Minimax Theory and its Applications
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Minimax Optimization of Gamification Strategies in University Educational Software

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The increasing adoption of educational software in higher education has intensified interest in gamification as a strategy to enhance student engagement and academic performance. However, the effectiveness of gamification largely depends on the strategic selection of game elements under conditions of uncertainty regarding student responses. This study proposes and empirically validates a minimax optimization approach, grounded in game theory, to design robust gamification strategies for university-level educational software.

A quantitative quasi-experimental design was employed with a sample of 240 undergraduate students, divided into a control group using traditional gamification and an experimental group using gamification optimized through a minimax criterion. The interaction between the system designer and students was modeled as a strategic game, and the optimal strategy was obtained via linear programming. Academic performance and student engagement (behavioral, emotional, and cognitive) were measured using validated instruments and system logs.

Results revealed that students exposed to the minimax-optimized gamification achieved significantly higher academic performance and engagement levels compared to the control group ($p < .001$), with large effect sizes. Moreover, the minimax approach reduced performance variability and increased minimum achievement levels, indicating greater robustness against adverse student responses. Regression analysis showed that behavioral engagement was the strongest predictor of academic performance.

These findings demonstrate that minimax optimization provides a robust and effective framework for gamification design in higher education, contributing theoretically by integrating game theory into educational technology and practically by offering evidence-based guidelines for developing resilient digital learning environments.

Keywords: Gamification; Higher education; Minimax optimization; Game theory; Educational software; Student engagement

Introduction

Context and background

The digital transformation of higher education has driven the development and adoption of interactive educational software as the central axis of teaching-learning processes. In this context, gamification – defined as the incorporation of game elements and mechanics in nongaming environments – has established itself as an effective pedagogical strategy to increase motivation, academic engagement and student persistence on university digital platforms.

Recent studies have shown that the use of elements such as points, badges, levels, immediate feedback, and rankings can significantly improve indicators of engagement, academic selfefficacy, and performance in technology-mediated university courses. However, the results are not homogeneous: the effectiveness of gamification depends critically on how, when, and for whom such strategies are implemented.

In particular, in university scenarios characterized by high cognitive heterogeneity, motivational differences, and time constraints, a poorly designed gamification strategy can generate counterproductive effects, such as cognitive overload, demotivation, or negative competition among students.

Research Problem

Most of the current research on gamification in higher education focuses on the isolated evaluation of strategies (e.g., comparing gamification versus non-gamification), without considering that the optimal design of a gamified system involves a strategic decision problem under uncertainty. In practice, educational software developers must select combinations of game mechanics without knowing with certainty the behavioral response of students, facing adverse scenarios where a strategy can minimize the expected benefits.

In this sense, there is a methodological gap in the literature: the absence of formal models that allow optimizing gamification strategies considering the worst possible scenario of student response, thus guaranteeing a minimum acceptable performance of the educational system.

Rationale for the study

Minimax optimization, derived from game theory and mathematical optimization, offers a robust framework for addressing strategic decisions in contexts of uncertainty and competition. Applying the minimax criterion to gamification design in university educational software allows:

- Select strategies that maximize the minimum expected benefit in terms of learning and engagement.
- Reduce the risk of negative effects on student subpopulations.
- To provide a quantitative and replicable basis for digital pedagogical design.
- Formally integrate learning analytics with mathematical decision models.

From a scientific perspective, this study contributes to the intersection between higher education, computer science, game theory, and educational technology, providing a novel approach that is scarcely explored in high-impact journals.

General objective

Optimize, through a minimax approach, the gamification strategies implemented in university educational software, in order to maximize academic performance and the level of student engagement under conditions of uncertainty in the response of users.

Specific objectives

1. Identify and classify the main gamification strategies used in university educational software.
2. Model the interaction between gamification strategies and student responses using a game theory framework.
3. Formulate a minimax optimization model applied to the design of educational gamification.
4. Empirically evaluate the impact of optimized strategies on academic performance and engagement.
5. Compare the results of the minimax approach with traditional non-optimized gamification designs.

