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Evaluating the Impact of Interdisciplinary Learning Factory Models on Innovation Skills Using Statistical Analysis

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ABSTRACT

This study examines the impact of interdisciplinary learning factory models on the development of students innovation skills in higher education environments that integrate academic learning with industrial practices. **The increasing demand** for graduates with strong innovative competencies highlights the need for interdisciplinary learning approaches that effectively bridge theoretical knowledge and real-world industrial applications within learning factory settings. **The main objective** of this research is to evaluate the influence of interdisciplinary learning factory models on key dimensions of innovation skills, including creative thinking, problem-solving, collaboration, and critical thinking abilities. **A quantitative research design** was employed using structured survey instruments administered to students participating in interdisciplinary learning factory programs, and the data were analyzed through statistical techniques, including descriptive analysis, reliability and validity testing, and inferential statistical methods to examine the relationships between variables. **The findings** indicate a significant and positive effect of interdisciplinary learning factory models on students innovation skills, demonstrating that integrated and collaborative learning environments effectively foster innovative competencies and enhance learning outcomes. **These results suggest** that interdisciplinary learning factory models represent a powerful educational strategy for strengthening innovation-oriented skills in higher education, offering theoretical contributions to learning factory research and practical implications for educational institutions in designing interdisciplinary learning frameworks that support sustainable innovation and alignment with industry needs.

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1. INTRODUCTION

The rapid evolution of digital technologies and automation has reshaped the nature of work and the competencies required in modern industries [1]. Within the context of Industry 4.0 and the emerging Industry 5.0 paradigm, organizations increasingly demand graduates who possess not only technical expertise but also advanced capabilities such as creativity, critical thinking, problem-solving, collaboration, and adaptability. These abilities are crucial for addressing complex challenges driven by technological disruption, global competition, and cyber-physical integration [2]. However, many higher education institutions continue to rely on discipline-centered curricula that emphasize theoretical mastery over integrative and practice-oriented learning. This misalignment between academic preparation and industrial expectations raises concerns about graduate readiness in innovation-driven economies. As a result, universities are compelled to redesign their educational models through cross-disciplinary integration, stronger industry collaboration, and technology-enhanced learning environments to better connect theory with practice [3].

In response to these challenges, the learning factory concept has emerged as an innovative educational model that integrates academic learning with real or simulated industrial environments [4]. A learning factory provides students with opportunities to engage in authentic production processes, collaborative projects, and technology-driven learning activities that reflect real-world industrial contexts. Unlike traditional laboratories, which often focus on isolated technical skills, learning factories encompass multiple dimensions of industrial practice, including technological systems, organizational processes, management strategies, and digital infrastructures [5]. When implemented within an interdisciplinary framework, learning factories enable students from diverse academic backgrounds such as engineering, information systems, management, design, and social sciences to collaborate in solving complex problems that mirror actual industrial challenges. This interdisciplinary collaboration is crucial because innovation in contemporary industries frequently emerges from the integration of knowledge across multiple domains rather than from isolated disciplinary expertise [6]. As a result, interdisciplinary learning factory models are increasingly recognized as promising pedagogical approaches for developing innovation skills and preparing students for the demands of modern industries. Nevertheless, despite the growing adoption of learning factory models in higher education, systematic evidence regarding their effectiveness in enhancing innovation skills remains limited and inconclusive [7].

From a pedagogical perspective, interdisciplinary learning factory models are grounded in several theoretical frameworks that emphasize experiential, collaborative, and integrative learning processes. Experiential learning theory highlights the role of active participation and reflection in transforming experience into knowledge, while constructivist learning theory underscores the importance of learners actively constructing meaning through interaction with their environment [8]. Additionally, collaborative learning theories emphasize the role of social interaction and teamwork in enhancing cognitive and behavioral outcomes. These theoretical perspectives suggest that interdisciplinary learning environments, such as learning factories, have significant potential to foster innovation skills by encouraging students to integrate knowledge, collaborate across disciplines, and engage in problem-solving activities that reflect real-world contexts [9]. At the same time, innovation skills are increasingly conceptualized as multidimensional constructs that encompass cognitive abilities, behavioral traits, and social competencies. These skills are not static attributes but are shaped by educational environments, pedagogical strategies, and institutional cultures. Although previous studies have explored the role of interdisciplinary learning and industry-oriented education in developing innovation skills, most research has relied on qualitative approaches, descriptive analyses, or limited case studies. Consequently, there is a lack of robust quantitative evidence that systematically examines the relationship between interdisciplinary learning factory models and innovation skills [10].

Furthermore, existing empirical studies often focus on specific disciplines or narrowly defined educational contexts, which limits the generalizability and scalability of their findings [11]. Many studies investigate the implementation of learning factories in engineering education or technical training without adequately considering the interdisciplinary dimensions that characterize contemporary innovation processes. Moreover, few studies employ advanced statistical techniques to measure the magnitude and significance of the impact of interdisciplinary learning factory models on innovation skills [12]. This methodological limitation constrains the ability of researchers and practitioners to draw reliable conclusions regarding the effectiveness of interdisciplinary learning environments. In addition, the rapid integration of digital technologies, such as artificial intelligence, data analytics, and smart manufacturing systems, has further complicated the learning factory landscape, creating new opportunities and challenges for interdisciplinary education. These developments underscore the need for comprehensive empirical research that not only examines the pedagogical value of interdisciplinary learning factory models but also quantitatively evaluates their impact on students innovation skills in diverse educational settings [13].

