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Supporting Self-Directed Learning and Research Interest through Project-Based Learning: A Pilot Study with an SDLR-Aligned Assessment Framework

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Abstract

This paper presents an evidence-based instructional study examining students' perceived project-based learning (PBL) elements and self-directed learning (SDL) outcomes to better understand the relationship between PBL, self-directed learning readiness (SDLR), and undergraduate research interest in a required senior-level mechanical control systems course. Implemented as a single-institution, exploratory pilot, the study employed a semester-long, three-phase PBL intervention in which students (N=43) engaged in mathematical modeling, MATLAB/Simulink simulation, iterative feedback, teamwork, and physical prototyping to extend learning beyond traditional lecture-based instruction.

A mixed-methods approach was used to examine student outcomes. Quantitative data were collected through a post-intervention survey incorporating constructs from Fisher's Self-Directed Learning Readiness Scale for Adults (SDLRS-A)—self-management, desire for learning, and self-control—along with measures of undergraduate research interest. Regression analysis revealed a statistically significant association between overall SDLR and research interest ($R^2 = 0.145$, $p = 0.026$). Qualitative thematic analysis of student reflections indicated that structured progress reporting, iterative feedback cycles, and hands-on simulation and prototyping were perceived as key mechanisms supporting engagement, persistence, confidence, and independent problem solving.

Beyond reporting associations, this study contributes a quantitative rubric framework that maps core PBL elements—problem definition, interdisciplinary integration, teamwork, and reflection—to measurable SDLR traits, enabling systematic evaluation and instructional alignment. While limited by its pilot design, the findings provide actionable evidence and practical assessment tools to inform PBL design, continuous improvement, and future multi-institutional studies aligned with ABET outcomes and undergraduate research preparation.

Keywords: Project-Based Learning, Self-Directed Learning Readiness, Engineering Education, Research Interest, Assessment Rubric, Controls & Simulation

1. Introduction

Rapid advances in artificial intelligence, robotics, automation, and control systems are reshaping both industrial practice and the skill sets expected of engineering graduates. Contemporary engineers are increasingly required to integrate mathematical modeling, coding, data analysis, and specialized software tools while adapting to evolving technologies and interdisciplinary contexts. However, traditional engineering curricula often struggle to keep pace with these demands, leaving limited room to cultivate the adaptive and self-regulatory skills needed for sustained professional growth[1].

This gap highlights the need for instructional approaches that not only convey technical content but also promote lifelong learning competencies.

Within this context, *Self-Directed Learning Readiness* (SDLR) has emerged as a critical educational outcome. SDLR reflects learners' capacity to plan, monitor, and regulate their own learning while maintaining motivation and persistence in complex tasks. Project-Based Learning (PBL) is widely recognized as a promising pedagogical approach for supporting SDLR, as it engages students in authentic, problem-centered activities that require autonomy, collaboration, and critical thinking[2,3]. However, prior research cautions that PBL does not automatically lead to improved SDLR; without appropriate structure and feedback, minimally guided environments may overwhelm learners and hinder self-regulatory development[4,5]. Consequently, there is a need to systematically examine how specific PBL components align with and support SDLR traits.

The importance of fostering SDLR has intensified as engineering programs have compressed degree requirements—often to a 120-credit model—despite expanding technical content and expectations. Accrediting bodies such as ABET now explicitly emphasize lifelong learning and adaptability as core student outcomes[6]. Empirical studies consistently link self-directed learning to academic success, critical thinking, and professional adaptability[7,8]. Moreover, SDL skills have been shown to support undergraduate research participation, career development, and interdisciplinary readiness, particularly for students from underrepresented or first-generation backgrounds who may face structural barriers to research engagement[9,10].

At its core, self-directed learning involves motivated inquiry, strategic use of diverse information sources, and reflective evaluation of progress[11,12]. These characteristics are not easily captured through traditional examinations alone, motivating the use of performance-based assessment strategies such as rubrics, reflections, and project artifacts[13]. In PBL environments, such tools enable more nuanced evaluation of how students manage complexity, persist through iteration, and integrate theory with practice. Undergraduate research and hands-on prototyping further strengthen these processes by situating learning in authentic engineering contexts.

