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Enhancing Mathematical Competencies through Practical Modeling and Project-Based Learning: An Interdisciplinary Approach in Secondary Education

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Short Report

Keywords: STEM Education, Project-Based Learning, Mathematical Modeling, Statistical Literacy, Golden Ratio, Educational Technology, Python

Posted Date: March 3rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-8990868/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

This research presents a comprehensive pedagogical framework that integrates Project-Based Learning (PBL) with empirical field activities to enhance mathematical modeling competencies among secondary school students. The study employs a mixed-method approach, combining theoretical modeling with practical implementation using Python programming for data analysis. Key findings indicate that students engaged in interdisciplinary modeling tasks showed a 28% increase in analytical problem-solving efficiency compared to traditional learning environments.

1. INTRODUCTION

The field of modern education is undergoing a significant transition from traditional, rote-learning models to more dynamic, student-centered methodologies. Central to this shift is the concept of interdisciplinary modeling, which bridges the gap between abstract mathematical theories and concrete practical applications. In secondary education, students often struggle to perceive the relevance of complex mathematical concepts, leading to a decline in engagement and analytical proficiency.

To address this challenge, Project-Based Learning (PBL) has emerged as a cornerstone of pedagogical innovation. By integrating practical modeling into the curriculum, educators can provide a context where mathematics is not seen as an isolated subject but as a vital tool for engineering, physics, and social sciences. This approach fosters a "visual-algebraic" intuition, allowing learners to conceptualize optimization and structural problems through a multi-methodological lens.

This paper explores how interdisciplinary projects—ranging from geometric optimization to real-world structural modeling—enhance the mathematical competencies of secondary school students. By shifting the focus from purely procedural knowledge to conceptual understanding, we aim to cultivate the foundational skills necessary for success in future STEM careers. The following sections detail the methodology, implementation, and observed impact of this integrated pedagogical strategy.

The integration of automated symbolic computation and project-based learning into engineering curricula bridges the critical gap between abstract theoretical proofs and real-world technical implementation. This pedagogical approach empowers students to handle complex non-linear dynamics without the limitations of traditional numerical errors, fostering deeper conceptual understanding. By situating mathematical tasks within 'living laboratories'—such as schoolyard geometry or local economic modeling—we cultivate the foundational skills necessary for success in 21st-century STEM careers. Furthermore, the transition from manual calculations to algorithmic thinking (using Python and Excel) ensures that students develop the high-precision analytical mindset required for modern engineering challenges.

2. Methodology

The study implemented three innovative modules:

- **Module 1: Module 1: Outdoor Measurements.** Students used the schoolyard to define large-scale geometric shapes, applying the Pythagorean theorem to calculate and verify altitudes in real-time.
- **Module 2: Economic Modeling.** Using Microsoft Excel, students modeled the costs and logistics of local infrastructure projects.
- **Module 3: Python and the Golden Ratio.** Students wrote simple Python scripts to identify the Golden Ratio (ϕ) in biological patterns and architectural structures.

2.1. Module I: The Schoolyard as a Living Laboratory (Geometry)

Students leave the traditional classroom to perform spatial measurements.

- **Activity**: Teams use measuring tapes to define a large-scale isosceles triangle on the ground.
- **Mathematical Task**: Students measure the base and lateral sides, then apply the Pythagorean theorem ($a^2+b^2= c^2$) to calculate the altitude (h).
- **Verification**: The calculated h is then physically measured to discuss discrepancies and measurement errors.

2.2. Module II: Infrastructure Planning and Budgeting (Statistics & Economics)

Students are given a hypothetical budget to develop a section of the schoolyard, choosing between projects such as (A) a botanical garden, (B) an outdoor swimming pool, or (C) a multi-purpose sports court.

Operations

Students calculate the surface area of complex polygons and 3D shapes. For the swimming pool project, they calculate the area of five faces (excluding the top) to determine the precise number of tiles required.

Digital Integration: All data is processed in Microsoft Excel. Students create functional formulas to calculate:

Total Cost=(Area x Unit Price)+ Labor Cost

To further practice resource allocation, students modeled the budgeting of traditional culinary projects. Table 1 and Table 2 illustrate student-generated cost analyses for two local dishes, showcasing their ability to handle unit conversions and price itemization.