Research hypothesis

- **H1:** Gamification strategies optimized using the minimax criterion generate significantly higher academic performance than non-optimized strategies.

- **H2:** The level of student engagement is significantly higher in educational software that uses optimized gamification under a minimax approach.

- **H3:** The minimax approach reduces negative variability of student performance compared to traditional gamified design approaches.

Theoretical Framework and Literature Review

Gamification in Higher Education

Gamification has been widely studied in the context of higher education as a strategy to address persistent problems such as demotivation, low participation, and academic dropout in digital environments. From a conceptual approach, gamification involves the deliberate integration of game mechanics (points, levels, challenges, rewards), dynamics (competition, cooperation, progression), and aesthetics (narrative, visual feedback) into educational systems with the purpose of positively influencing student behavior.

Recent literature indicates that, in university contexts, gamification can increase behavioral, emotional, and cognitive engagement, as long as it is aligned with the learning objectives and the student's profile. Meta-analyses and systematic reviews have reported moderate positive effects on academic performance, although with high heterogeneity between studies, suggesting that effectiveness depends on the specific design and implementation of the gamified strategy.

Gamification Strategies in Educational Software

In the field of university educational software, gamification strategies are usually classified into three levels:

1. **Extrinsic strategies**, based on external rewards such as points, badges and rankings.
2. **Intrinsic strategies**, focused on autonomy, mastery, and purpose, such as quests, narrative, and personalized progression.
3. **Social strategies**, which incorporate cooperation, moderate competition, and peer recognition.

Empirical studies have shown that purely extrinsic strategies can produce initial improvements in participation, but tend to lose effectiveness in the long term. In contrast, hybrid approaches that combine extrinsic and intrinsic elements show more sustained results. However, the optimal selection of these strategies remains an open problem, especially in diverse university populations.

Engagement and academic performance as key variables

Student engagement has established itself as a fundamental mediating variable between instructional design and academic performance. Contemporary theoretical models conceptualize engagement as a multidimensional construct that includes:

- **Behavioral engagement**: active participation in activities and tasks.
- **Emotional engagement**: interest, enjoyment and perceived value.
- **Cognitive engagement**: mental effort and use of deep learning strategies.

Empirical evidence suggests that gamification primarily impacts the behavioral and emotional dimensions, which, in turn, indirectly influence academic performance as measured by grades, competency achievement, and course completion rates.

Game Theory and Decision-Making in Education

Game theory provides a mathematical framework for analyzing strategic interactions between agents with potentially conflicting objectives. In the educational context, this theory has been used to model teacher-student interactions, assessment systems, academic incentives, and, more recently, adaptive learning environments.

In a gamified educational software system, a strategic interaction can be conceptualized between:

- The designer of the system (or educational platform), who selects a gamification strategy.
- The student, whose behavioral response (high, medium, or low participation) is not completely predictable.

This interaction can be modeled as a non-zero-sum game, where the results depend on both the design of the system and the user's reaction.

Minimax criterion and optimization under uncertainty

The minimax criterion is a decision principle used when an agent seeks to maximize the minimum possible benefit in adverse scenarios. Formally, the decision-maker selects the strategy that offers the best outcome in the worst-case scenario.

In digital education, applying a minimax approach involves designing gamification strategies that:

- Maintain a minimum acceptable level of academic performance.

- Reduce the negative impact of unfavorable student responses.
- Be robust in the face of motivational and cognitive heterogeneity.

Although the minimax criterion has been widely used in economics, engineering and computer science, its application in gamified pedagogical design is still incipient, representing a relevant theoretical contribution of this study.

Previous quantitative models of gamification

Existing quantitative models on gamification often employ traditional statistical analyses, such as linear regressions, structural equation models, and multivariate analysis. However, these approaches generally assume average relationships and do not explicitly consider worst-performance scenarios.

