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EMBEDDING SUSTAINABILITY CONSTRAINTS INTO UNDERGRADUATE INVENTORY CONTROL INSTRUCTION

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ABSTRACT

Saudi Arabia's Vision 2030 emphasizes sustainable economic diversification and responsible resource management, positioning sustainability as a key priority in higher education reform. However, research in Saudi higher education has largely focused on policy alignment and sustainability awareness, with limited empirical attention to structurally embedding sustainability within specific quantitative business models. In quantitative courses, optimization tools such as the Economic Order Quantity (EOQ) model are typically taught under purely financial objectives, while environmental considerations remain contextual rather than structural. This study addresses this gap by integrating sustainability-related cost parameters directly into the EOQ model and examining their instructional impact within an undergraduate Quantitative Business Analysis course. Using a within-subject quasi-experimental design, 46 students solved both classical and sustainability-integrated EOQ problems. Two outcomes were assessed: computational accuracy and trade-off reasoning. Paired-samples t-test results, with Bonferroni correction ($\alpha = 0.025$), indicated no statistically significant difference in computational accuracy between the two conditions, while a statistically significant improvement was observed in trade-off reasoning for sustainability-integrated problems. These findings suggest that embedding sustainability within model parameters enhances students' conceptual understanding of optimization trade-offs without increasing computational difficulty. The study contributes to sustainability integration in business education by demonstrating that structural reformulation of quantitative models can improve analytical reasoning while preserving procedural performance.

KEYWORDS: Education for Sustainable Development – Inventory Control Model - Mathematics Education - Quantitative Business Analysis.

1. INTRODUCTION

Education for Sustainable Development (ESD) has become a central priority in higher education under the United Nations Sustainable Development Goals (SDGs). UNESCO emphasizes that sustainability should be embedded across disciplines rather than treated as an isolated theme, promoting an integrated approach in which sustainability principles shape both knowledge and decision-making processes within academic programs [1]. Accordingly, universities are increasingly expected to redesign curricula so that sustainability is not only taught conceptually but also operationalized within disciplinary practices [2]. This shift reflects a broader recognition that addressing global sustainability challenges requires graduates who can apply sustainability principles within domain-specific analytical frameworks.

In business education, this expectation extends beyond standalone ethics or sustainability courses toward integration within core quantitative subjects. Rather than confining sustainability to separate modules, scholars have argued for embedding sustainability within quantitative business instruction to better align analytical tools with responsible decision-making [3]. Recent research further reinforces this direction, suggesting that integrating sustainability into core analytical and managerial coursework is essential for preparing students to develop sustainable business strategies and support data-driven transformation [4]. However, despite these advances, existing approaches have largely relied on contextual or case-based integration, where sustainability is introduced through narrative scenarios rather than embedded within the mathematical structure of the models themselves. As a result, sustainability often remains outermost to the analytical logic that governs decision-making.

Mathematics plays a central role in shaping economic and operational decisions. Quantitative models determine how resources are allocated, costs are minimized, and trade-offs are evaluated [5]. Within modelling competency frameworks, emphasis is placed on interpreting results, evaluating assumptions, and relating mathematical outputs to real-world contexts [6]. In this regard, the structure of a model—its variables, parameters, and objective function—plays a critical role in shaping both analytical outcomes and their interpretation. When sustainability considerations are absent from these structural components, optimization processes remain confined to purely financial objectives, limiting the extent to which students engage with broader decision-making implications. Meaningful integration of ESD in quantitative education therefore requires structural reformulation of models rather than contextual framing alone.

Operations research literature provides clear examples of such structural reformulation in professional contexts. The classical Economic Order Quantity (EOQ) model has been extended into multi-objective frameworks that incorporate environmental and social criteria, thereby shifting the nature of optimization problems [7]. Similarly, sustainability-oriented inventory models have integrated environmental cost components directly into cost structures, demonstrating that internalizing environmental impacts leads to different optimal decisions and trade-offs [8]. In a related direction, stochastic inventory models introduce demand variability to better reflect real-world uncertainty, resulting in modified cost behaviors and decision outcomes [9]. Collectively, these studies highlight a fundamental principle: sustainability becomes analytically meaningful only when embedded within the structure of the model rather than treated as an external consideration.

Within the Saudi context, Vision 2030 emphasizes sustainable economic diversification and responsible resource management, positioning sustainability as a key priority in higher education reform [10]– [12]. Despite this national emphasis, research in Saudi higher education has largely focused on policy alignment, institutional strategies, and sustainability awareness [13]– [15]. While there have been calls for curriculum alignment with sustainability priorities [2], [16], limited empirical attention has been given to how sustainability can be structurally embedded within specific quantitative business models at the undergraduate level. This indicates a gap between strategic policy objectives and discipline-specific instructional practices.