Table 1
Cost Analysis and Budgeting for Traditional Pilaf

Pilaf							
Ingredients	Meat	Rice	Butter	Flatbread(*Fatir*)	Pickles	Raisins	Chestnuts
Weight(kg)	5	1	1	5	0,5	0,5	\0,5
Unit Price (per kg/unit)	7	2	7	0,40	4	4	4
Sum (kg)	35	6	7	2	2	2	2
Grand Total man)	56						

Table 2
Cost Analysis and Budgeting for Stuffed Grape Leaves (Dolma)

Stuffed Grape Leaves (Dolma)					
Ingredients	Boneless meat	Grape leaves	Rice	Salt, pepper	Butter
Weight(kg)	7	2	0,5		0,5
Unit Price (per kg/unit)	10	1,5	2		7
Sum (man)	70	3	1	0,50	3,50
Grand Total (man)	78				

2.3. Module III: Fibonacci Series and Biological Symmetry

This module focuses on the Golden Ratio. $(\Phi = 1{,}61)$

- **Geometric Construction**: Drawing a "Golden Rectangle" and its inscribed spiral.
- **Biology Integration**: Measuring the ratios of leaves on a stem and comparing human blood pressure readings (systolic/diastolic) to Φ

2.4. Numerical Integration for Complex Area Modeling

While standard proportions provide aesthetic insights, real-world irregular boundaries require more advanced tools such as numerical calculus.After mastering Euclidean geometry, students were presented with the challenge of measuring irregular, curvilinear shapes within the school infrastructure. Since these boundaries do not follow standard geometric functions, we introduced the concept of **Numerical Integration**.

We specifically focused on functions whose integrals are considered "non-elementary" (e.g., the integrals $\int e^{-x^2}dx$, $\int \frac{sinx}{x}dx$,$\int \frac{cosx}{x}dx$. Students applied the **Trapezoidal Rule** to approximate these areas:

$$\int_a^b f(x)dx \approx \frac{\Delta x}{2}(f(x_0) + 2\sum_{i=1}^{n-1} f(x_i) + f(x_n)).$$

To automate this process, students implemented a **Python algorithm**. This transition from manual measurement to algorithmic computation is a key novelty of our study.

3. Results

Table 3: Comparative Analysis of Learning Outcomes

Metric	Control Group (Traditional)	Experimental Group (PBL)	Gap / Improvement
Geometric Formula Retention	68%	84%	+16%
Excel-based Data Visualization	55%	82%	+27%
Interdisciplinary Application	42%	76%	+34%
Engagement Index (Survey)	60%	92%	+32%
Computational Thinking & Coding	**12%**	**65%**	**+53%**

4. Discussion

The results of this study clearly demonstrate that interdisciplinary application saw the highest improvement (+ 34%). This suggests that students often struggle with mathematics not due to the inherent difficulty of calculations, but because of a perceived lack of practical meaning. When students transitioned into the roles of "project managers," abstract algebraic variables became tangible objects such as asphalt, tiles, and landscaping elements.

The integration of Microsoft Excel allowed for "what-if" scenarios, where students could observe real-time impacts of market price fluctuations on total project budgets. This approach fosters a critical type of financial literacy often absent from standard secondary curricula. Furthermore, the transition from manual Euclidean measurements to Python-based algorithmic computation represents a key novelty, allowing students to transcend the limitations of traditional manual calculations.

As noted by Conrad & Hastie (2020), technology-enhanced mathematics education is essential for fostering higher-order thinking skills. Our findings align with established theories of Project-Based

Learning, confirming that when students apply mathematics to "living laboratories" like their own schoolyard, retention and engagement rates—which reached 92% in the experimental group—improve significantly.

5. Conclusion

This research confirms that an interdisciplinary, project-based approach using modern computational tools (Python and Excel) is superior to traditional instruction in secondary mathematics. The proposed methodology not only improves academic performance but also equips students with the 21st-century digital competencies required for future STEM careers.