Designing curricula that intentionally enhance SDLR therefore requires careful integration of several elements: meaningful learner choice, opportunities for reflection and revision, interdisciplinary problem contexts, and a shift in the instructor's role from content transmitter to mentor. Prior studies emphasize real-world relevance[14], interdisciplinary integration[15], collaborative learning[16], and iterative problem-solving cycles[17] as key features of effective PBL. When aligned with SDLR traits, these elements can promote learner autonomy, metacognitive awareness, and resilience.

Assessing SDLR in PBL settings necessitates instruments that capture its multidimensional nature. The Self-Directed Learning Readiness Scale (SDLRS)[18] and Fisher's SDLRS-A[19] are among the most widely used tools, with the latter emphasizing self-management, desire for learning, and self-control—dimensions well aligned with engineering project work. In particular, self-management supports planning and execution of modeling and prototyping tasks; learning desire drives deeper exploration of simulation and control concepts; and self-control underpins persistence during iterative design and troubleshooting.

The present study is an exploratory pilot conducted in a senior-level mechanical control systems course. It integrates semester-long, interdisciplinary projects that extend beyond traditional coursework to include Arduino programming, MATLAB/Simulink simulation, and hardware-in-the-loop experimentation. Rather than establishing causal relationships, the study aims to identify which PBL elements are most strongly associated with SDLR and undergraduate research interest, and to develop a rubric-based framework to support systematic instructional alignment. Using post-intervention survey data and student reflections, this work contributes actionable evidence to inform PBL design, continuous improvement, and future multi-institutional studies focused on equitable and sustainable engineering education. In addition to examining student outcomes, this work proposes an evidence-informed rubric framework that translates observed relationships between project-based learning elements and self-directed learning readiness into practical guidance for instructional design.

2. Methodology

This study was designed as an exploratory pilot in a single-institution to examine the relationship between project-based learning (PBL), self-directed learning readiness (SDLR) and undergraduate research interest in a course on senior-level mechanical control systems. The methodological approach emphasizes feasibility, instructional insight, and assessment alignment rather than causal inference.

2.1 Educational Context

The study was conducted in a senior-level *Introduction to Control Systems* (required core) course in a Mechanical Engineering program, at a public state university. The instruction combined traditional elements (lectures, homework, exams, and in-class activities) with a semester-long team-based project designed to promote open-ended problem solving, interdisciplinary integration, and independent inquiry. $(n = 43)$ Student participants contributed to this study, senior undergraduate students $(77\%; n = 33)$ and 13% juniors ($n = 10$). The majority of the participants are male (65%) and 19% female undergraduate students. In this sample, 56% of students reported a GPA above 3.0, 21% had a GPA between 2.5 and 3.0, and fewer than 9% had a GPA below 2.5. Additionally, about 13% of participants are first-generation college students (the first in their immediate family to attend college).

2.2 Project-Based Learning Design

Students completed one of four engineering projects: (i) a self-balancing robot with a gripper, (ii) an aerodynamic ball levitation system, (iii) an anti-swing PID controller for bridge cranes, or (iv) an IoT-based smart kitchen automation system. Each project followed a common three-phase structure.

In the first phase, students conducted self-directed literature reviews and developed conceptual models, including block diagrams and preliminary hardware selection. The second phase focused on mathematical modeling and MATLAB/Simulink simulation, where students derived system equations, designed controllers, and evaluated performance metrics such as stability, transient response, and steady-state error. In the final phase, teams implemented and experimentally tested their designs using physical prototypes or hardware-in-the-loop simulations. Projects concluded with a poster presentation emphasizing reflection on model–experiment discrepancies and lessons learned. Figure 1 presents a representative student-built prototype developed and showcased during the final poster session.

Figure 1: Representative student-built prototype showcased during the poster session

2.3 Data Collection Instruments

Student outcomes were examined using a post-intervention survey administered via Qualtrics at the end of the semester. The instrument was grounded in Fisher's validated Self-Directed Learning Readiness Scale for Adults (SDLRS-A)[19], which measures self-management, desire for learning, and self-control. Additional elements assessed undergraduate research interest and student perceptions of specific components of the PBL, including progress reporting, simulation, and prototype development.

The survey included both Likert-scale items and open-ended reflection prompts to capture quantitative trends and qualitative insights into the' learning experiences of the students. Participation was voluntary and responses were anonymized.

2.4 Data Analysis and Rubric Development

Quantitative survey data were analyzed using SPSS Version 27. Descriptive statistics summarized the response patterns, and an Ordinary Least Squares (OLS) regression model examined the association between overall SDLR and undergraduate research interest, with key PBL components included as covariates. Given the exploratory nature of the study, analyses focused on identifying meaningful relationships rather than causal effects.