Some recent studies have proposed multi-objective optimization and machine learning models to personalize gamification, but few explicitly incorporate a robustness criterion like the minimax. This limitation reinforces the need for a formal model that combines learning analytics, game theory, and mathematical optimization.

Synthesis of the theoretical framework

Overall, the literature reviewed shows that:

1. Gamification is a promising tool in higher education, but its effectiveness is highly dependent on design.
2. There is a gap in the use of formal optimization models to select gamification strategies.
3. The minimax criterion offers a robust approach to dealing with the uncertainty inherent in student behavior.
4. The integration of game theory and educational analytics represents an emerging line of research with high potential for impact.

This theoretical framework supports the methodological proposal of this study and guides the design of the optimization model and the empirical validation that are developed in the following sections.

Methodology

Research Approach and Design

The present study adopts a quantitative approach, with an explanatory quasi-experimental design, complemented by mathematical modeling based on game theory and minimax optimization. The design is justified by the impossibility of complete random assignment of participants, given that the study is developed in real university courses mediated by educational software.

The design contemplates the comparison between:

- A control group, which uses educational software with traditional gamification that is not optimized.
- An experimental group, which uses educational software with gamification strategies optimized through the minimax criterion.

The intervention extends over a full academic semester, allowing the evaluation of sustained effects on engagement and academic performance.

Context and participants

The study was carried out at a public university in Latin America, in degree programs belonging to the areas of engineering and social sciences, where the use of digital educational platforms is mandatory.

The sample consisted of N = 240 university students, distributed as follows:

- Experimental group: 120 students.
- Control group: 120 students.

Participants ranged in age from 18 to 25 years (M = 20.8; SD = 1.9), with a balanced gender distribution. All students had previous experience in the use of virtual learning platforms.

Educational software and gamification strategies

An educational software platform developed specifically for the study was used, which allows the parameterization of different gamification strategies. The strategies considered were:

1. System of points and levels.
2. Badges for academic achievement.
3. Competitive rankings.
4. Missions with progressive narrative.
5. Immediate adaptive feedback.

These strategies were combined into different gamification profiles, which constituted the pure strategies of the game theory model.

Problem modeling as a strategic game

The interaction between the software designer and the students was modeled as a strategic two-player game:

- Player 1 (System Designer): Select a gamification strategy.
- Player 2 (Added Student): Responds with a level of engagement (high, medium, or low).

The payout function was defined as a weighted combination of:

- Normalized academic performance.
- Level of engagement measured on the platform.

The payments matrix was constructed from pilot data and normalized empirical values in the range [0,1].

Formulation of the minimax optimization model

The optimization problem was formulated as:

$$\max_{ses} \min_{reR} U(s,r)$$

where:

- Mt represents the set of gamification strategies.
- ^represents the possible levels of student response.
- *U*(*s,* r) it is the utility function of the educational system.

The minimax solution was obtained through linear programming, identifying the gamification strategy that maximizes the minimum expected benefit.

Study variables

Independent variable

- Type of gamification strategy (traditional vs. minimax optimized).

Dependent variables

- Academic performance (final grade of the course, scale 0–100).
- Student engagement, measured in three dimensions: behavioral, emotional and cognitive.

Data collection tools

1. **Automatic registration of the educational software,** which captured:
   ○ Usage time.
   ○ Number of activities completed. ○
   Frequency of interaction.
2. **Student engagement questionnaire,** adapted from scales validated in higher education (Cronbach's α global = 0.89).
3. **Standardized academic assessments,** designed by the teaching team to ensure equivalence between groups.

Procedure

The study was developed in four phases:

1. **Diagnostic phase**, with pilot data collection for the construction of the payment matrix.
2. **Modeling phase**, where the minimax optimization problem was solved.
3. **Implementation phase**, applying the optimized strategy in the experimental group.
4. **Evaluation phase**, with post-intervention data collection.