Against this backdrop, this study aims to evaluate the impact of interdisciplinary learning factory models on students innovation skills using statistical analysis [14]. The primary objective of this research is to measure the extent to which interdisciplinary learning factory environments contribute to the development of key innovation competencies, including creativity, critical thinking, problem-solving, and collaboration. By adopting a quantitative research design and employing rigorous statistical methods, this study seeks to provide empirical evidence that clarifies the relationship between interdisciplinary learning factory models and innovation-related outcomes [15]. The findings of this research are expected to contribute to the theoretical advancement of learning factory and interdisciplinary education research by offering a systematic understanding of how integrated learning environments influence innovation skills. Additionally, this study provides practical insights for educators, curriculum designers, and policymakers in designing interdisciplinary learning strategies that align with industry demands and support sustainable educational innovation. Ultimately, this research highlights the strategic role of interdisciplinary learning factory models in strengthening the alignment between academic learning and industrial practice, thereby preparing graduates to thrive in increasingly complex, technology-driven, and innovation-oriented global environments [16].

2. LITERATURE REVIEW

2.1. Learning Factory in Higher Education

The learning factory has emerged as a transformative educational concept designed to integrate academic learning with industrial practices in higher education [17]. It provides an authentic learning environment where students engage in hands-on activities, collaborative projects, and technology-driven problem-solving processes that reflect real industrial systems [18]. Recent research has emphasized that learning factories play a crucial role in enhancing experiential learning by combining theoretical knowledge with practical applications, thereby improving students understanding of complex industrial processes and systems. In contemporary educational contexts, learning factories are increasingly supported by digital technologies, such as smart manufacturing systems, digital simulation tools, and data-driven learning platforms, which further expand their pedagogical potential [19].

In recent developments, scholars have highlighted the importance of extending learning factory models beyond technical training toward more integrative educational frameworks [20]. This shift reflects the growing recognition that modern industrial challenges require interdisciplinary knowledge integration rather than isolated disciplinary expertise. Interdisciplinary learning factory environments enable students from different academic backgrounds to collaborate in solving complex problems that mirror real-world industrial scenarios [21]. Although learning factories have been widely implemented in engineering and technology education, their broader educational impact, particularly on innovation-related competencies, has not been sufficiently explored through systematic empirical research. This limitation indicates the need for more rigorous investigations into the educational outcomes of interdisciplinary learning factory models [22].

2.2. Interdisciplinary Learning in Higher Education

Interdisciplinary learning has become a central paradigm in contemporary higher education as institutions seek to address complex societal and industrial challenges that transcend traditional disciplinary boundaries [23]. It involves the integration of knowledge, methods, and perspectives from multiple disciplines to foster holistic understanding and innovative problem-solving. Recent studies have demonstrated that interdisciplinary learning enhances students cognitive flexibility, critical thinking, and collaborative abilities by exposing them to diverse perspectives and knowledge domains [24]. Through interdisciplinary learning, students are encouraged to synthesize ideas, negotiate meaning, and develop solutions that reflect the complexity of real-world problems.

In the context of learning factory environments, interdisciplinary learning plays a particularly significant role because industrial innovation often emerges from collaboration among professionals from different fields [25]. Interdisciplinary project-based learning within learning factories allows students to experience the dynamics of real industrial teams, where technical, managerial, and digital competencies intersect. However, while the benefits of interdisciplinary learning have been widely discussed in theoretical and qualitative studies, there is still a lack of quantitative evidence that measures its impact on specific competencies, especially innovation skills. This gap highlights the necessity of empirical studies that systematically evaluate the outcomes of interdisciplinary learning factory models using quantitative approaches [26].

2.3. Innovation Skills in Higher Education

Innovation skills represent a multidimensional competency framework encompassing creative thinking, analytical reasoning, problem-solving capacity, and collaborative effectiveness [27]. Unlike interdisciplinary learning, which functions as a pedagogical process, innovation skills refer to measurable learning outcomes reflecting students' ability to generate, evaluate, and implement novel ideas in dynamic contexts. These competencies are increasingly recognized as strategic human capital assets within knowledge-based economies. Therefore, innovation skills serve as the outcome construct in this study, operationalized through distinct cognitive and collaborative dimensions [28].

Recent research indicates that innovation skills are influenced by various factors, including pedagogical approaches, learning environments, institutional culture, and industry engagement [29]. Experiential learning, collaborative learning, and technology-enhanced learning environments have been identified as key drivers of innovation skill development. Interdisciplinary learning, in particular, has been recognized as a powerful mechanism for fostering innovation because it encourages students to integrate knowledge across domains and approach problems from multiple perspectives [30]. Nevertheless, many existing studies rely on qualitative observations or self-reported measures, which limits the robustness and generalizability of their findings. Therefore, there is a growing need for quantitative research that systematically examines how interdisciplinary learning environments, such as learning factories, contribute to the development of innovation skills [31].

2.4. Interdisciplinary Learning Factory Models and Educational Outcomes

Interdisciplinary learning factory models represent an integration of learning factory environments with interdisciplinary pedagogical approaches [32]. These models are designed to provide students with opportunities to engage in collaborative, technology-driven, and industry-oriented learning experiences that reflect the complexity of modern industrial systems. Recent studies suggest that interdisciplinary learning factory models can enhance various educational outcomes, including technical competence, teamwork skills, problem-solving abilities, and learning engagement [33]. Moreover, these models are increasingly viewed as strategic tools for aligning higher education with industry demands and fostering innovation-driven learning cultures.

