

METHODOLOGY

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Framework for interdisciplinary research between engineering and behavioral sciences

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Abstract

The integration of engineering with behavioral sciences, such as education and psychology, facilitates the combination of technical capabilities with the study of human behavior, which contributes to the design of more effective interventions. However, this interaction faces challenges due to paradigmatic differences and skills. This paper aims to analyze areas of convergence and opportunities in interdisciplinary research between engineering and behavioral sciences, as well as to propose a framework for the execution of research. Empirical research is a point of convergence between both disciplines, where methods such as observation and experimentation are used. While behavioral sciences focus on complex social interactions, engineering focuses on system design and evaluation. The proposed framework seeks to distinguish and deepen the roles of each researcher through a collaborative process approach that includes active participation in identifying needs, executing research, and producing scientific results. To ensure the effectiveness of the framework, its validation through case studies and empirical research, the creation of interdisciplinary collaborative networks, and the standardization of methodological guidelines are recommended. In addition, the incorporation of specific quality checklists will strengthen the structure and reproducibility of interdisciplinary research, driving scientific and technological advances in the understanding and application of engineering interventions in human contexts.

Keywords Interdisciplinary research, Engineering, Behavioral science, Methodology framework

Interdisciplinary research between engineering and behavioral sciences is increasingly recognized as critical to addressing complex societal challenges [40, 99, 106]. This integration strengthens the technical capabilities of engineering and deepens the understanding of human behavior for the design and effective implementation of solutions to various contemporary problems [6].

Both disciplines are diverse and, in some cases, divergent. Behavioral sciences are tools for intervention in the social context and encompass disciplines such as psychology, neuroscience, anthropology, sociology, education, health, and their diversifications [32]. While engineers generally focus on design science, which refers to the design and



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investigation of artifacts that are designed to interact in a problematic context in order to improve it, it seeks to produce variables, optimize processes, and is even presented for commercial purposes [15, 20, 69, 102].

Resistance to the integration of engineering into the behavioral sciences is historical [28, 58, 77] and can be explained by the tendency of the engineering culture to prioritize technocentric approaches, which makes it difficult to embrace social responsibility and commitment [70]. While the goal of engineering is to improve individual and collective life, its designs can generate unintended consequences that result in undesirable social and behavioral impacts [92]. This resistance may also be related to an apolitical stance within engineering, which tends to focus on corporate concerns rather than critically addressing the social order and the implications of science and technology [77]. Additionally, behavioral science has pointed out that machine learning has conceptual and accuracy-related errors, which further contribute to resistance in its adoption [13].

These divergences have extended to research; engineering research focuses on the science of design in a specific context, while the behavioral sciences analyze and understand integral changes in relation to the exposure and implementation of these designs; thus, interdisciplinary research allows considering the problem from different points of view and applying research methods from a variety of related scientific disciplines, such as natural, technical, and humanitarian [53].

The development of a region and the generation of scientific and technological knowledge do not arise from the knowledge of a single discipline [7, 10, 91]. It is the integrality of knowledge and training that allows for clear and timely solutions, but above all, it points to the construction of new models with diverse approaches to knowledge [38]. Thus, the call for sustainability and high-quality solutions can be addressed with an interdisciplinary perspective, focusing on innovation, information, and collaboration between different stakeholders [57].

Despite the publication of interdisciplinary projects, the authors face difficulties such as epistemic, ideological, and personal differences; the main obstacle lies in the interpretation of results, since the criteria of each discipline may not coincide with those of other disciplines [21, 80, 86, 93]. Therefore, it is essential that researchers recognize the fragmentation inherent in their areas of expertise to facilitate effective integration [55]. In general, the challenge for researchers is also to master explicit and tacit skills [50]. Four factors have also been identified as critical to the success of the interaction of disciplines: the paradigms or epistemologies, the skills and competencies of the scientists, the institutional context of the research, and the organization of the researchers [33].

