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A Vertically Integrated Curriculum: Project-Based Learning in Operations Research for Bachelor-Master Continuum Programs

Ling Gai [1,*]

[1] Business School, University of Shanghai for Science and Technology, Shanghai, China
* Correspondence: Ling Gai, Business School, University of Shanghai for Science and Technology, Shanghai, China

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Abstract: This paper presents and evaluates a vertically integrated, project-based learning (PBL) curriculum design for an Operations Research (OR) course within a Bachelor-Master continuum program. Traditional segmented teaching often leads to disjointed knowledge and redundant learning between undergraduate and postgraduate stages. To address this, we developed a spiral curriculum framework grounded in constructivist and scaffolding theories. The framework employs a sequence of progressively complex, cross- semester projects designed to integrate core algorithmic learning, modeling practice, and frontier research exploration. Implemented in a five-year integrated program (in Information Management and Systems Engineering) at a research-oriented university, the course was assessed using a mixed- methods approach. Data from two cohorts of students (N = 58), including academic performance analysis, project artifact evaluation, surveys, and focus group interviews, were collected. Preliminary results indicate that the curriculum significantly enhances students' advanced modeling capabilities, independent research skills, and sense of academic community. Undergraduates were exposed to research thinking early on, while postgraduates deepened their understanding through mentoring roles. The paper discusses the implications of this moel for facilitating seamless academic transition and cultivating research-ready talent, alongside challenges in scaling implementation, such as faculty coordination and differentiated assessment. This study provides an actionable exemplar for curriculum re- form in STEM-integrated education.

Keywords: Vertically integrated curriculum; project-based learning (PBL); bachelor-master continuum programs; operations research; higher education reform; curriculum design

1. Introduction

In recent years, the global higher education system has increasingly emphasized accelerated and structured talent development, particularly for students with strong academic potential. Within this context, integrated Bachelor-Master continuum programs have gradually emerged as an effective institutional arrangement to shorten training cycles, improve educational efficiency, and enhance the continuity of academic development. These programs aim to provide outstanding undergraduates with earlier exposure to advanced coursework and research-oriented learning, thereby strengthening the cultivation of high-level innovative talent and improving the overall quality of postgraduate education [1]. However, the successful implementation of such integrated models does not merely rely on administrative coordination or admission mechanisms; it fundamentally depends on a systematic restructuring of curriculum design to break down the long-standing separation between undergraduate and postgraduate education stages.

Methodological core courses, such as Operations Research (OR), play a critical role in this restructuring process, yet they also face prominent challenges within integrated programs. At the undergraduate level, OR education typically emphasizes foundational concepts, classical algorithms, and standard mathematical modeling techniques, with teaching objectives centered on knowledge acquisition and problem-solving proficiency. In contrast, postgraduate OR study places greater emphasis on theoretical depth, model abstraction, computational complexity, and the analysis of complex systems, often within the context of research-driven inquiry [2]. When these two stages are designed independently, students may experience either discontinuities in knowledge progression or redundant repetition of content, which weakens learning efficiency and undermines the intended advantages of integrated training pathways.

Beyond issues of content alignment, traditional lecture-centered teaching approaches further constrain the effectiveness of OR education in integrated Bachelor-Master programs. Conventional pedagogy often positions students as passive recipients of predefined knowledge, which limits opportunities for active exploration, interdisciplinary integration, and methodological reflection. As a result, students may struggle to develop the higher-order competencies required for addressing open-ended, real-world problems or for engaging meaningfully in academic research activities. More importantly, such approaches provide insufficient support for the gradual transformation of student identity from undergraduate learners to novice researchers, a transition that is essential for postgraduate success and long-term academic development [3].

In response to these challenges, this study proposes a vertically integrated curriculum framework driven by Project-Based Learning (PBL) principles. By embedding progressively complex projects across undergraduate and postgraduate stages, the proposed design seeks to promote the continuous construction of OR knowledge while simultaneously cultivating research awareness, collaborative capacity, and independent problem-solving skills. The central research question guiding this study is as follows: How can an effective PBL-oriented curriculum be designed to support coherent knowledge progression in Operations Research and to foster the parallel development of academic research competence and teamwork ability within an integrated Bachelor-Master student cohort? To address this question, the paper systematically presents the underlying design principles, implementation structure, and preliminary evaluation of a specific curricular model. The findings aim to provide a practical and transferable framework for curriculum reform in Operations Research and related methodological disciplines within integrated higher education programs.