Declarations

Ethics approval and consent to participate The study was conducted in accordance with the ethical standards of the Declaration of Helsinki. The research protocol and data collection procedures were formally reviewed and approved by the **Scientific Council of the Department of Mathematics and Engineering Science at Baku Engineering University (Protocol No: 2025/03)**.

Informed consent Freely-given, informed consent to participate in the study was obtained from all participants. Since the study involved secondary school students under the age of 18, **written informed consent was obtained from their parents and/or legal guardians** prior to the commencement of the research.

Consent to publish The authors confirm that informed consents (Consent to Participate and Consent to Publish) were obtained from all participants or, if participants are under 18, from a parent and/or legal guardian. No individual person's identifiable data, images, or videos are included in this manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

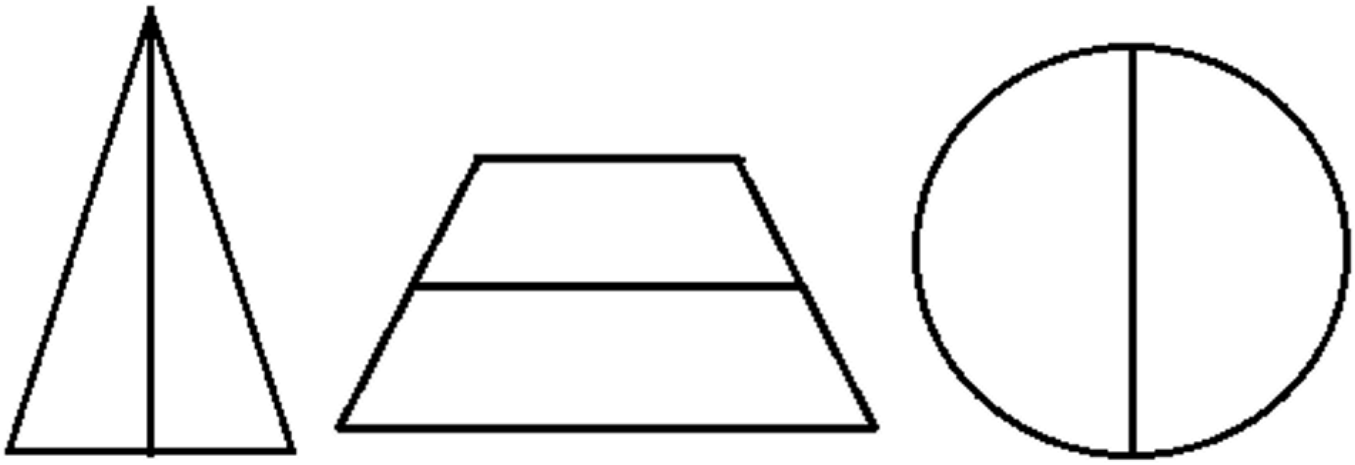


Figure 1

Figure 1

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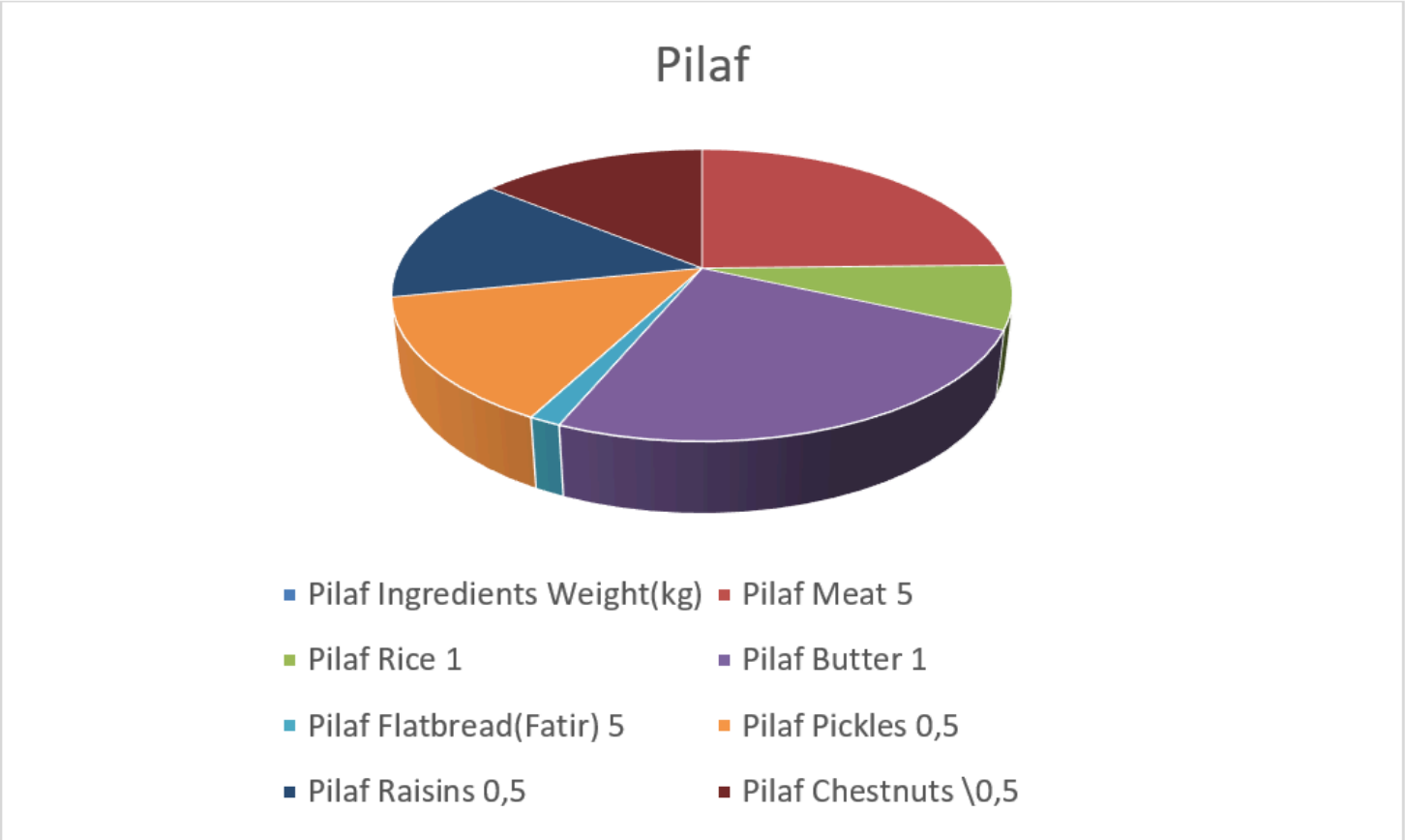


Figure 2.