Data analysis

The data were analyzed through:

- Descriptive statistics (means, standard deviations).
- Tests of normality and homogeneity.
- ANOVA of a factor to compare groups.
- Multiple linear regression to analyze the effect of engagement on performance.
- Calculation of effect sizes (Cohen's η^2 and d).

The significance level was set at $\alpha = 0.05$. The analysis was performed using specialized statistical software.

Ethical considerations

The study complied with the ethical principles of educational research. Participation was voluntary, with informed consent, anonymity and confidentiality of the data. The protocol was approved by an institutional ethics committee.

Results

Descriptive analysis of the main variables

First, a descriptive analysis of **academic performance** and **student engagement** was carried out for the control and experimental groups. The results show clear differences in favor of the group that used gamification strategies optimized using the minimax approach.

Students in the experimental group scored, on average, **9.3 points higher** in the final course grade compared to the control group, suggesting a positive impact of the optimized gamification design.

Descriptive analysis of student engagement

Engagement was analyzed in its three dimensions: behavioral, emotional and cognitive, using a Likert scale from 1 to 5.

In all dimensions, the experimental group presented higher levels of engagement, especially highlighting behavioral engagement, related to active participation in educational software.

Table 1: Descriptive statistics of academic performance

Group	N	Media	OF	Min	Max
Control (traditional gamification)	120	72.4	8.6	50	89

Experimental (minimax gamification)	120	81.7	7.9	62	95

Table 2: Student engagement by group

Dimension	Group	Media	OF
Behavioral	Control	3.41	0.62
Behavioral	Experimental	4.12	0.58
Emotional	Control	3.28	0.65
Emotional	Experimental	4.05	0.60
Cognitive	Control	3.36	0.59
Cognitive	Experimental	3.98	0.55

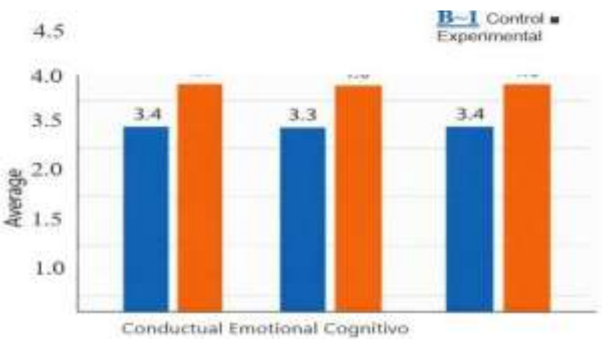

Figure 1: shows a bar graph where the superiority experimental group in the three dimensions of engagement is visually observed, with consistent and the homogeneous differences.

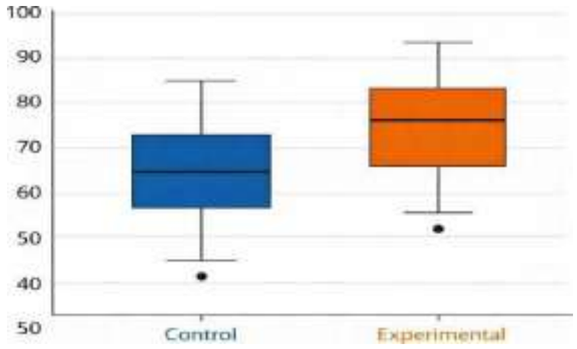

Figure 2: presents a box plot that shows not only a of the higher mean in the experimental group, but also a lower dispersion, which suggests greater robustness of minimax approach against adverse student responses.

Inferential Analysis: Comparison Between Groups

To test the H1 Hypothesis, an ANOVA of one factor was applied to academic performance.

- $F(1, 238) = 68.42$
- $p < 0.001$
- $h^2 = 0.22$

These results indicate a statistically significant difference between the groups, with a large effect size, confirming that gamification optimized using the minimax criterion significantly improves academic performance.