Despite their potential, empirical evidence regarding the impact of interdisciplinary learning factory models on innovation skills remains limited. Many studies focus on descriptive evaluations or case-based analyses, which provide valuable insights but do not offer statistically validated conclusions [34]. Furthermore, the diversity of learning factory implementations across institutions and disciplines complicates the development of standardized evaluation frameworks. This situation underscores the importance of systematic research that employs quantitative methodologies to measure the educational impact of interdisciplinary learning factory models. By addressing this gap, researchers can provide evidence-based insights that support the design and implementation of more effective interdisciplinary learning environments in higher education [35].

2.5. Quantitative Evaluation of Educational Innovation

Quantitative research methods play a critical role in evaluating the effectiveness of educational innovations by providing empirical evidence based on measurable data [36]. Statistical techniques such as regression analysis, structural equation modeling, and multivariate analysis are widely used to examine relationships between educational variables and learning outcomes. These methods enable researchers to identify causal relationships, measure the magnitude of effects, and validate theoretical models in educational research. In the context of innovation-oriented education, quantitative approaches are particularly valuable for assessing complex constructs such as innovation skills, which involve multiple interrelated dimensions [37].

In interdisciplinary learning factory research, quantitative evaluation provides a systematic means of measuring the impact of learning environments on students competencies [38]. Recent empirical studies have demonstrated that statistical analysis can reveal significant relationships between pedagogical models and learning outcomes, thereby offering evidence-based insights for educational practice and policy. However, the application of quantitative methodologies in learning factory research remains relatively limited, particularly in studies that focus on interdisciplinary models and innovation skills [39]. This limitation highlights the necessity of rigorous quantitative investigations that integrate interdisciplinary learning frameworks with robust statistical analysis. Therefore, this study contributes to the existing body of knowledge by quantitatively evaluating the impact of interdisciplinary learning factory models on students innovation skills, thereby addressing a critical gap in contemporary educational research [40].

3. RESEARCH METHODOLOGY

3.1. Research Design

This study employs a quantitative research design to evaluate the impact of interdisciplinary learning factory models on students innovation skills. The quantitative approach is selected to systematically measure relationships between variables and to provide empirical evidence based on statistical analysis [41]. The research adopts an explanatory design, aiming to explain the causal relationship between interdisciplinary learning factory models as independent variables and innovation skills as dependent variables. Data are collected using structured questionnaires distributed to students who have participated in interdisciplinary learning factory programs in higher education institutions.

The research process is conducted in several stages, including research design development, instrument construction, data collection, data validation, and statistical analysis [42]. This structured approach ensures methodological rigor and enhances the reliability and validity of the findings. The overall research framework is designed to capture both the conceptual and empirical dimensions of interdisciplinary learning factory implementation and its influence on innovation-related competencies.

3.2. Research Framework

The conceptual framework of this study is based on the assumption that interdisciplinary learning factory models influence students innovation skills through collaborative, experiential, and technology-enhanced learning processes. The interdisciplinary learning factory model (X) is operationalized into four measurable dimensions:

- Interdisciplinary collaboration
- Project-based industrial learning
- Technology integration
- Industry engagement

Each dimension is measured using multiple Likert-scale items reflecting students' experiential exposure and perceived learning intensity. Innovation skills (Y) are operationalized into four core dimensions, namely creative thinking, problem-solving ability, critical thinking, and collaborative competence, each measured through reflective self-assessment indicators adapted from innovation competency frameworks. This operationalization ensures that each construct is empirically measurable and aligned with the statistical model used in this study.

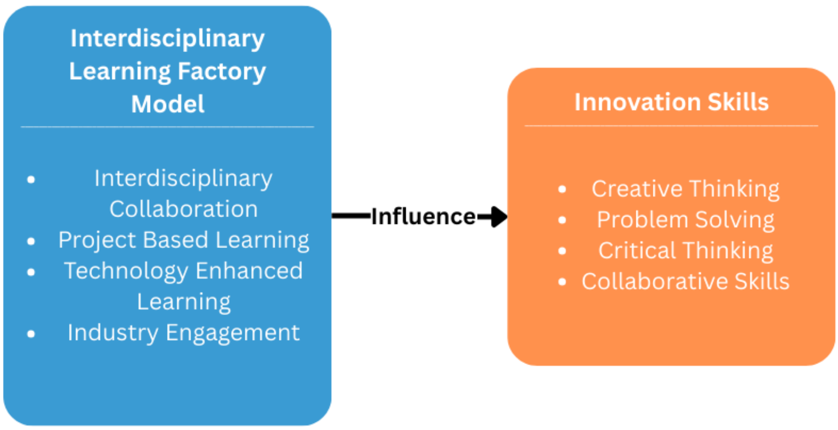

Figure 1. Conceptual Research Framework

Figure 1 illustrates the conceptual research framework that explains the relationship between interdisciplinary learning factory models and students' innovation skills. In this framework, interdisciplinary learning factory models are positioned as the independent variable (X), representing an integrated educational approach that combines cross-disciplinary learning, industry-based learning, project-based learning, and technology integration within a learning factory environment. These dimensions reflect the core characteristics of interdisciplinary learning, where theoretical knowledge, practical industrial experience, and digital technologies are systematically integrated to support holistic learning processes.