Inventory control, particularly the EOQ model, represents a foundational topic in Quantitative Business Analysis (QBA) courses. The classical EOQ model determines the optimal order quantity that balances ordering and holding costs:

$$EOQ = \sqrt{\frac{2DC_o}{C_h}}$$

where (D) represents annual demand, (C_o) ordering cost, and (C_h) holding cost. In its traditional formulation, the model assumes purely financial objectives and excludes environmental impacts such as carbon emissions from storage or waste disposal costs. Although sustainability considerations may be introduced through contextual examples, they are

rarely incorporated into the model's parameters. Consequently, environmental factors remain secondary to the optimization logic, and students are not required to analytically engage with sustainability-related trade-offs.

Despite advances in sustainable inventory modelling within operations research and increasing calls to embed sustainability in business curricula, it remains unclear whether structurally integrating sustainability parameters into EOQ instruction influences students' analytical performance. Limited empirical evidence exists on whether such reformulation affects students' computational accuracy or enhances their understanding of optimization trade-offs between financial and environmental objectives. This gap is especially pronounced in the Saudi higher education context, where empirical studies examining discipline-specific instructional interventions remain scarce.

Accordingly, this study integrates sustainability-related cost parameters directly into the EOQ model and empirically examines their instructional impact within undergraduate quantitative business education. By comparing students' performance on classical and sustainability-integrated EOQ problems, the study aims to provide evidence on how structural model reformulation influences both procedural accuracy and trade-off reasoning. In doing so, it contributes to the literature by bridging operations research modelling with business education and by advancing sustainability integration from policy discourse toward analytically grounded instructional practice.

2. OBJECTIVES AND METHODOLOGY

This study aims to redesign traditional EOQ instruction by structurally embedding sustainability-related holding cost components within the model's parameters and to empirically evaluate whether this reformulation influences undergraduate students' analytical performance. Accordingly, the study addresses the following research questions:

RQ1: How can traditional EOQ problems be systematically redesigned to embed sustainability-related holding costs within undergraduate instruction?

RQ2: To what extent does the inclusion of sustainability parameters influence students' computational accuracy and their understanding of optimization trade-offs between financial and environmental costs?

To empirically address these research questions, a set of hypotheses was formulated to enable statistical testing of differences between classical and sustainability-integrated EOQ conditions. These hypotheses focus on evaluating both procedural performance (computational accuracy) and higher-order analytical performance (trade-off reasoning).

H1: Computational Accuracy

$H0_1$ (Null Hypothesis):

There is no statistically significant difference in students' computational accuracy between classical EOQ problems and sustainability-integrated EOQ problems.

$H1_1$ (Alternative Hypothesis):

There is a statistically significant difference in students' computational accuracy between classical EOQ problems and sustainability-integrated EOQ problems.

H2: Trade-Off Reasoning

$H0_2$ (Null Hypothesis):

There is no statistically significant difference in students' trade-off reasoning scores between classical EOQ problems and sustainability-integrated EOQ problems.

$H1_2$ (Alternative Hypothesis):

Students demonstrate significantly higher trade-off reasoning scores when solving sustainability-integrated EOQ problems compared to classical EOQ problems.

3. RESEARCH DESIGN

A within-subject quasi-experimental design was adopted. The same group of participants solved both classical EOQ problems and sustainability-integrated EOQ problems. By holding participant characteristics constant, this design reduces variability attributable to differences in mathematical ability and increases statistical power. The instructional intervention involved redefining the traditional holding-cost parameter to incorporate sustainability-related components—such as carbon-related storage costs and waste-management costs—which can collectively be referred to as environmental cost. This modification changes the optimization structure conceptually, while preserving mathematical equivalence in the overall problem formulation.

Table 1: EOQ Model Reformulation

Component	Classical EOQ	Sustainability-Integrated EOQ
Holding Cost	C_h	$C_h + C_e$
Objective	Minimize cost	Minimize cost + environmental impact
Structure	Economic only	Economic + environmental

4. PARTICIPANTS AND INSTRUMENT

The study was conducted with undergraduate students at a private university in Jeddah, Saudi Arabia, who completed a Quantitative Business Analysis course. All participants had previously been introduced to the classical EOQ model prior to the intervention.