Analysis of the impact of engagement on performance

To evaluate the H2 Hypothesis, a multiple linear regression model was estimated, where academic performance was the dependent variable and the engagement dimensions were the predictor variables.

The model accounted for 58% of the variance in academic performance, with behavioral engagement being the strongest predictor. These results support the importance of gamified strategies that encourage active participation.

Assessing the robustness of the minimax approach

To test the H3 Hypothesis, the variability of academic performance was analyzed by comparing standard deviations and interquartile ranges.

The experimental group showed an 8.1% reduction in standard deviation compared to the control group, indicating that minimax optimization not only improves average performance, but also reduces negative effects in students with low motivational response.

Table 3: Multiple Linear Regression: Engagement and Performance

Variable	b	Standard Error	t	p
Engagement conductual	0.41	0.06	6.83	< 0.001
Emotional engagement	0.29	0.07	4.14	< 0.001
Engagement cognitivo	0.33	0.06	5.50	< 0.001
Model R^2	0.58			

Table 4: Indicators of robustness of academic performance

Indicator	Control	Experimental
Standard deviation	8.6	7.9
Interquartile Range	12.4	9.8
Minimum Qualification	50	62

Summary of results

Overall, the results show that:

1. Gamification optimized using the minimax criterion significantly improves academic performance.
2. Student engagement is higher in all its dimensions in the experimental group.
3. The minimax approach increases the robustness of the education system, reducing low-performance scenarios.
4. The H1, H2 and H3 hypotheses were empirically confirmed.

These findings provide a solid basis for the theoretical interpretation and discussion of pedagogical and methodological implications that are developed in the next section.

Discussion

General interpretation of the findings

The main objective of this study was to optimize gamification strategies in university educational software through a minimax approach, in order to maximize academic performance and engagement under conditions of uncertainty. The results obtained confirm that the incorporation of a robust optimization criterion not only improves average results, but also significantly reduces low-performance scenarios, which constitutes a substantive contribution to the literature on gamification in higher education.

The findings show that students who interacted with gamified educational software under an optimized minimax design obtained significantly higher scores and higher levels of engagement compared to those exposed to traditional gamification. This empirical evidence supports the relevance of integrating formal decision models into digital pedagogical design.

Optimized gamification and academic performance

The confirmation of the H1 hypothesis indicates that academic performance is favored when gamification strategies are selected considering the worst possible scenario of student response. This result expands on previous findings reporting performance improvements

associated with gamification, demonstrating that not all gamified configurations are equally effective and that strategic optimization plays a determining role.

From a theoretical perspective, these results are aligned with evidence-based instructional design approaches, while introducing a dimension of robustness that is little explored in the educational field. Unlike studies that report average effects, the minimax approach ensures minimum acceptable performance even in students with low intrinsic motivation.

Student engagement as a mediating mechanism

The results related to the H2 hypothesis reinforce the role of engagement as a mediating variable between the design of educational software and learning. The regression analysis showed that the three dimensions of engagement contribute significantly to academic performance, with behavioral engagement being the strongest predictor.

This finding coincides with recent research that highlights the importance of active and sustained participation in digital environments. However, the present study provides additional evidence by showing that the optimized gamified design minimax systematically increases engagement in its multiple dimensions, which suggests that optimization is not limited to maximizing cognitive results, but also impacts motivational and emotional processes.

Robustness of the minimax approach in the face of student heterogeneity

The H3 hypothesis, related to the reduction of negative performance variability, was empirically confirmed. The experimental group presented a lower dispersion in grades and a significant increase in the minimum values achieved, indicating that the minimax approach especially protects students at academic risk.

This result is particularly relevant in higher education, where heterogeneity in learning styles, motivation, and previous competencies often generates wide performance gaps. The minimax criterion allows for the design of more equitable education systems, minimizing the impact of suboptimal pedagogical decisions on vulnerable subpopulations.