Furthermore, innovation skills are conceptualized as the dependent variable (Y), encompassing several key competencies, including creativity, problem-solving ability, critical thinking, collaboration, and digital innovation. These competencies represent essential skills required in contemporary educational and industrial contexts, particularly in environments characterized by rapid technological change and interdisciplinary collaboration. The arrows connecting the components of interdisciplinary learning factory models to innovation skills indicate the hypothesized influence of each learning dimension on the development of students' innovative competencies.

The framework also emphasizes the dynamic interaction between educational strategies and learning outcomes, suggesting that interdisciplinary learning factory models can significantly enhance innovation skills by fostering experiential learning, collaborative problem-solving, and technology-supported learning practices. By structuring the relationship between variables in this way, Figure 1 provides a theoretical foundation for the empirical analysis conducted in this study and guides the formulation of research hypotheses and statistical testing. Overall, the conceptual framework serves as an integrative model that links interdisciplinary educational practices with measurable innovation outcomes, thereby supporting the investigation of how learning factory-based interdisciplinary approaches contribute to the development of innovation-oriented competencies in higher education.

3.3. Population and Sample

The population of this study consists of university students who have participated in interdisciplinary learning factory programs in higher education institutions. These students are selected because they have direct experience with interdisciplinary learning environments and learning factory-based activities.

A sample was drawn using a purposive sampling technique to ensure that respondents meet the criteria relevant to the research objectives. Purposive sampling was intentionally selected because only students with direct and verified participation in interdisciplinary learning factory programs could provide valid and context-specific responses regarding innovation skill development. Employing random sampling might have introduced respondents without sufficient exposure to the interdisciplinary environment, thereby weakening construct validity. Therefore, purposive selection enhances internal consistency between theoretical constructs and empirical measurement, strengthening the methodological rigor of the study. Data were collected through structured questionnaires distributed directly to participants who met the inclusion criteria.

A total of 186 students participated in this study, all of whom had been involved in interdisciplinary learning factory programs for at least one semester. The respondents consisted of 54% male and 46% female students. In terms of academic background, 48% were from engineering programs, 27% from information systems, 15% from management, and 10% from other related disciplines. Regarding academic level, 62% were third-year students and 38% were fourth-year students. This demographic distribution enhances transparency and supports the generalizability of the findings.

Table 1. Population and Sample Description

Category	Description
Population	Students involved in interdisciplinary learning factory programs in higher education institutions
Sampling technique	Purposive sampling
Sample size	186 students
Gender distribution	Male (54%), Female (46%)
Academic background	Engineering (48%), Information Systems (27%), Management (15%), Others (10%)
Academic level	Third year (62%), Fourth year (38%) Unit of analysis
Individual students	Higher education institutions implementing interdisciplinary
Research context	learning factory programs

Beyond descriptive representation, the demographic structure presented in Table 1 ensures disciplinary diversity and academic maturity among respondents, which strengthens the analytical validity of the regression model. The inclusion of students from multiple disciplines reflects the interdisciplinary nature of the learning factory environment, thereby aligning the sample characteristics with the conceptual framework of the study. This diversity enhances the robustness of statistical inference and supports broader interpretability of the findings within interdisciplinary educational contexts.

Moreover, Table 1 outlines the unit of analysis at the individual student level and the research context within higher education institutions. This approach enables the study to capture students' perceptions and competencies related to innovation skills development in interdisciplinary learning factory settings, providing a methodological basis for subsequent statistical analysis and strengthening the validity of the research findings.

3.4. Research Variables and Indicators

This study employs two main variables to examine the impact of interdisciplinary learning factory models on students' innovation skills in higher education. The independent variable is the interdisciplinary learning factory model, which refers to a learning approach that integrates interdisciplinary collaboration, technology-enhanced learning, project-based activities, and industry-oriented practices within a learning factory environment. This variable is conceptualized as a holistic educational framework that combines knowledge from multiple disciplines with practical industrial applications to create meaningful and authentic learning experiences for students.

The interdisciplinary learning factory model is operationalized through several indicators, including interdisciplinary collaboration among students from different academic backgrounds, integration of digital and educational technologies in learning processes, implementation of project-based learning activities, and engagement with industry-related problems and contexts. These indicators represent key dimensions of interdisciplinary learning environments and reflect the extent to which learning factory models facilitate cross-disciplinary interaction, experiential learning, and technological integration in higher education.

The dependent variable in this study is innovation skills, which refer to students' abilities to generate creative ideas, solve complex problems, think critically, and collaborate effectively in interdisciplinary contexts. Innovation skills are measured through multiple dimensions, including creative thinking, problem-solving ability, critical thinking, and collaborative competence. These dimensions represent essential competencies required in contemporary educational and industrial settings and are widely recognized as key outcomes of interdisciplinary and experiential learning approaches.

By conceptualizing interdisciplinary learning factory models as the independent variable and innovation skills as the dependent variable, this study establishes a clear analytical framework to investigate the relationship between interdisciplinary learning environments and students' innovation competencies. The operationalization of variables and indicators provides a systematic basis for statistical analysis and ensures that the research findings accurately reflect the impact of interdisciplinary learning factory models on innovation skill development.

3.5. Instrument Development and Data Collection

Data were collected using a structured questionnaire developed based on the operationalized indicators of the research variables. The instrument consisted of 24 items, with 12 items measuring interdisciplinary learning factory dimensions (interdisciplinary collaboration, technology integration, project-based learning, and industry engagement) and 12 items measuring innovation skill dimensions (creative thinking, problem-solving ability, critical thinking, and collaborative competence). A five-point Likert scale (1 = strongly disagree to 5 = strongly agree) was used to ensure consistency and suitability for regression-based statistical analysis. Prior to large-scale distribution, the instrument was pilot tested to assess clarity, reliability, and construct validity.

