyuni, 2023).

Overall, the large-scale teaching experiment provided evidence that students progressed through the learning stages anticipated in the HLT. The sequence of contextual simulation, animated visualization, collaborative investigation, alternative net construction, and reflective discussion supported students in developing increasingly sophisticated reasoning about nets of polyhedrons. The findings suggest that the proposed learning trajectory functioned as an effective pathway for supporting conceptual development in geometry learning.

Table 4. Comparison Between Predicted and Actual Student Responses

Learning Activity	Predicted Response (HLT)	Actual Response
Animated video	Students visualize folding processes	Most students correctly related nets to solids and discussed folding directions.
Gift shop simulation	Students identify valid and invalid nets	Students actively analyzed wrapping patterns and justified their choices.
Group investigation	Students compare net configurations	Students discussed alternative solutions and corrected misconceptions.

Learning Activity	Predicted Response (HLT)	Actual Response
Alternative net construction	Students create valid nets	Most groups successfully designed alternative nets.
Presentation and reflection	Students communicate reasoning	Students explained solutions confidently, but some still struggled to provide written explanations.

The comparison in table 4 between the predicted responses described in the HLT and the actual classroom responses indicates that most instructional assumptions were supported during implementation. Students demonstrated the expected progression from identifying net patterns to constructing and communicating mathematical ideas. Nevertheless, the findings also revealed that some students required additional support in expressing their reasoning in written form. These results informed the refinement of the learning trajectory and provided empirical evidence of how students developed their understanding of nets of polyhedrons throughout the learning process.

The implementation of the developed learning design demonstrated that integrating the Problem-Based Learning (PBL) model with a contextual approach, simulation activities, animated videos, and student worksheets effectively enhanced students' active engagement and conceptual understanding of nets of polyhedrons. These findings support previous studies indicating that PBL is effective in improving problem-solving skills and conceptual understanding in mathematics because it enables students to construct knowledge through meaningful learning experiences (Sari & Fathoni, 2022; Bhari et al., 2023; Putri et al., 2023). More importantly, the findings provide evidence of how students' understanding developed across successive learning activities, thereby contributing to the refinement of the proposed learning trajectory.

The increased learning activity during group discussions and presentations indicated that a collaborative learning environment encouraged students to actively construct knowledge. This finding is consistent with research showing that Problem-Based Learning improves social interaction and mathematical communication skills through structured group discussions (Zetriuslita et al., 2023). In this study, students not only completed tasks but also engaged in argumentation and justification processes, which are essential components of meaningful mathematics learning.

The use of animated video media proved effective in helping students visualize the transformation of two-dimensional nets into three-dimensional solid shapes. Initial difficulties in understanding spatial concepts were reduced through dynamic visual representations. This finding aligns with studies showing that animation-based media can improve spatial visualization skills and support students in understanding abstract geometric concepts (Widiastawan et al., 2023; Lestari & Sari, 2022). Thus, visual media play an important role in bridging the gap between two-dimensional representations and three-dimensional objects.

In addition, the use of a contextual simulation in the "gift shop" scenario provided students with a more authentic learning experience. This real-life context allowed students to connect mathematical concepts with everyday situations, making learning more meaningful. This finding is in line with the principles of contextual learning, which emphasize the relationship between learning materials and students' real-world experiences (Dianartasi & Sthephani, 2021; Amalia et al., 2022). This approach also supports design research theory, which highlights the importance of context in constructing conceptual understanding.

However, the findings also revealed that although students' conceptual understanding improved, their ability to express mathematical reasoning in written form still required further development. The discrepancy between verbal and written explanations indicates that conceptual internalization had not yet been fully stabilized into formal representation. This finding is consistent with research suggesting that mathematical communication skills require additional scaffolding even when students demonstrate conceptual understanding intuitively (Nurbaiti & Rezeki, 2021).