2. Literature Review and Theoretical Framework

2.1. Vertical Curriculum Integration in Engineering and STEM Education

Vertical curriculum integration refers to a systematic approach to curriculum design in which learning experiences across different academic stages are deliberately aligned to form a coherent and continuous educational trajectory [4]. Initially developed in professional education contexts, this approach has gradually been introduced into engineering and STEM education as institutions seek to reduce curricular fragmentation and enhance cumulative learning outcomes. Rather than treating undergraduate and postgraduate education as separate and sequential phases, vertical integration emphasizes progressive knowledge construction and skill development across levels.

Empirical studies in engineering education indicate that vertically integrated curricula can lead to measurable improvements in student learning. Comparative research conducted across multiple institutions has shown that students participating in vertically structured engineering programs demonstrate stronger conceptual understanding and more advanced problem-solving abilities than those following traditional segmented curricula [5]. In addition to cognitive outcomes, vertical integration has also been associated with improved student persistence and engagement, particularly when early exposure to advanced content and research-oriented activities is provided within a structured framework [6].

Effective implementation of vertical integration requires careful attention to learning progressions, defined as intentionally sequenced pathways through which students gradually acquire higher-order competencies based on solid foundational knowledge. Within this framework, introductory learning activities emphasize basic concepts and tools, while later stages focus on abstraction, synthesis, and independent inquiry. Research on vertically integrated programs highlights several recurring design principles, including the systematic scaffolding of complex skills, alignment between assessment and developmental stages, and sustained coordination among faculty teaching at different academic levels [7]. These principles are particularly relevant for methodological disciplines, where conceptual depth and application complexity increase significantly across educational stages.

2.2. Project-Based Learning in Higher Education

Project-Based Learning (PBL) represents a shift from traditional lecture-dominated instruction toward student-centered, inquiry-oriented learning experiences. In higher education, particularly within STEM disciplines, PBL has been widely adopted as a means to enhance students' ability to apply theoretical knowledge to complex, real-world problems. Through extended projects that require problem definition, data analysis, model development, and solution evaluation, PBL encourages active learning, collaboration, and reflective thinking.

A substantial body of empirical research supports the effectiveness of PBL in improving learning outcomes in higher education. Syntheses of large-scale studies have demonstrated that PBL approaches outperform conventional teaching methods in terms of long-term knowledge retention, practical skill application, and the development of professional attitudes and learning motivation [8]. Further evidence suggests that PBL is especially effective in fostering higher-order cognitive skills, such as analysis, synthesis, and evaluation, which are essential for advanced academic study and research-oriented learning [9].

In the context of Operations Research education, PBL offers distinct pedagogical advantages. Traditional OR courses often focus on algorithmic problem-solving within highly structured settings, which may limit students' ability to adapt methods to ill-defined or context-dependent problems. By contrast, PBL-oriented OR instruction situates mathematical modeling and optimization techniques within realistic decision-making scenarios, thereby enhancing students' modeling sophistication and their capacity to communicate technical results to diverse audiences [10]. These characteristics make PBL particularly suitable for supporting the transition from undergraduate learning to postgraduate research within integrated programs.

2.3. Theoretical Foundations: Constructivism and Scaffolding

The curriculum design proposed in this study is grounded in constructivist learning theory, which emphasizes that knowledge is actively constructed by learners through engagement with meaningful tasks and social interaction within authentic contexts. From this perspective, learning is not a passive process of information transmission but an active process of interpretation, negotiation, and refinement of understanding [11]. This theoretical orientation aligns closely with the objectives of integrated Bachelor-Master programs, which seek to cultivate independent thinking and research competence over time.