The data collection process is conducted in several stages, including questionnaire distribution, response collection, and data verification. Ethical considerations are addressed by ensuring voluntary participation and confidentiality of respondents information. The collected data are then prepared for statistical analysis through coding and data cleaning procedures.

Table 2. Data Collection Procedure

Stage	Activity	Output
Instrument design	Development of questionnaire items	Research instrument
Pilot testing	Reliability and validity testing	Validated instrument
Data distribution	Questionnaire administration	Raw data
Data processing	Coding and cleaning	Ready-to-analyze data
Statistical analysis	Hypothesis testing	Research findings

Table 2 describes the data collection procedure implemented in this research. Data were collected using structured questionnaires distributed to students involved in interdisciplinary learning factory programs. The questionnaire was designed based on the identified variables and indicators, ensuring content relevance and construct validity.

In addition, Table 2 outlines the stages of data collection, including instrument development, pilot testing, distribution of questionnaires, and data verification. This systematic procedure ensures that the data collection process is conducted in a rigorous and consistent manner, thereby enhancing the reliability and credibility of the research findings.

3.6. Data Analysis Techniques

This study employs statistical analysis to examine the relationship between interdisciplinary learning factory models and innovation skills. The analysis includes descriptive statistics, reliability and validity testing, and inferential statistical techniques. Depending on the research objectives, techniques such as regression analysis, Structural Equation Modeling (SEM), or Partial Least Squares Structural Equation Modeling (PLS-SEM) can be applied.

The data analysis process begins with descriptive analysis to understand respondents characteristics and variable distributions. Reliability testing is conducted using internal consistency measures, while validity testing ensures that the instrument accurately measures the intended constructs. Inferential analysis is then performed to test hypotheses and determine the significance of relationships between variables.

Table 3. Data Analysis Methods

Analysis Type	Technique	Purpose
Descriptive analysis	Mean, standard deviation	Describe data characteristics
Reliability testing	Internal consistency analysis	Assess instrument reliability
Validity testing	Construct and convergent validity	Ensure measurement accuracy
Inferential analysis	Regression / SEM / PLS-SEM	Test relationships between variables
Hypothesis testing	Statistical significance testing	Evaluate research hypotheses

Table 3 presents the data analysis methods employed in this study. Descriptive statistical analysis is used to examine the general characteristics of respondents and variable distributions, while inferential statistical techniques are applied to test the relationships between interdisciplinary learning factory models and innovation skills. These techniques include reliability and validity testing, correlation analysis, and regression analysis.

Furthermore, Table 3 highlights the sequence of analytical steps performed in the study, from preliminary data screening to hypothesis testing. This structured analytical framework ensures that the research findings are supported by robust statistical evidence and provides a comprehensive understanding of the impact of interdisciplinary learning factory models on students' innovation skills.

3.7. Research Procedure

The research procedure is conducted systematically to ensure methodological rigor and analytical coherence. Each stage in Figure 2 represents a logically interconnected analytical process. Problem identification establishes the research gap, which directly informs the conceptual framework and hypothesis formulation.

Instrument development operationalizes theoretical constructs into measurable variables, ensuring empirical alignment. Data collection and validation provide statistically reliable input for regression modeling. The analytical stage applies inferential statistical testing to evaluate hypothesized relationships, while the interpretation stage contextualizes statistical findings within theoretical frameworks. This structured progression ensures that the empirical results are directly grounded in the initial research objectives and theoretical assumptions.

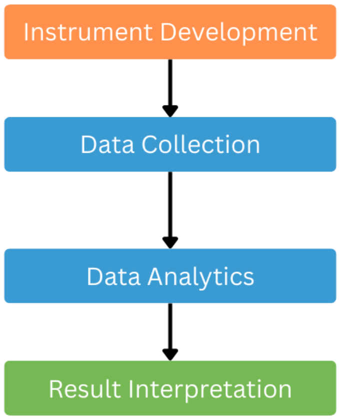

Figure 2. Research Procedure Flow

Figure 2 presents the research procedure flow that describes the systematic stages undertaken in this study to evaluate the impact of interdisciplinary learning factory models on students' innovation skills. The procedure begins with the identification of research problems, which are derived from gaps in previous studies and the growing demand for empirical evidence regarding the effectiveness of interdisciplinary learning environments in higher education. This stage is followed by an extensive literature review, which serves as the foundation for developing the conceptual framework and defining the key variables examined in the study.

The next stage involves the design and validation of research instruments, where measurement indicators for interdisciplinary learning factory models and innovation skills are operationalized into structured questionnaire items. Instrument validation is conducted to ensure the reliability and validity of the measurement tools before large-scale data collection. Subsequently, data collection is carried out by distributing questionnaires to students who have participated in interdisciplinary learning factory programs. The collected data are then processed through coding and cleaning procedures to ensure accuracy and readiness for statistical analysis.

In the subsequent phase, statistical analysis is performed using quantitative techniques to examine the relationships between the independent and dependent variables. This includes descriptive analysis, reliability and validity testing, and inferential statistical analysis to test the research hypotheses and determine the significance of the effects of interdisciplinary learning factory models on innovation skills. The results obtained from the statistical analysis are then interpreted to generate meaningful insights into the effectiveness of interdisciplinary learning factory approaches.