Recent research on this type of convergence suggests standardizing open scientific practices in the behavioral sciences and engineering [2, 12, 17, 43, 73, 84]. Likewise, we have identified the need for readjustments and methodological advances for the effective design of interdisciplinary research projects that combine engineering and social and behavioral sciences [26, 27]. In this context, the lack of an explicit design in engineering research [4], the lack of methodological interaction between the different areas of knowledge, the participation of professionals, and the standardization of scientific reports.

This article represents a theoretical proposal. The objective is to analyze areas of convergence and opportunities in interdisciplinary research between engineering and behavioral sciences, as well as to propose a framework for the implementation of interdisciplinary research as a collaborative process.

1 Difference between methods

Research in the fields of engineering and behavioral sciences has empirical research as its point of congruence. The most representative methods of empirical sciences par excellence are observation, survey, and experimentation [8, 22, 60].

Behavioral science research seeks the prerequisites of interactions and practices deeply entangled with events and dependencies of social and cultural pathways [56, 59, 83]. The process involves various sampling techniques, measurement instruments, and validation procedures to analyze social behaviors and interactions [45, 79]. It is a transdisciplinary field that studies behavior, decision-making, and responses from various theoretical and methodological perspectives [3, 35].

On the other hand, in the engineering field, research covers requirements engineering, systems management and configuration, functional analysis, architectural design and evaluation, decision-making, change management, modeling, scalability, and innovation, among others [5, 20, 54, 65, 94]. It focuses on design science, has its own independent structure, and is transversal to engineering design and development, the specific methodologies are processes based on structural models known as the empirical cycle and the design cycle [102].

In design science, there are two types of problems: design problems that demand a change in the real world as required by stakeholders and knowledge problems that do not seek to change the world but to increase its understanding. The distinction between these two types of problems is diluted in the reports because it is common for questions to be formulated as knowledge questions; however, their approach and resolution are different [102]. Thus, design problems must be solved through the design cycle and knowledge problems through the empirical cycle under a process of 4 activities: 1. Definition of the objectives of the experiment, 2. Design of the experiment, 3. Execution of the experiments, and 4. Analysis of the results [47].

In engineering, research can follow either a case-based or a sample-based approach. Case-based research, similar to that in the behavioral sciences, evaluates an artifact within its context, analyzes its architecture and mechanisms, and derives iterative conclusions applicable to similar artifacts. In contrast, sample-based research employs data analysis to generalize findings through inferential statistics. This integrated framework facilitates a deeper understanding of artifacts and their impact across different contexts [102].

Engineering design is characterized by two key aspects: an artifact is always created with a purpose, and design is both a verb and a noun—meaning it is both an action and an outcome [15]. This purpose becomes particularly relevant when integrating behavioral sciences.

While engineering research is practical and applied, behavioral sciences have a theoretical purpose [51]. From a methodological perspective, behavioral scientists focus on explanatory modeling, whereas engineers are predictive modelers [13]. Thus, the integration of methods creates an environment for interdisciplinary research, enabling data provision, processing, interpretation, and, ultimately, problem-solving.

The methodology for interdisciplinary research (MIR) follows a process-oriented approach in which the research question or hypothesis guides decisions at each stage. This approach places a common objective at the core of the research, regardless of its disciplinary origin, and incorporates a structured procedure to define team roles.

Initially, the interdisciplinary team analyzes the conceptual design of the study (what and why to investigate); subsequently, it examines the technical design (how). Once consensus is reached, the fieldwork is conducted, which can be developed modularly and independently. Finally, the collected evidence is integrated into an interdisciplinary synthesis reflected in the final report [95].

1.1 Successful projects in interdisciplinary research

The study of human–environment interactions, including behavioral sciences, requires distinct research knowledge and methodologies. Interdisciplinary research integrates information, data, methods, tools, concepts, and/or theories from two or more disciplines, focusing on a complex question, problem, topic, or theme, thereby yielding contributions that exceed the sum of their parts [74].

Interdisciplinarity fosters innovation and creativity [30] and facilitates knowledge and technology transfer across various fields [104]. For instance, collaboration between computer scientists and behavioral scientists has enabled diverse research efforts, such as the automatic analysis of interactive play therapy sessions with children and the diagnosis of bipolar disorder using multimodal signals and human-AI collaboration, leading to the development of tools related to well-being [81].