Qualitative responses were thematically analyzed to identify perceived mechanisms through which

PBL activities supported SDLR and research engagement. Insights from both quantitative and qualitative analyses informed the development of a rubric-based framework that maps core PBL elements such as problem definition, interdisciplinary integration, teamwork, and reflection to specific SDLR traits. This rubric, presented in the Appendix, is intended to support instructional alignment, formative assessment, and future multi-institutional studies.

2.5 Rationale for a PBL–SDLR-Aligned Rubric

Although validated instruments such as SDLR-A (e.g., Knowel's SDLR for Adult Learning, Zimmerman's Self-regulated learning theory and Garrison's SDL in higher education) provide reliable outcome measures of an individual's self-directed learning readiness, due to their summative nature and focus, they provide limited guidance and interpretability on how specific instructional practices contribute to observed results[20–22]. In addition, conventional project-based learning rubrics typically emphasize technical deliverables, teamwork, or process completion, with minimal SDLR-aligned assessment criteria within rubrics and with limited alignment to learning theories underlying self-directed learning[3,23,24]. Thoughtfully designed PBL enhances SDLR such as strategy management and goal-setting; however, recent studies especially in engineering education reminds educators of persistent challenges in linking and translating PBL designs into measurable and actionable learning practices and outcomes, which highlights the need for more practical and pedagogical frameworks that more explicitly connect PBL instructional goals and designs to more improved learner's competencies[25,26]. As a result, instructors can face constrained instructional refinement and obscured learning mechanisms associated with learners' self-efficacy, and lack a practical framework and actionable feedback that help them connect PBL design decisions to ' SDLR development of learners. The proposed rubric, as a bridge between theories and classroom practice, aims to address such disconnections and instructional assessment inconveniences. The goal is to develop a framework that more explicitly links PBL elements to SDLR improvement, synthesizes PBL design features and SDLR theory into an instructional framework and a more actionable contribution that supports the intentional design, implementation and refinement of PBL activities.

A framework is needed that organizes PBL elements across the full project lifecycle—from problem formulation and modeling to feedback use and reflection—and aligns them with validated SDLR constructs for targeted design and implementation. By making self-directed learning processes explicit, the rubric supports intentional project design, formative feedback, and iterative course improvement. Its primary contribution lies in providing instructors with a structured way to emphasize and scaffold SDLR within PBL environments, while establishing a foundation for subsequent empirical validation. A sample rubric is presented in the appendix as a design framework rather than a validated assessment instrument, with empirical evaluation reserved for future studies.

3. Results and Discussion

This section presents and interprets quantitative and qualitative findings examining how project-based learning (PBL) elements relate to students' self-directed learning readiness (SDLR) and undergraduate research interest. Results are organized around perceived instructional mechanisms,

Table 1: Conceptual comparison between conventional PBL rubrics and the proposed SDLR-aligned framework

Feature	Conventional PBL Rubrics	Proposed Rubric Framework
Primary focus	Final product or teamwork quality	Development of self-directed learning readiness
Lifecycle coverage	Partial (often execution only)	Full PBL lifecycle (problem to reflection)
Alignment to learning theory	Implicit or none	Explicitly aligned to validated SDLR traits
Assessment type	Descriptive or summative	Quantitative, formative, and iterative
Instructor usability	Evaluation-oriented	Design, implementation, and assessment tool
Scalability	Course-specific	Adaptable across courses and institutions

cognitive challenge, and observed associations between SDLR and research engagement.

3.1 Perceived Instructional Mechanisms Supporting SDLR

Students reported strong perceived benefits of the PBL experience for developing self-directed learning behaviors. In particular, structured progress reports and iterative feedback emerged as central mechanisms supporting planning, monitoring, and persistence. Approximately 30% of students identified progress reporting as a key contributor to overall project success, while others emphasized its role in maintaining momentum (25.5%) and enabling timely feedback from instructors and peers (16.5%), as shown in Fig. 2.