Finally, the research procedure concludes with the formulation of conclusions and implications, which highlight the theoretical contributions and practical relevance of the findings. The procedure illustrated in Figure 2 demonstrates a structured and rigorous methodological process that ensures the validity, reliability, and scientific robustness of the study. By following this systematic flow, the research provides empirical evidence that supports the role of interdisciplinary learning factory models in enhancing students' innovation skills and offers a methodological reference for future studies in interdisciplinary and technology-enhanced learning contexts.

4. RESULTS AND FINDINGS

4.1. Overview of Research Findings

This section presents the empirical findings obtained from the statistical analysis conducted to evaluate the influence of interdisciplinary learning factory models on students' innovation skills in higher education. The analysis was structured systematically to address the research objectives and examine the hypothesized relationship between interdisciplinary learning environments and innovation-related competencies. The results indicate that students who participated in interdisciplinary learning factory programs reported high levels of perceived engagement, interdisciplinary collaboration, and exposure to industry-relevant projects. The integration of cross-disciplinary teamwork, technology-enhanced learning tools, and project-based industrial simulations appears to create a structured educational ecosystem that promotes innovation-oriented behavior. Overall, the statistical findings demonstrate that interdisciplinary learning factory models are not merely complementary educational initiatives but function as strategic learning frameworks that shape students' cognitive and collaborative development.

Furthermore, inferential statistical results confirm that the interdisciplinary learning factory model significantly influences innovation skills across multiple dimensions. The positive and statistically significant relationships identified in correlation and regression analyses indicate that the learning factory environment systematically contributes to creative thinking, problem-solving ability, critical thinking, and collaborative competence. These findings suggest that innovation skills are not developed in isolation but emerge from structured interdisciplinary interaction and experiential learning processes embedded within learning factory contexts. The consistency between descriptive trends and inferential outcomes strengthens the robustness of the research model and provides empirical support for the theoretical framework underlying this study.

4.2. Descriptive Analysis of Interdisciplinary Learning Factory Models and Innovation Skills

The descriptive statistical analysis reveals that students perceive interdisciplinary learning factory implementation at a high level of effectiveness, as reflected in the overall mean score of 4.12. Indicators related to interdisciplinary collaboration and project-based learning demonstrate particularly strong responses, suggesting that students actively engage in cross-disciplinary discussions and practical industrial simulations. The relatively low standard deviation indicates consistent perceptions among respondents, implying that the learning factory experience provides a structured and uniformly delivered educational model. This consistency is important in demonstrating that interdisciplinary learning factory programs are systematically implemented rather than sporadically applied. The findings indicate that students experience meaningful integration of theoretical knowledge with practical industrial challenges, reinforcing the applied and experiential nature of the learning model.

Regarding innovation skills, the descriptive results show an overall mean of 4.05, reflecting a high level of self-reported innovation competence among participants. Creative thinking and collaborative skills emerge as the strongest dimensions, indicating that interdisciplinary environments effectively stimulate idea generation and teamwork dynamics. Problem-solving and critical thinking skills, while slightly lower, remain within the moderate-to-high range, suggesting that analytical competencies are also positively influenced by interdisciplinary engagement. This pattern implies that interdisciplinary learning factory environments initially strengthen interactive and ideation-based competencies, which subsequently support deeper analytical reasoning. The descriptive findings therefore provide preliminary evidence that interdisciplinary learning factories foster a multidimensional innovation ecosystem within higher education.

4.3. Reliability and Validity of Measurement Instruments

The reliability analysis demonstrates that all measurement constructs exceed the recommended Cronbach's Alpha threshold of 0.70, confirming strong internal consistency among the questionnaire items. This result indicates that the indicators used to measure interdisciplinary learning factory models and innovation skills are statistically reliable and capable of consistently capturing the intended constructs. Strong internal consistency ensures that each dimension of the research model is measured cohesively and reduces potential measurement error. The reliability findings strengthen the methodological rigor of the study and provide confidence that subsequent statistical analyses are grounded in stable measurement instruments.

Validity testing further confirms that all indicators significantly correlate with their respective constructs, demonstrating satisfactory convergent validity. The clear differentiation between independent and dependent variables indicates acceptable discriminant validity, ensuring that interdisciplinary learning factory constructs are empirically distinct from innovation skill dimensions. Establishing both reliability and validity is crucial in quantitative research because it ensures that the observed statistical relationships genuinely reflect conceptual associations rather than measurement artifacts. The robustness of the measurement model provides a solid empirical foundation for interpreting the correlation and regression results presented in subsequent sections.

4.4. Correlation Between Interdisciplinary Learning Factory Models and Innovation Skills

The correlation analysis reveals a strong positive relationship (r = 0.68) between interdisciplinary learning factory models and students' innovation skills, indicating a substantial association between structured interdisciplinary learning environments and the development of innovative competencies. The statistical significance level ($p < 0.001$) confirms that this relationship is unlikely to have occurred by chance, thereby reinforcing the robustness of the empirical findings. This magnitude of correlation suggests that higher levels of exposure to interdisciplinary learning factory environments are associated with higher levels of innovation-related abilities among students.

This finding implies that interdisciplinary learning factory models, which integrate collaboration, project-based learning, technology utilization, and industry engagement, play a meaningful role in enhancing key dimensions of innovation skills, including creative thinking, problem-solving, critical thinking, and collaborative competence. The results support experiential and collaborative learning theories, which emphasize that knowledge is developed through active engagement, interaction, and real-world problem-solving. In this context, the learning factory environment provides a structured platform where students can integrate knowledge across disciplines, thereby fostering cognitive flexibility and innovation-oriented thinking.