Interdisciplinary integration in engineering education highlights the importance of understanding the connections between the humanities and technical disciplines [46, 76]. Thus, the integration of education and engineering is recognized as essential for enhancing both fields [38, 78], as it enables innovative teaching methods in engineering education [31, 75, 90, 105] while simultaneously applying engineering principles to improve educational processes [25, 39, 44, 87].

In addition, there have been research successes related to the arts and aesthetics: eMotion (Mapping Museum Experience), which focused on aesthetic experiences in a fine arts museum setting [49, 67, 97, 98, 101], and ECR (Experimental Concert Research), which investigated the musical experience at concerts [97, 98] with intensive cooperation with behavioral scientists, technicians, programmers, and art professionals.

Associates in other areas have also allowed the study of the relationship between the acoustic and mechanical properties of different types of asphalt and the quality of life of people living in the vicinity of treated roads and the influence of noise-reducing asphalt layers on the quality of life with the participation of engineers, physicians, and psychologists [100].

1.2 Analysis of the methodological approaches used in interdisciplinary research between engineering and behavioral sciences

There are relatively new and unknown approaches arising from the convergence between the behavioral area and computing. For example, four categories of models are distinguished according to computational social science approaches: descriptive, predictive, explanatory, or integrative, with their respective levels of depth [43].

This classification of methodological models, based on computational social science approaches, can be extended to other engineering fields. It can be integrated into the proposed framework as a tool for selecting the most suitable model based on the specific objectives of interdisciplinary research.

Table 1 Research situations and modeling approaches

Where is the focus?	Research situations	
	Without intervention or distribution changes	Under interventions or distribution changes
Focused on characteristics or specific effects	Quadrant 1—Descriptive modeling: Describes past or present situations (but not causal or predictive)	Quadrant 2—Explanatory modeling: Estimates the effects of changing a situation (but many effects are small)
Focused on predictions	Quadrant 3—Predictive modeling: Forecasts results for similar situations in the future (but may fail under changes)	Quadrant 4—Integrative modeling: Predicts results and estimates effects in unseen situations

A scheme for organizing empirical modeling in two dimensions, representing the different levels of emphasis placed on prediction and explanation. Adapted from [43]

Table 2 Level of Analysis in Research Quadrants

Level	Quadrant 1 Describes something	Quadrant 2 Tests a causal statement	Quadrant 3 Test a predictive (passive) statement	Quadrant 4 Test both causality and predictive accuracy
Low	Reports stylized facts	Test for an effect different from zero	Predicts directional or aggregated results	Predicts directional or aggregated results under changes or interventions
Medium	Reports population averages	Test for directional effects	Predicts the magnitude and direction of aggregated results	Predicts the magnitude and direction of aggregated results under changes or interventions
High	Reports individual results	Estimates the magnitude and direction of an effect	Predicts the magnitude and direction of individual results	Predicts the magnitude and direction of individual results under changes or interventions

A labeling scheme to clarify the nature and level of research contributions. Adapted from [43]

In Table 1, the rows highlight the specific features that require attention and the specific features that might affect an outcome, while the columns specify what types of situations are being modeled: a 'fixed' situation in which there are no changes or interventions, or one in which features or inputs are actively manipulated or change due to other uncontrolled forces.

The depth sought in research situations can also lead to controversy between scientific disciplines. To address this challenge, a labeling scheme is proposed to precisely define the nature and level of research complexity. This tool supports decision-making within the proposed framework, fostering consensus and overcoming the methodological debates that often hinder progress in interdisciplinary research.

For example, when developing predictive models, the scheme helps determine whether the research is passive—aimed at verifying a predictive statement—or whether the goal is to construct a model capable of anticipating both the magnitude and direction of change in an outcome, based on the behavior of the dataset at the group level. In Table 2, the rows distinguish between different levels of complexity in each quadrant [43].