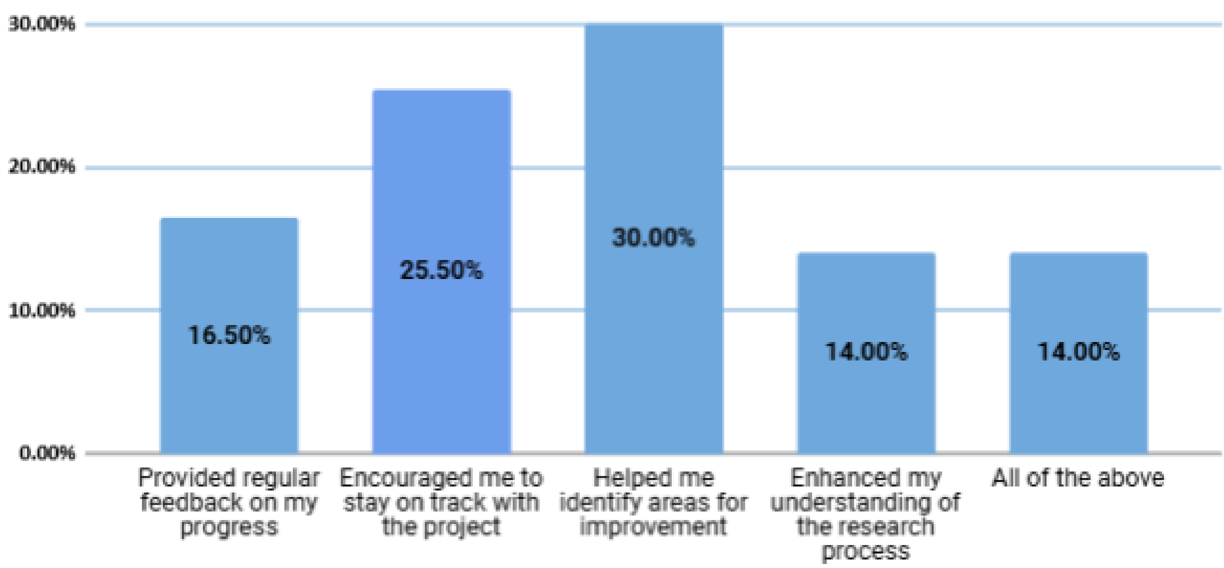

Figure 2: Perceived contribution of progress reports to engagement and success in the semester-long project.

These findings suggest that progress artifacts functioned as scaffolds for self-management by externalizing goal setting and progress monitoring without constraining student autonomy. Consistent with this interpretation, a large majority of students agreed or strongly agreed that the PBL experience motivated their self-directed learning (Table 2). When asked which aspects most increased their interest in research-oriented work, students most frequently cited instructor and peer feedback, recognition of their work, and opportunities to showcase results (Table 3). Together, these responses highlight the role of formative feedback and visibility in sustaining engagement and persistence in open-ended engineering tasks.

Table 2: Impact of PBL on Self-Directed Learning Motivation

Project-based learning motivated my SDL	**Percentage**
Strongly agree	40%
Somewhat agree	47%
Neutral	0%
Somewhat disagree	13%
Strongly disagree	0%

Table 3: Aspects of PBL that Increased Research Interest

Aspect	**Percentage**
Opportunity to showcase my work	12%
Interactions and feedback from instructor and team	38%
Networking	24%
Gaining recognition for my research interest	31%

3.2 Cognitive Challenge and Productive Struggle

Students consistently identified mathematical modeling and MATLAB/Simulink simulation as the most challenging components of the project, followed by prototype development and system integration (Fig. 4). Open-ended responses indicated that difficulties often arose when translating theoretical models into computational and physical implementations.

Importantly, these challenges were not framed as deterrents. Instead, students described iterative modeling, debugging, and experimental testing as central learning experiences that strengthened problem-solving confidence and reinforced the value of verification and persistence—key characteristics of SDLR. A summary of student-perceived PBL elements influencing SDLR development is shown in Fig. 4.

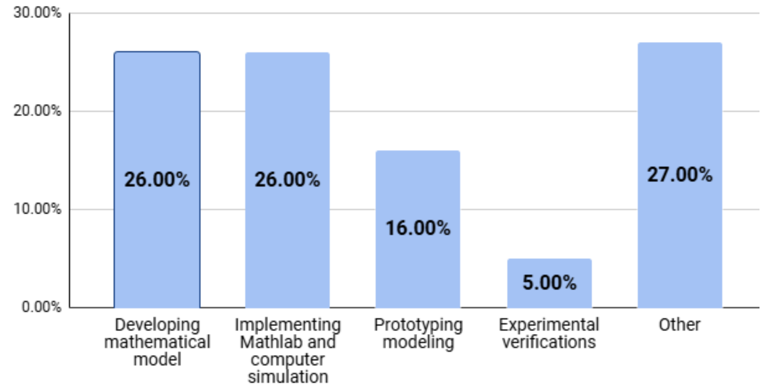

Figure 3: Challenging aspects of the project as ranked by participants.