The assessment instrument consisted of two parallel sections: (1) classical EOQ problems and (2) sustainability-integrated EOQ problems. Both sections contained the same number of items, identical total weight, and equal maximum scores to ensure statistical comparability. Two outcome measures were collected: computational accuracy of EOQ calculations and a rubric-based trade-off reasoning score assessing students' interpretation of financial and environmental cost implications.

Content validity of the research instrument was assessed using the Content Validity Ratio (CVR) proposed by [17]. A panel of six experts in mathematics education, supply chain management, and sustainability evaluated the relevance of the test items. All experts rated the items as essential, resulting in a CVR value of 1.00, which exceeds the minimum acceptable threshold for six experts. Experts also evaluated alignment with course learning objectives, structural equivalence between classical and sustainability-integrated items, clarity of wording, and appropriateness of sustainability parameter integration. Revisions were implemented based on feedback to ensure parallelism and instructional relevance.

Instrument reliability was assessed using Cronbach's alpha based on pilot responses (n = 23). The reliability coefficients were $\alpha = 0.74$ for Section A and $\alpha = 0.76$ for Section B, indicating acceptable internal consistency [18]. Inter-rater reliability for the open-ended reasoning items was evaluated using Cohen's kappa, yielding $\kappa = 0.48$ for the Q2-B/Q5-B pair and $\kappa = 0.40$ for the Q3-B/Q6-B pair, indicating moderate agreement between raters [19]. These results suggest that the instrument demonstrates satisfactory reliability for use in the study.

Table 2: Reliability and Validity Results

Measure	Value	Interpretation
Cronbach's α (A)	0.734	Acceptable
Cronbach's α (B)	0.781	Acceptable
CVR	1.00	Excellent
Cohen's κ	0.40–0.48	Moderate agreement

5. RESULTS AND DISCUSSION

To examine the impact of sustainability integration on students' performance, paired-samples t-tests were conducted for both computation accuracy and trade-off reasoning. Since two comparisons were performed, the Bonferroni correction was applied to control for Type I error, resulting in a corrected significance level of $\alpha = 0.025$ (0.05/2) [20].

A. Computational Accuracy

A paired-samples t-test indicated no statistically significant difference in computational accuracy between classical EOQ problems (M = 9.04, Var = 4.35) and sustainability-integrated EOQ problems (M = 9.07, Var = 4.68), $t(45) = -0.21$, $p = 0.837$. As the p-value exceeds the Bonferroni-adjusted threshold ($\alpha = 0.025$), the null hypothesis ($H0_1$) cannot be rejected.

Table 3: Computational Accuracy Results

Condition	Mean	Variance	n
Classical	9.04	4.35	46
Sustainability	9.07	4.68	46

The absence of significant differences indicates that embedding sustainability-related cost parameters does not affect students' ability to perform EOQ calculations. This can be explained by the structural nature of the EOQ model, where sustainability integration was implemented through modification of the holding cost parameter without altering the mathematical procedure required to compute the optimal order quantity. As a result, the computational steps remained identical across both conditions.

This finding is consistent with operations research literature demonstrating that model extensions can modify decision outcomes without necessarily changing the underlying solution procedure. For example, sustainability-oriented EOQ models incorporate environmental cost components within existing cost structures while preserving the analytical form of the model [7], [8]. Similarly, stochastic inventory models introduce demand variability to better reflect real-world uncertainty, influencing cost behavior without fundamentally altering solution procedures [9].

From an educational perspective, these results

suggest that sustainability can be embedded within quantitative instruction without increasing procedural complexity. This supports prior arguments that sustainability integration in business education should not displace core analytical content but can be incorporated within existing frameworks [3]. This finding aligns with broader trends in business education, where sustainability integration is increasingly recognized as essential for preparing students to navigate complex, real-world decision environments that involve multiple stakeholders and competing objectives [4].

B. Trade-Off Reasoning

A paired samples test revealed a statistically significant difference in trade-off reasoning scores between the classical (M = 2.91, Var = 0.75) and sustainability-integrated conditions (M = 3.02, Var = 0.73), $t(45) = -2.34$, $p = 0.0236$. Since the p-value is below the Bonferroni-adjusted significance level ($p < 0.025$), the null hypothesis ($H0_2$) is rejected.

Although the magnitude of the difference is modest, the results indicate that students demonstrated significantly improved trade-off reasoning when solving sustainability-integrated EOQ problems. This suggests that embedding environmental cost components within the holding cost parameter makes the trade-offs inherent in the model more explicit, thereby enhancing students' conceptual understanding of optimization.