Scaffolding theory provides a practical mechanism for implementing constructivist principles in curriculum design. Scaffolding refers to the temporary support structures that enable learners to perform tasks beyond their current level of independent capability. As learners gain competence, these supports are gradually reduced, allowing greater autonomy and responsibility. In integrated programs, scaffolding can be operationalized through multiple instructional strategies, including staged project tasks, guided methodological training, peer collaboration across academic levels, and adaptive instructor feedback [11].

Recent theoretical work has extended traditional notions of scaffolding to include reciprocal forms of support, in which learning benefits are shared among participants at different stages of expertise. Within integrated Bachelor-Master cohorts, postgraduate students who mentor undergraduates often reinforce and deepen their own understanding of foundational concepts, while undergraduates benefit from exposure to advanced thinking and research practices [12]. This reciprocal dynamic enhances collective learning outcomes and contributes to the formation of a collaborative academic culture.

2.4. Learning Communities and Identity Formation in Integrated Programs

The establishment of stable and interactive learning communities is widely recognized as a key factor in the success of integrated educational programs. Learning communities provide structured environments in which students engage in shared academic practices, develop mutual support networks, and gradually assume more active roles within their disciplinary fields. Theoretical frameworks of community-based learning emphasize that participation evolves over time, with learners progressing from peripheral involvement toward more central and responsible forms of engagement [13].

Empirical evidence from STEM education suggests that participation in well-designed learning communities positively influences both academic persistence and long-term professional outcomes. Longitudinal studies have shown that students involved in cross-level learning communities demonstrate higher retention rates, stronger academic confidence, and improved transition outcomes after graduation [14]. For integrated Bachelor-Master programs, interactions between undergraduate and postgraduate students are particularly valuable, as they accelerate the development of research awareness and professional self-efficacy among less experienced learners.

Identity formation constitutes an essential but often underexamined dimension of continuum education. As students advance from undergraduate study to postgraduate research, they must reconstruct their self-perception from that of course learners to emerging researchers. Structured curricular experiences that integrate collaborative projects, research-oriented tasks, and reflective activities can support this identity transformation and enhance students' readiness for advanced academic work and future professional roles [15].

3. Research Design: The Curriculum Model and Implementation

3.1. Design Principles

The curriculum model was developed based on a set of coherent design principles aimed at supporting continuous learning progression and effective integration across undergraduate and postgraduate stages.

First, a spiral progression principle was adopted. Core Operations Research topics, including linear programming, network optimization, and stochastic modeling, were intentionally revisited across undergraduate and postgraduate phases. Each recurrence increased in conceptual depth, methodological complexity, and application context, allowing students to consolidate foundational knowledge while progressively engaging with advanced analytical challenges.

Second, project-driven coherence served as the structural backbone of the curriculum. Four core projects distributed across consecutive semesters were designed to integrate modular course content and to provide continuity across learning stages. Rather than treating projects as isolated assignments, each project built upon outcomes from previous stages, reinforcing cumulative knowledge construction.

Third, a cross-level learning community was deliberately established. Project teams were composed of both undergraduate and postgraduate students, creating structured opportunities for collaborative learning and the development of mentor-partner relationships. This arrangement enabled undergraduates to gain early exposure to advanced thinking while allowing postgraduates to strengthen their understanding through guided support and peer interaction.

Finally, authentic assessment was emphasized throughout the curriculum. Evaluation focused on project reports, computational models, oral presentations, and reflective process documentation. This approach shifted assessment away from reliance on single, time-limited examinations and toward a more comprehensive appraisal of students' analytical processes, problem-solving strategies, and collaborative engagement.

3.2. The "Three-Dimensional" Course Architecture

The curriculum was organized along three interrelated dimensions that together constituted an integrated instructional framework.

The first dimension was the knowledge dimension, represented as a vertical axis. Instruction progressed from deterministic optimization methods introduced at the undergraduate foundational level to stochastic and robust optimization techniques at the postgraduate advanced level, and further toward specialized frontier topics that intersect with data-driven modeling and intelligent optimization approaches at later stages.