On the other hand, from the perspective of action research, research is conceived as a spiral process between action (change and improvement) and research (understanding and comprehension). It consists of several stages: the first, termed *conceptualization*, establishes the theoretical foundations. The second, called *investigative correlations*, identifies relationships between different approaches, considering perspectives from various fields, such as behavioral sciences and engineering. Subsequently, the *data collection and consultation* phase takes place, which is considered the core of the research. This phase includes information gathering, analysis, formulation of results,

and validation. It is followed by the *prototype development* stage, where the invention is implemented, and finally, the *personalization* stage, where innovation priorities for implementation are identified [57]. Upon completion of the cycle, it restarts.

Research by [43] suggests three key points for the application of computational social science methodology: integration of explanatory and predictive models and employing an explicit labeling system to clarify individual research contributions with the identification of quadrants and levels. The importance of research design lies in differentiating multi-method approaches [64, 85]. In addition, throughout the design process, an explicit discussion among all stakeholders is essential, without neglecting ethical issues related to human subjects [95].

Also, the key data sources derived from the action research and used in the discussion are based on the project proposal, scientific deliverables, and use cases, which are integrated with the final comments collected from the project partners [57].

1.3 Argumentation and proposal for an interdisciplinary research between behavioral sciences and engineering

The research models that integrate behavioral sciences and engineering have in common the search for knowledge through empirical methods to solve a problem; the proposal is to synergistically link the research processes through a framework that allows solving real problems from different perspectives and is visualized in Fig. 1. Where: the rectangles specify the activities that make up the research process, the arrows indicate the flow of the process, and the colored rectangles represent the relative participation of each area in the activities corresponding to specific tasks within the process (subprocess). Additionally, the dashed lines allow grouping of the activities of the empirical cycle and the design cycle. Finally, the brackets enclose the activities corresponding to each stage of the interdisciplinary research process.

Interdisciplinary research between engineering and behavioral sciences is proposed as a process structured in three phases, which begins with the identification of a need that requires a solution (input), continues with the execution of the research (development), and ends with scientific products or artifacts/systems (output). This process is based on the action-research model, with modifications that disaggregate the activities and the level of responsibility of the research professionals in each area and are distributed in 5 sequential stages: 1. Research conceptualization and correlation. 2. Data collection and queries, 3. Reporting of results, 4. Prototype development, and 5. Customization and implementation. In total, the process includes 14 substages.

The first stage, conceptualization and correlation of research, focuses on the construction of fundamental concepts, a process that should be led mainly by professionals in behavioral sciences, given their focus on conceptualization and trying to understand human behavior in internal and social aspects, while engineering professionals, once the concepts are defined, will be able to structure technical problems and design solutions.

At this stage, research questions and problems are also formulated, both in knowledge and design, in a process of collaboration between both areas with the natural perspectives of each discipline. And finally, research objectives are formulated that require shared participation, albeit with varying degrees of involvement that vary according to the specific objective. When the emphasis is on understanding the factors that influence some phenomenon, the leadership lies with the behavioral sciences; on the other hand,