However, it is important to note that the observed relationship represents a statistically significant association rather than a direct causal effect, as the study employs a cross-sectional research design. While the findings demonstrate that interdisciplinary learning factory models are strongly linked to innovation skills, they do not confirm causality. Therefore, future research using longitudinal or experimental approaches is recommended to further examine the causal mechanisms and to provide a deeper understanding of how interdisciplinary learning environments contribute to the development of innovation competencies over time.

4.5. Impact of Interdisciplinary Learning Factory Models on Innovation Skills

The regression analysis indicates a statistically significant relationship between interdisciplinary learning factory models and students' innovation skills. The regression coefficient (β = 0.57, $p < 0.001$) suggests that higher levels of exposure to interdisciplinary learning factory environments are associated with higher levels of innovation competencies. This result demonstrates that interdisciplinary learning factory models have a meaningful predictive influence on innovation skills, reinforcing the findings obtained from the correlation analysis. The magnitude of the regression coefficient reflects a moderately strong effect, indicating that interdisciplinary learning environments contribute substantially to the development of innovation-related abilities.

A more detailed examination of the model reveals that specific dimensions of the interdisciplinary learning factory particularly interdisciplinary collaboration and technology integration exert stronger contributions to innovation skill development compared to other components such as project-based learning and industry engagement. This finding suggests that direct interaction across disciplines and the use of digital technologies play a central role in enhancing students' ability to think creatively, solve complex problems, and collaborate effectively. The integration of these elements creates a dynamic learning environment that supports both cognitive and social dimensions of innovation, enabling students to develop adaptive and integrative problem-solving strategies.

However, it is important to interpret these results with caution. Although the regression analysis demonstrates a significant predictive relationship, the cross-sectional design of the study limits the ability to infer causal effects. The observed influence should therefore be understood as an association rather than definitive causation. Future research is recommended to employ longitudinal or experimental designs to further investigate causal pathways and to explore how different components of interdisciplinary learning factory models contribute to innovation skill development over time.

4.6. Statistical Summary of Research Results

The overall statistical findings of this study are summarized in Table 4, which presents the descriptive statistics, correlation coefficients, regression coefficients, and significance values related to the impact of interdisciplinary learning factory models on innovation skills. This table consolidates the key empirical results obtained from the descriptive and inferential analyses, allowing a comprehensive evaluation of the strength and direction of the relationships between variables. The inclusion of mean and standard deviation values provides insight into students' perceptions, while the correlation and regression coefficients demonstrate the magnitude of association and predictive influence of interdisciplinary learning factory models on innovation competencies.

Following Table 4, the results indicate that the interdisciplinary learning factory model has a strong positive correlation with innovation skills (r = 0.68), confirming a substantial association between structured

Table 4. Statistical Results of the Impact of Interdisciplinary Learning Factory Models on Innovation Skills

Variable	Mean	Standard Deviation	Correlation (r)	Regression Coefficient (β)	Significance (p-value)
Interdisciplinary Learning Factory Model	4.12	0.53	0.68	0.57	< 0.001
Innovation Skills	4.05	0.49	-	-	-
Creative Thinking	4.18	0.51	0.62	0.46	< 0.01
Problem-Solving Skills	3.97	0.55	0.59	0.41	< 0.01
Critical Thinking Skills	3.89	0.57	0.56	0.38	< 0.05
Collaborative Skills	4.15	0.50	0.64	0.49	< 0.01

interdisciplinary learning environments and innovation competence. The regression coefficient (β = 0.57) further demonstrates that interdisciplinary learning factory models significantly predict innovation skills at a high level of statistical significance ($p < 0.001$). Among the innovation dimensions, creative thinking and collaborative skills show relatively stronger coefficients compared to problem-solving and critical thinking, indicating that interdisciplinary environments particularly stimulate ideation processes and teamwork dynamics. The consistency between descriptive indicators and inferential statistics strengthens the internal validity of the findings and confirms that interdisciplinary learning factory models function as structured innovation ecosystems capable of enhancing multidimensional innovation competencies.

4.7. Interpretation of Findings in Relation to Research Objectives

These findings not only align with prior empirical studies but also provide deeper analytical insight into the structural mechanisms underlying innovation skill formation. Rather than merely confirming positive associations, the regression results indicate that interdisciplinary learning factory models operate as structured cognitive integration systems in which experiential engagement and collaborative interaction function as mediating mechanisms for higher-order skill development. This shifts the discussion from simple empirical validation toward a process-oriented understanding of how interdisciplinary environments shape innovation competencies.

From a theoretical standpoint, the study advances experiential and collaborative learning theories by empirically illustrating that interdisciplinary exposure amplifies creative and collaborative dimensions before strengthening analytical and problem-solving capacities. This sequential reinforcement pattern suggests that innovation development follows an integrative cognitive trajectory, where social learning processes precede and support analytical refinement. By conceptualizing interdisciplinary learning factories as dynamic innovation ecosystems, the study contributes a refined explanatory model that links pedagogical structure, cognitive integration, and measurable innovation outcomes. Therefore, the theoretical contribution lies not only in validating prior assumptions but in clarifying the mechanism through which interdisciplinary pedagogy translates into quantifiable innovation competencies in higher education contexts.