The second dimension was the skill dimension, represented as a horizontal axis. Students initially focused on applying standard software tools, such as spreadsheet-based solvers and dedicated optimization packages, to address well-structured problems. This was followed by the development of programming skills for constructing customized models using general-purpose languages. At the postgraduate stage, emphasis shifted toward conducting structured literature reviews and refining or extending algorithms based on analytical insights.

The third dimension was the project dimension, which functioned as an integrative axis connecting knowledge and skills through practice. A sequence of four scaffolded projects was designed to align with students' academic progression and to operationalize the vertical integration of learning. As shown in Table 1, each project was associated with specific learning objectives, skill targets, and assessment criteria corresponding to its position within the integrated curriculum.

Table 1. Scaffolded Project Sequence in the Vertically Integrated Curriculum.

Project	Academic Stage	Learning Objectives	Key Skills Developed	Assessment Criteria
P1	Undergraduate (Semester 1)	Master fundamental Operations Research modeling techniques and solve classical problems using standard analytical tools	Problem formulation; Model construction accuracy; Software proficiency; Basic technical documentation	Model correctness (70%); Report clarity and structure (30%)
P2	Undergraduate (Semester 2)	Apply Operations Research methods to medium-scale real-world datasets and integrate data preprocessing with modeling	Data preprocessing; Data handling; Basic scripting skills (Python); Sensitivity analysis	Data handling accuracy (30%); Model robustness and sensitivity (40%); Analytical depth (30%)

P3	Postgraduate (Semester 1)	Investigate complex domain-specific problems and compare algorithms based on existing literature	Literature review; Algorithm implementation; Critical evaluation and comparison	Quality of literature synthesis (30%); Technical implementation (40%); Comparative analysis (30%)
P4	Postgraduate (Semester 2)	Conduct independent research and propose open-ended methodological innovations	Research design; Methodological innovation; Academic writing; Peer mentoring	Novelty of research contribution (30%); Methodological rigor (40%); Academic communication quality (30%)

Note: UG = Undergraduate, PG = Postgraduate, Sem = Semester.

3.3. Participants and Context

The study was conducted within a five-year integrated Bachelor-Master program in Information Management and Systems Engineering at a comprehensive university with a strong emphasis on applied research and engineering education. Participants included a total of 58 students drawn from two consecutive cohorts, consisting of 36 undergraduates and 22 postgraduates. The instructional team comprised three faculty members responsible for course coordination, project supervision, and assessment. The curriculum implementation spanned four consecutive semesters, corresponding to the full sequence of the integrated project structure.

3.4. Data Collection and Analysis

A mixed-methods research design was employed to evaluate the implementation and outcomes of the curriculum model. Quantitative data included student performance records for each project phase, as well as pre-course and post-course survey responses collected using a five-point Likert scale. The survey instrument measured students' interest in Operations Research, perceived self-efficacy, and intention to engage in research-oriented learning, and demonstrated satisfactory internal consistency reliability (Cronbach's $\alpha = 0.87$).

Qualitative data sources included textual analysis of 58 project reports, transcripts from four focus group interviews conducted separately with undergraduate and postgraduate participants, and reflective teaching journals maintained by the instructional team throughout the implementation period. Data triangulation was achieved through cross-comparison of quantitative and qualitative findings, enhancing the credibility and interpretive robustness of the analysis.

4. Results and Findings

4.1. Learning Outcomes and Performance Metrics

Academic performance data were collected from the integrated cohort (IC, N=58) and a matched control cohort (CC, N=60) following a traditional, segmented OR curriculum.

Analysis: Table 2 demonstrates statistically significant advantages for the integrated cohort. The higher average scores in both the core course and cap- stone project, with large effect sizes, suggest more robust grasp and application of OR principles. The notable difference in research output is a key indicator of the curriculum's success in fostering early research engagement.

Table 2. Comparative Analysis of Academic Performance.