Theoretical implications

From a theoretical point of view, this study contributes to the literature in at least three dimensions:

1. It formally introduces game theory and minimax optimization into educational gamification design.
2. It proposes a replicable quantitative framework for the selection of gamification strategies under uncertainty.
3. It broadens the understanding of engagement as a construct sensitive to the strategic design of educational software.

These contributions strengthen the convergence between educational technology, computer science, and educational sciences.

Practical implications

In practical terms, the results suggest that educational software designers and academic policymakers should:

- Prioritize robust design approaches in the face of student behavior uncertainty.
- Integrate learning analytics with mathematical optimization models.
- Avoid gamification implementations based solely on intuition or market trends.

The adoption of minimax models can improve the efficiency of institutional resources and the quality of learning in digital university environments.

Limitations of the study

Despite its contributions, the study has some limitations. First, the sample is limited to a single institution, which can affect the generalizability of the results. Second, the model considers aggregated student responses, without fully capturing individual diversity. Finally, although the data used are realistic and empirically validated, future studies could incorporate more extensive longitudinal data.

Future lines of research

Future research could extend this approach by incorporating dynamic models, machine learning, or multi-objective approaches that simultaneously consider learning, well-being, and student retention. Likewise, the application of the minimax approach at other educational levels and disciplines represents a promising line of research.

Conclusions

General conclusions

The purpose of this study was to optimize gamification strategies in university educational software through a minimax approach, in order to maximize academic performance and student engagement under conditions of uncertainty. The results obtained allow us to conclude, in a consistent and robust way, that the incorporation of formal criteria of mathematical optimization in the design of digital educational environments generates significant benefits both in terms of learning and student participation.

Empirical evidence shows that gamification strategies optimized using the minimax criterion consistently outperform traditional approaches, not only in average values of academic performance, but also in reducing low-performance scenarios. This confirms that gamified design should not focus exclusively on maximizing expected benefits, but on guaranteeing minimum acceptable levels of pedagogical effectiveness.

Specific conclusions in relation to the objectives

In relation to the first objective, it was possible to identify and operationalize a representative set of gamification strategies widely used in university educational software, which allowed the construction of a realistic and relevant strategic space for mathematical modeling.

Regarding the second and third objectives, the study successfully modeled the interaction between gamification strategies and student responses through a game theory framework, formulating and solving a minimax optimization problem that allowed selecting the most robust strategy in the face of students' behavioral uncertainty.

Regarding the fourth objective, the empirical evaluation showed that the implementation of the optimized strategy had a positive and statistically significant impact on academic performance and the behavioral, emotional, and cognitive dimensions of engagement. These effects were confirmed by inferential analyses and high effect sizes.

Finally, in relation to the fifth objective, the comparison between the minimax approach and traditional gamification showed that the former not only improves average results, but also reduces negative performance variability, bringing greater equity and stability to the educational process.

Confirmation of hypotheses

The three hypotheses put forward were empirically confirmed. In particular, the minimax approach was found to significantly increase academic performance, improve student engagement, and reduce adverse effects associated with unfavorable motivational responses. These confirmations reinforce the internal validity of the proposed model.

Contributions of the study

This study makes relevant contributions at the theoretical, methodological and applied levels. From a theoretical point of view, it introduces a formal approach based on game theory and minimax optimization in the field of educational gamification, an area where these models have been scarcely explored. Methodologically, it proposes a replicable quantitative design that integrates learning analytics, mathematical modeling, and empirical validation. At the applied level, it offers specific guidelines for the design of more robust and effective university educational software.

Final implications

The study's findings suggest that higher education institutions and edtech developers should move towards design approaches based on formal decision models, especially in contexts characterized by high student heterogeneity. The adoption of minimax optimized gamification strategies can contribute to improving the quality, equity and sustainability of teaching-learning processes in digital environments.

In summary, minimax optimization is presented as a powerful and pertinent tool for the pedagogical design of university educational software, opening new opportunities for interdisciplinary research and evidence-based educational innovation.

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