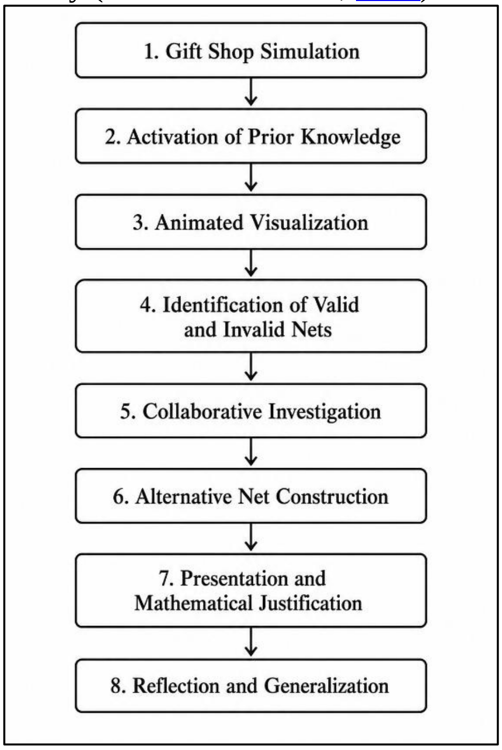


Figure 6. Refined Learning Trajectory for Learning Nets of Polyhedrons

Based on figure 6, the retrospective analysis, a refined learning trajectory for learning nets of polyhedrons was generated. The trajectory began with a contextual simulation involving gift-wrapping problems that activated students' prior knowledge of package shapes. Animated videos were then used to support students in visualizing the relationship between two-dimensional nets and three-dimensional solids. Through collaborative investigation using worksheets, students analyzed valid and invalid net configurations and discussed their reasoning with peers. Students then constructed alternative net designs and presented their findings to the class. Finally, reflective discussions enabled students to consolidate their understanding and recognize that a single solid may have multiple valid net representations.

The retrospective analysis indicated that contextual simulation and animated visualization played important roles in supporting students' conceptual development. Furthermore, collaborative discussion and presentation activities facilitated students' transition from intuitive observations to more formal mathematical reasoning. Therefore, the refined learning trajectory provides an empirically grounded sequence of learning activities for teaching nets of polyhedrons at the junior high school level.

Overall, the results of this study indicate that the developed learning design is not only effective in improving students' understanding of nets of polyhedrons but also supports the development of collaboration, communication, and spatial visualization skills. Therefore, this learning design can be considered a promising instructional trajectory for geometry instruction at the junior high school level.

CONCLUSION

This study developed and refined a learning trajectory for learning nets of polyhedrons through a design research approach integrating Problem-Based Learning (PBL), contextual simulation, animated video media, and student worksheets. Through iterative cycles of preliminary design, teaching experiments, and retrospective analysis, the study generated an empirically grounded learning trajectory that describes how students progressively develop their understanding of nets of polyhedrons.

The findings indicate that students' understanding evolved from recognizing packaging patterns in a familiar context to reasoning about the structural properties of nets, evaluating valid and invalid configurations, constructing alternative nets, and communicating mathematical ideas. Contextual simulation and animated visualization supported students in connecting real-world experiences with geometric concepts, while collaborative investigation and classroom discussion facilitated the development of increasingly sophisticated mathematical reasoning.

The retrospective analysis resulted in a refined learning trajectory consisting of contextual simulation, activation of prior knowledge, animated visualization, identification of valid and invalid nets, collaborative investigation, alternative net construction, presentation and mathematical justification, and reflection and generalization. This trajectory provides a structured pathway for supporting students' conceptual development in learning nets of polyhedrons.

Although students demonstrated improved conceptual understanding and spatial visualization, difficulties in expressing mathematical reasoning through written communication were still observed. Therefore, future studies may explore additional scaffolding strategies to support students' mathematical communication skills. This study has several limitations. It was conducted in a single school with a limited number of participants and employed a design research approach that focused on the qualitative analysis of the learning process. Therefore, the resulting learning trajectory is not intended to be generalized across all educational contexts but rather to serve as an empirically grounded instructional design within the context of this study. Future research is recommended to implement and evaluate this learning trajectory in schools with different educational levels and more diverse student characteristics to obtain broader evidence regarding its applicability and further refinement. Overall, the refined learning trajectory developed in this study can serve as a practical and theoretically informed alternative for geometry instruction at the junior high school level.

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