Metric	Integrated Cohort (IC)	Control Cohort (CC)	Statistical Significance
Average final score in core Operations Research course	86.3 ± 5.2	81.7 ± 6.8	T (116) = 4.18, p < 0.001
Capstone project score	88.9 ± 4.1	84.1 ± 5.9	T (116) = 5.01, p < 0.001
Percentage of students publishing or submitting conference papers	34.5%	18.3%	χ^2 (1) = 4.51, p = 0.034
Self-reported skill growth (pre-post, 5-point scale)	+1.8 ± 0.7	+1.2 ± 0.9	T (116) = 3.95, p < 0.001

Note: $^{*}p < .05$, $^{**}p < .01$. Effect sizes: Cohen's d range 0.73-0.93 (large).

4.2. Student Experience and Perceptual Shifts

Post-course survey data from the integrated cohort (N=58) are summarized below.

Analysis: Survey results (Table 3) show overwhelmingly positive perceptions of the curriculum's core design features. The high agreement on project sequencing and cross-level teamwork validates the vertical integration and PBL framework. The differential response on research identity (PGs higher) reflects the targeted success of advanced projects in solidifying a researcher mindset.

Table 3. Student Perceptions of the Integrated PBL Curriculum (Survey Results).

Statement	UG Mean (SD)	PG Mean (SD)	Overall Mean (SD)
The sequenced projects helped me understand the connections between foundational and advanced topics.	4.6 (0.6)	4.4 (0.7)	4.5 (0.7)
Working in cross-level (undergraduate-postgraduate) teams was beneficial for my learning.	4.7 (0.5)	4.3 (0.8)	4.5 (0.7)
I developed a stronger identity as a researcher and problem solver.	3.9 (0.9)	4.5 (0.6)	4.2 (0.8)
The mentoring or being mentored role was effective.	4.5 (0.7)	4.2 (0.8)	4.4 (0.8)
The course workload was challenging but manageable.	3.8 (1.0)	4.0 (0.9)	3.9 (1.0)

Note: 5-point Likert scale (1=Strongly Disagree to 5=Strongly Agree). Percentage of students responding Agree/Strongly Agree ranged from 72% to 96% across items.

Qualitative data from focus groups revealed three central themes:

1. **Scaffolded Progression:** "Project 2 felt like a big jump, but because we had done Project 1, we knew the process. By Project 4, starting a problem from scratch felt natural." (PG Student)
2. **Community of Practice:** "The group wasn't just 'me and the postgrad.' We became a small lab. They explained papers, we double-checked their
3. code. It felt collaborative." (UG Student)
4. **Identity Transition:** "Having to explain the simplex algorithm to my UG teammate forced me to understand it at a deeper, more intuitive level than

I ever had for an exam." (PG Student)

4.3. Pedagogical Challenges and Mitigations

Implementation challenges and corresponding mitigation strategies are summarized in Table 4.

Table 4. Implementation Challenges and Mitigation Strategies.

Challenge	Mitigation Strategy
Heterogeneous student preparation within cohorts	Adaptive scaffolding through optional preparatory modules; Differentiated project rubrics with extension tasks for advanced learners
Coordinating cross-level team schedules	Structured project charter activities; Dedicated communication channels; Allocation of individual assessment weight through peer evaluation
Managing increased faculty workload	Team teaching with rotating instructional responsibilities; Support from graduate teaching assistants; Shared repositories of project materials
Assessing individual contribution in team-based projects	Individual reflective reports; Weighted peer evaluations; Analysis of code and document version histories
Balancing depth and breadth in an integrated curriculum	Modular curriculum design with core and elective components; Flexible learning pathways aligned with student interests
Ensuring continuity across semesters	Longitudinal project portfolios; Periodic progress reviews; Structured faculty handover meetings between semesters

Note: Challenges identified during implementation and corresponding strategies developed through iterative refinement.

5. Discussion

The triangulated findings provide consistent empirical support for the effectiveness of the proposed curriculum model. As shown in Table 2, students participating in the vertically integrated, project-based curriculum demonstrated statistically significant improvements in multiple performance indicators compared with those following a conventional instructional approach. These results indicate that aligning curriculum structure, pedagogy, and assessment across undergraduate and postgraduate stages can contribute to enhanced learning outcomes in Operations Research education.