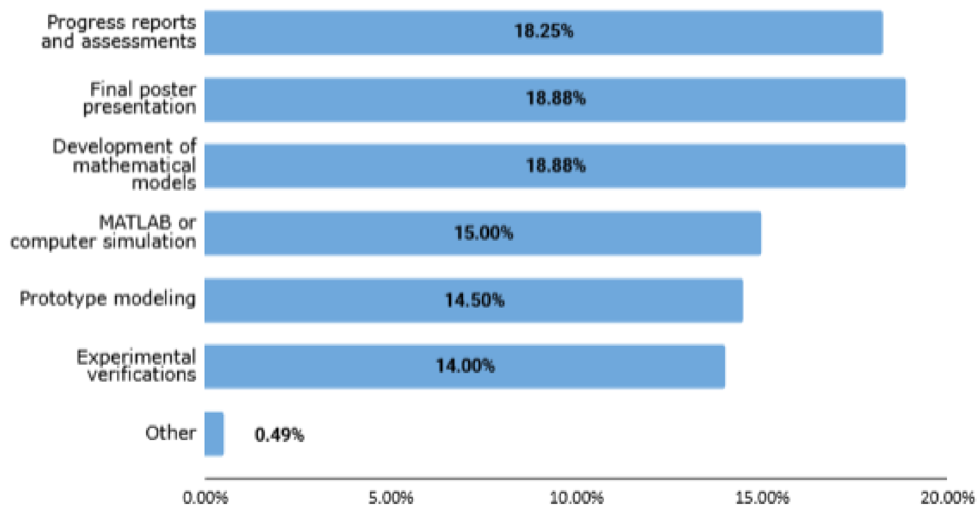

Figure 4: Perceived influential elements of research-based instruction on students' SDLR.

3.3 Association Between SDLR and Research Interest

An Ordinary Least Squares regression analysis examined the relationship between overall SDLR and undergraduate research interest. The model was statistically significant ($R^2 = 0.145$, $F(1, 32) = 5.446$, $p = 0.026$), indicating that higher levels of SDLR were associated with greater interest in research-oriented activities. This result suggests that students who perceive themselves as more capable of managing and regulating their learning are also more inclined to engage with open-ended, inquiry-driven tasks.

3.4 Synthesis of Quantitative and Qualitative Findings

Across quantitative and qualitative data, a consistent pattern emerges: PBL environments that combine cognitive challenge with structured feedback support the development of SDLR. Modeling, simulation, and prototyping introduced productive difficulty, while progress reporting, feedback, and reflection provided scaffolds that enabled students to persist through uncertainty. This interaction between challenge and structure appears to be a key mechanism by which PBL supports both self-directed learning behaviors and readiness for research-oriented engagement.

4. Conclusion and Future Work

This exploratory pilot study provides evidence that thoughtfully structured project-based learning can support the development of self-directed learning readiness and foster engagement with research-oriented activities in engineering education. Projects integrating mathematical modeling, simulation, and physical prototyping were perceived as particularly effective in promoting planning, persistence, and independent problem solving when paired with structured feedback mechanisms.

A key contribution of this work is the proposal of an SDLR-aligned rubric framework that translates observed instructional mechanisms into practical guidance for PBL design and alignment. Rather than serving as a validated assessment instrument, the rubric provides a structured means for instructors to emphasize, scaffold, and reflect on self-directed learning processes within project-based courses.

As a single-course, post-intervention study, the findings are indicative rather than causal. Future work will incorporate pre/post designs, comparison groups, and multi-course or multi-institutional implementations to examine changes in SDLR over time and to empirically validate the proposed rubric. Comparative studies across project types and disciplinary contexts will further clarify which PBL elements most strongly influence specific SDLR dimensions, supporting scalable and evidence-based instructional strategies in engineering education.