4.8. Summary of Research Results

In summary, the results of this study demonstrate that interdisciplinary learning factory models exert a significant and positive influence on students' innovation skills. Descriptive findings indicate high levels of student engagement and perceived competence, while inferential analyses confirm strong relational and predictive effects between interdisciplinary learning environments and innovation outcomes. The correlation coefficient (r = 0.68) reflects a substantial association, and the regression coefficient (β = 0.57) indicates that interdisciplinary learning factory models meaningfully predict innovation competence. Among the innovation dimensions, creative thinking and collaborative skills appear as the most strongly influenced components, followed by problem-solving and critical thinking. These findings collectively validate the proposed research model and provide empirical confirmation that interdisciplinary learning factory implementation enhances multidimensional innovation competencies.

Furthermore, the coherence between descriptive statistics, reliability and validity testing, correlation analysis, and regression outcomes strengthens the internal consistency and robustness of the study. The evidence suggests that interdisciplinary learning factories operate as structured educational systems that integrate cross-disciplinary collaboration, digital technology utilization, and industry-oriented projects into a unified learning framework. By creating authentic and interactive learning experiences, these environments foster adaptive thinking and collaborative innovation capabilities required in contemporary industrial contexts. Overall, the study provides strong quantitative support for positioning interdisciplinary learning factory models as strategic pedagogical approaches capable of strengthening innovation-oriented higher education systems and preparing graduates for complex, technology-driven environments.

MANAGERIAL IMPLICATIONS

The results of this study indicate that interdisciplinary learning factory models should be positioned as a strategic component in higher education management rather than as supplementary learning initiatives. The significant impact of interdisciplinary learning environments on students' innovation skills implies that universities need to redesign curriculum structures, learning policies, and institutional strategies to support cross-disciplinary collaboration and experiential learning. Academic leaders and program managers are encouraged to integrate interdisciplinary learning factory approaches into formal curricula and institutional development plans to ensure sustainable innovation-oriented learning outcomes.

The findings also highlight the importance of designing learning factory environments that emphasize collaborative, project-based, and technology-enhanced learning practices. Educational managers and learning factory coordinators should focus on strengthening interdisciplinary teamwork, integrating digital technologies into learning processes, and establishing strong partnerships with industry stakeholders. These managerial efforts are essential to create authentic learning experiences that reflect real industrial challenges and to enhance students' creative thinking, problem-solving abilities, and collaborative competencies.

Furthermore, the study suggests that managerial decision-making in higher education should increasingly rely on empirical evidence and data-driven evaluation. The measurable relationship between interdisciplinary learning factory models and innovation skills demonstrates the value of systematic assessment in improving educational programs. University management and policymakers are encouraged to implement continuous evaluation mechanisms, utilize learning analytics, and adopt long-term strategies that align interdisciplinary learning factory initiatives with institutional goals and industry needs. Such managerial approaches can strengthen the effectiveness of interdisciplinary learning factory programs and contribute to the development of innovative and future-ready graduates.

CONCLUSION

The findings of this study demonstrate that interdisciplinary learning factory models have a significant and positive impact on students' innovation skills in higher education. The integration of interdisciplinary collaboration, technology-enhanced learning, project-based activities, and industry-oriented practices within learning factory environments contributes to the development of key dimensions of innovation competence, including creative thinking, problem-solving ability, critical thinking, and collaborative skills. The statistical analysis confirms that interdisciplinary learning factory models are not only effective as an educational approach but also serve as a strategic framework for fostering innovation-oriented competencies that are essential in contemporary educational and industrial contexts.

This study answers the research question by providing empirical evidence that interdisciplinary learning factory models significantly influence students' innovation skills. The results indicate a strong relationship between interdisciplinary learning environments and innovation competence, supporting the assumption that cross-disciplinary integration and practical learning experiences enhance students' innovative capabilities. This study has several limitations. Methodologically, the research relies on self-reported survey data, which may introduce response bias and subjective evaluation effects. Contextually, the sample is limited to specific higher education institutions implementing interdisciplinary learning factory programs, which may restrict broader generalizability across diverse educational systems. Analytically, the study applies a cross-sectional quantitative design using regression analysis, which limits causal inference over time and does not capture longitudinal learning dynamics. These limitations suggest the need for future research employing longitudinal, multi-institutional, and mixed-method approaches to strengthen causal interpretation and expand contextual applicability.

Future research is recommended to expand the scope of investigation by involving more diverse educational contexts, institutions, and disciplines to enhance the generalizability of findings. Further studies could integrate qualitative approaches to explore in-depth perspectives on how interdisciplinary learning factory models influence innovation skills and learning processes. Additionally, future research may incorporate advanced analytical methods and emerging technologies, such as artificial intelligence and learning analytics, to examine the dynamic interactions between interdisciplinary learning environments and innovation competence. Such efforts are expected to enrich the theoretical framework and practical implementation of interdisciplinary learning factory models, contributing to the continuous development of innovative and sustainable educational practices.

5. DECLARATIONS

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5.2. Author Contributions

Validation was conducted by: SD. Conceptualization was completed by: KM. The methodology was developed by: MM. Formal analysis was performed by: FA. Writing, review, and editing were carried out by: SD. Visualization was completed by: NF. All authors, including: SD, KM, MM, and FA, have reviewed and approved the final version of the manuscript.

5.3. Data Availability Statement

The corresponding author is willing to share the data associated with this study upon request.

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5.5. Declaration of Competing Interest

The authors declare that they have no known financial conflicts or personal relationships that could have influenced the outcomes or publication of this work.

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