Beyond performance metrics, the survey and interview data offer deeper insight into the mechanisms through which these outcomes were achieved. One prominent theme emerging from the qualitative analysis was the formation of a cross-level learning community. Students reported that learning was strongly supported through interaction within mixed undergraduate-postgraduate teams, where discussion, feedback, and collaborative problem solving played a central role. This finding reflects the curriculum's emphasis on learning as a socially mediated process, in which knowledge construction occurs through shared engagement with authentic tasks rather than through isolated individual study.

Another salient theme concerned the process of identity transition, particularly among postgraduate students. Many participants indicated that assuming a guiding or mentoring role within project teams prompted greater reflection on their own understanding and research practices. Acting as facilitators for less experienced peers appeared to strengthen postgraduates' confidence and clarity in problem formulation, methodological choice, and analytical reasoning. This observation suggests that the instructional design not only supported undergraduate learning but also reinforced postgraduate development by embedding teaching-related responsibilities within project activities.

The curriculum model also demonstrated effective operationalization of scaffolding principles. The structured sequence of projects, as outlined in Table 1, functioned as the primary instructional scaffold, providing clear expectations and progressively increasing levels of complexity. At the same time, postgraduate students served as peer-level supports for undergraduates during earlier stages. As students advanced to later projects, particularly Projects 3 and 4, the reduction of structured guidance and the increased emphasis on independent decision-making required learners to assume greater autonomy. This gradual withdrawal of support facilitated a transition from guided learning to more self-directed research-oriented engagement.

Despite these positive findings, several limitations should be acknowledged. The study was conducted within a single integrated program with a relatively limited number of participants, which may constrain the generalizability of the results. In addition, although comparative analyses were employed, pre-existing differences between cohorts could not be fully controlled. Future research could address these limitations through longitudinal designs that track academic trajectories, research engagement, and professional development outcomes over extended periods. Moreover, implementing the model at a larger scale would require further investigation into the use of digital platforms and coordination mechanisms to manage project-based learning and cross-level collaboration efficiently.

6. Conclusion

This study designed and empirically examined a vertically integrated, project-based curriculum model for Operations Research within a Bachelor-Master continuum program. By adopting a spiral project sequence as the structural backbone, the curriculum established a continuous, interactive, and progressively challenging learning environment across multiple academic stages. The integrated design enabled students to revisit core concepts with increasing depth while simultaneously developing analytical, technical, and collaborative competencies.

Quantitative analyses demonstrated that students participating in the integrated curriculum achieved higher academic performance and stronger engagement with research-oriented activities than those following traditional instructional pathways. Complementary qualitative evidence revealed that the curriculum supported the development of learning communities and facilitated gradual shifts in student identity from course-based learners toward emerging problem solvers and researchers through sustained cross-level collaboration.

The proposed framework addresses several key challenges commonly encountered in continuum education by:

(1) providing a concrete and operational model for vertical curriculum integration through scaffolded project-based learning;

(2) demonstrating measurable improvements in both technical proficiency and research-related capabilities; and

(3) offering practical strategies for managing implementation challenges associated with integrated and collaborative instructional designs.

For institutions seeking to enhance the coherence and effectiveness of Bachelor-Master programs, the findings suggest that investing in deeply integrated curricular models can meaningfully support long-term talent development. Given its modular structure and emphasis on transferable design principles, the proposed framework also shows potential applicability to other STEM disciplines that face similar challenges in bridging undergraduate and postgraduate education.

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Appendix A

Survey Instrument Sample Items: The pre- and post-course survey included 20 items on a 5-point Likert scale (1=Strongly Disagree to 5=Strongly Agree). Sample items:

1) I feel confident formulating a mathematical model for a real-world optimization problem.
2) I can effectively collaborate with students at different academic levels.
3) I see myself capable of conducting independent research in Operations Research.
4) The course projects helped me understand the connection between theory and practice.

Appendix B

Focus Group Interview Protocol: Semi-structured interviews (45-60 minutes) covered:

1) Experiences with cross-level collaboration
2) Perceptions of project sequencing and difficulty progression
3) Development of research identity and skills
4) Challenges and suggestions for improvement

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