Table 4: Trade-Off Reasoning Results

Condition	Mean	Variance	n
Classical	2.91	0.75	46
Sustainability	3.02	0.73	46

This finding can be interpreted through modelling competency theory, which emphasizes that modelling involves interpreting results, evaluating assumptions, and relating mathematical outputs to real-world contexts [6]. By incorporating environmental cost components into the holding cost, the sustainability-integrated model required students to interpret how these changes affect decision outcomes and to evaluate trade-offs between economic and environmental considerations.

In operations research, modifications to model structure are known to influence analytical outcomes and decision interpretation. For example, stochastic inventory models that incorporate demand variability alter cost behavior and provide a more realistic representation of decision environments [9]. Similarly, embedding sustainability-related cost parameters in EOQ models represents a structural reformulation that leads to different optimization outcomes. While prior research has primarily examined these effects in professional contexts [7], [8], the present study demonstrates that such structural changes also have pedagogical value by enhancing students' reasoning about trade-offs.

From an educational perspective, these findings support arguments in ESD literature that sustainability integration should influence decision-making processes rather than remain a contextual addition [1]. Unlike contextualized word problems, which may increase engagement without altering analytical structure, the sustainability-integrated EOQ problems in this study required students to engage directly with how model parameters shape optimization outcomes.

Taken together, the findings indicate that sustainability integration operates differently across learning outcomes. While computational accuracy remains unaffected, trade-off reasoning improves significantly. This suggests that embedding sustainability within the structure of quantitative models enhances conceptual understanding without increasing computational burden.

These results contribute to literature by bridging a gap between operations research, modelling studies and business education research. While prior studies have demonstrated how sustainability can be embedded within optimization models [7], [8], [9], and others have advocated integrating sustainability into business curricula [3], limited empirical research has examined the instructional impact of such structural integration on student learning outcomes in quantitative business courses.

In the Saudi higher education context, where sustainability integration has largely focused on policy alignment and curriculum reform, these findings provide evidence that sustainability can be embedded at the model level within specific quantitative topics, producing measurable improvements in students' analytical reasoning. This highlights the importance of moving beyond general curriculum alignment toward discipline-specific instructional design that integrates sustainability into core analytical frameworks.

6. CONCLUSION

This study examined the instructional impact of embedding sustainability-related cost parameters within the EOQ model in undergraduate quantitative business education. The findings indicate that sustainability integration does not affect

computational accuracy, while it leads to a statistically significant improvement in trade-off reasoning, after applying a Bonferroni-adjusted significance level.

The results can be understood through modelling competency theory, which highlights that modelling involves not only performing calculations but also interpreting results, evaluating assumptions, and relating mathematical outputs to real-world contexts [6]. Embedding environmental cost components within the EOQ model required students to engage in these processes, thereby enhancing their ability to reason about optimization trade-offs. At the same time, operations research literature shows modifying model structures such as incorporating sustainability-related or stochastic parameters—alters cost behavior and decision interpretation without necessarily changing the underlying computational procedure [7], [8], [9]. This explains why computational performance remained stable while reasoning improved.

From an educational perspective, the findings support the integration of sustainability within core quantitative business courses rather than treating it as a separate or purely contextual topic. Unlike approaches that rely on case-based contextualization, this study demonstrates that embedding sustainability directly within model parameters enables students to engage with sustainability through analytical decision-making processes.

In the Saudi higher education context, where sustainability integration has largely focused on policy alignment and curriculum reform, this study provides empirical evidence that meaningful integration can be achieved at the disciplinary and model level. This highlights the importance of designing instructional approaches that embed sustainability within the core analytical structures of business education.

However, several limitations should be acknowledged. The study was conducted within a single institutional context, which may limit the generalizability of the findings. In addition, the observed improvement in trade-off reasoning, while statistically significant, is modest in magnitude, and the assessment focused on short-term performance within a controlled setting. Future research may extend this approach to other quantitative topics, such as linear programming, regression, and financial modelling, and examine its long-term impact on students' decision-making competencies in sustainability-oriented contexts.

DECLARATIONS

A. Ethics Approval and Consent to Participate

Ethical approval was obtained from the Institutional Review Board of the University of Business and Technology before data collection. Participants were informed about the study's purpose, their voluntary participation, and their right to withdraw at any time. Written informed consent was obtained from all participants. No identifying information was collected, and all data were stored securely in password protected files accessible only to the researcher. The study adhered to internationally recognized ethical standards for research involving human participants.

B. Consent to Publication

All participants provided written consent for their participation and for the publication of anonymized data generated from the study.

C. Data availability

The datasets generated or analyzed during the current study are not publicly available due to respondents' privacy but are available from the corresponding author on reasonable request.

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