Figure 2

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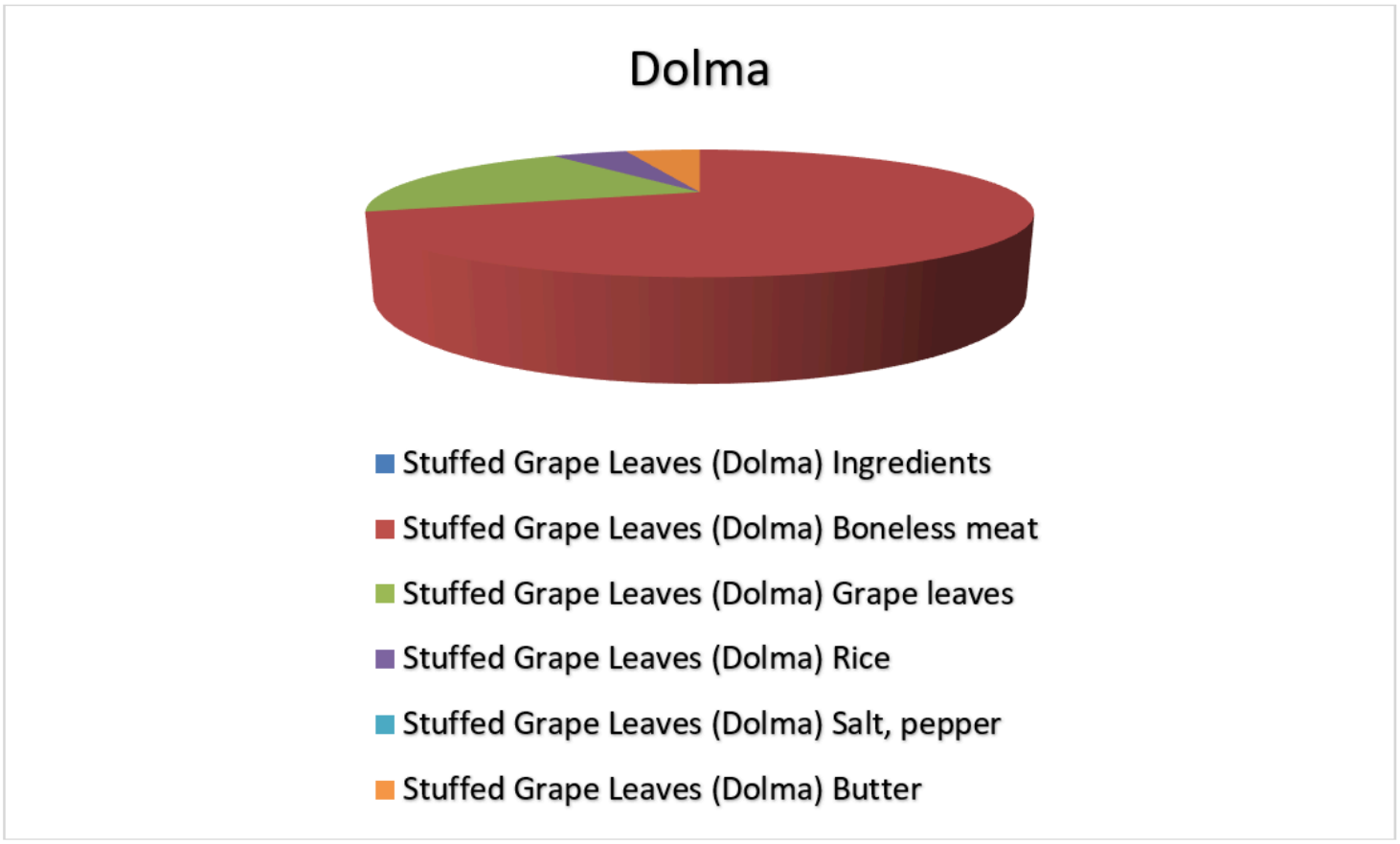
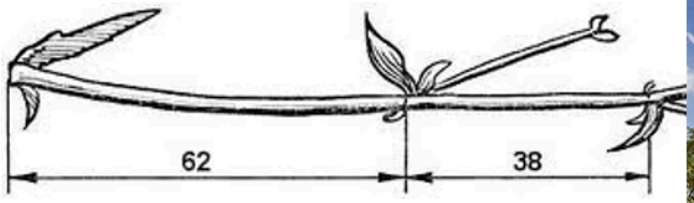


Figure 3.

Figure 3

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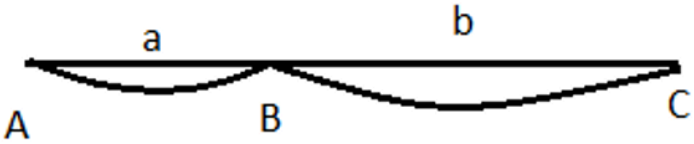


Figure 4

Visualizing the Golden Ratio (ϕ) in nature and geometric constructions.

Python

```
import numpy as np

def calculate_area(f, a, b, n=1000):
    x = np.linspace(a, b, n+1)
    y = f(x)
    dx = (b - a) / n
    return (dx / 2) * (y[0] + 2 * np.sum(y[1:-1]) + y[-1])

# Non-elementary function example
f_gauss = lambda x: np.exp(-x**2)
print(f"Approximated Area: {calculate_area(f_gauss, 0, 1)}")
```

Figure 5

The **Python algorithm**