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A. Enhanced Rubric Framework for Guiding and Analyzing the Impact of Project-Based Learning on Individual Self-Directed Learning Readiness

This appendix presents an enhanced and implementable rubric framework intended to support the design, alignment, and analysis of project-based learning (PBL) with respect to individual self-directed learning readiness (SDLR). The framework is proposed as an evidence-informed instructional guide rather than a validated measurement instrument and is included to translate study findings into actionable pedagogical practice. Existing SDLR instruments measure learner readiness but do not inform instructional design, while conventional PBL rubrics assess project execution without explicit alignment to SDLR constructs; the proposed framework is intended to bridge this gap.

A.1 Purpose and Scope

While PBL activities are typically completed in teams, the outcome of interest in this work is individual development of SDLR. Team projects provide a shared learning environment, whereas changes in SDLR are measured at the student level using validated self-report instruments. The rubric is designed to support interpretation and future implementation without conflating team performance with individual learning outcomes.

A.2 Rubric Design Principles

The rubric is guided by three principles:

- **Completeness:** Coverage of the full PBL lifecycle, from problem formulation through reflection and knowledge transfer.
- **Theoretical Alignment:** Mapping of observable PBL behaviors to validated SDLR traits derived from Fisher's SDLRS-A (self-management, desire for learning, and self-control).
- **Usability:** Applicability for instructional design, formative feedback, and reflective analysis without requiring advanced statistical expertise.

A.3 Rubric Structure and Components

Table 4 summarizes the proposed rubric structure. Each row represents a core PBL element aligned with one or more SDLR traits. A weight factor w_{ij} denotes the hypothesized contribution of PBL element i to SDLR trait j, which may be examined and refined in future studies.

Table 4: Proposed rubric mapping PBL elements to individual SDLR traits

PBL Element	**SDLR Trait**	**Weight**	**Observable Individual-Level Indicators**
Problem Definition and Scoping	Self-Management	w_1	Independently frames the problem, identifies constraints, and develops an initial plan.
Literature Review and Knowledge Acquisition	Desire for Learning	w_2	Seeks and synthesizes information beyond provided materials.
Interdisciplinary Integration	Desire for Learning	w_3	Integrates concepts across technical domains to justify design decisions.
Modeling and Simulation	Self-Control	w_4	Develops and revises models; verifies assumptions against observed behavior.
Prototype Development and Experimentation	Self-Control	w_5	Iteratively refines prototypes and persists through implementation challenges.
Project Planning and Time Management	Self-Management	w_6	Establishes milestones and adapts plans based on progress.
Collaboration and Communication	Self-Management	w_7	Contributes meaningfully to team coordination and communication.
Feedback Utilization	Self-Control	w_8	Incorporates instructor, peer, or system feedback into subsequent iterations.
Reflection and Self-Assessment	Self-Control	w_9	Evaluates learning strategies and identifies areas for improvement.
Knowledge Transfer and Application	Desire for Learning	w_{10}	Applies learned concepts to new or extended contexts.

A.4 Scoring Scale and Evidence Sources

Each PBL element may be rated using a four-level scale reflecting the degree of individual autonomy and self-regulation demonstrated:

- 0: No evidence or instructor-directed execution
- 1: Limited autonomy with substantial guidance
- 2: Moderate autonomy with appropriate scaffolding
- 3: High autonomy with reflective and strategic decision-making

Potential evidence sources include individual reflections, progress reports, design notebooks, simulation artifacts, prototype iterations, and presentation narratives.

A.5 Analytical Formulation (Proposed)

For future studies employing pre/post designs, individual SDLR change for student k may be expressed as:

$$\Delta SDLR_j^{(k)} = SDLR_{j,\text{post}}^{(k)} - SDLR_{j,\text{pre}}^{(k)}.$$

The hypothesized contribution of PBL element i to SDLR change may then be represented as:

$$I_i^{(k)} = \sum_{j=1}^{n} w_{ij} \cdot \Delta SDLR_j^{(k)}.$$

These expressions are provided to illustrate how the rubric could be integrated into future empirical analyses and were not applied in the present study.

A.6 Implementation Guidance

The rubric supports an iterative instructional cycle:

1. Identify SDLR traits to emphasize.
2. Select PBL elements aligned with those traits.
3. Embed formative checkpoints during project execution.
4. Collect post-intervention SDLR measures.
5. Refine instructional design in subsequent offerings.

By linking instructional intent, observable behaviors, and individual learning outcomes, the framework provides a structured foundation for future validation and scalable application in team-based PBL environments.