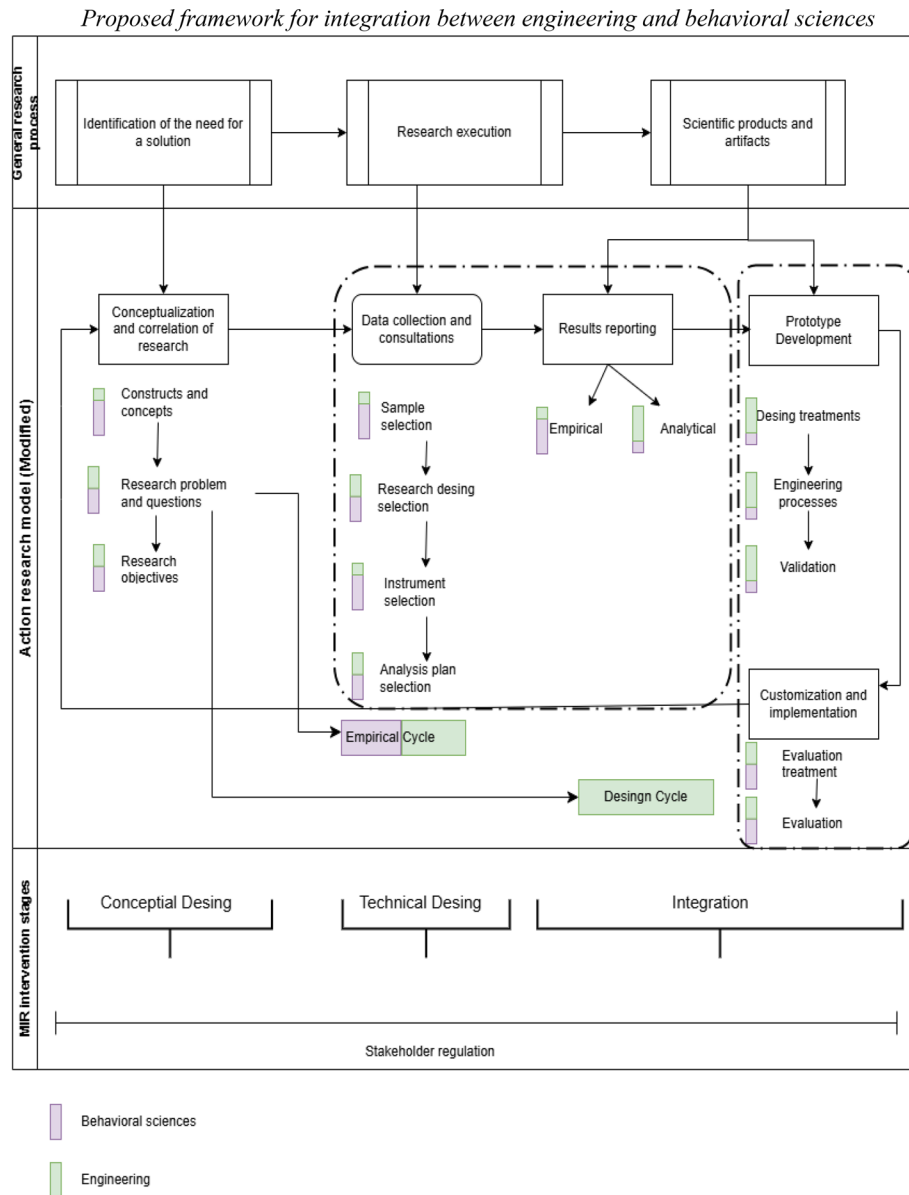


Fig. 1 Proposed framework for integration between engineering and behavioral sciences. The color bar shows the level of participation of each area in the main activities proposed; the more predominant a color is, the greater its participation. The estimated participation is secondary, significant, and predominant, respectively. The dashed lines indicate the time at which the empirical cycle and the design cycle are executed

when the results of a technical solution need to be assessed, engineering takes the pre-dominant role.

The resolution of knowledge research problems should be led by behavioral scientists, while design problems should be led by engineering scientists. When solving design problems, the design cycle is executed [102] with prototype development with greater participation of the engineering area, while in the customization and implementation stage, participation is shared with the search to please the initial requirements posed in the research problem, in which design and knowledge combine in both areas of knowledge.

This interdisciplinary interaction ensures that the fundamental concepts and objectives are comprehensive, operational, and feasible to be addressed in later stages of the framework, thus laying a solid foundation for the integration of technological intervention strategies with adequate theoretical and methodological support.

On the other hand, to solve the problem and the conceptual questions, we proceed with the activities of the second stage: data collection and consultations, and with the third stage: the report of results. In the area of engineering, these processes are known as the empirical cycle [102] and in the behavioral sciences as the methodological process and reporting of results. Participation in this section is completely shared and independent with parallel but communicative processes, in which researchers show their methodological domains, in which undoubtedly behavioral scientists are the ones who have better criteria and arguments for the selection of samples and instruments, while engineers can give the support of the optimization techniques employed in these processes, such as the use of digital forms, automated screening, etc.

It is in the selection of research design (*) that the labeling suggestion [43] can be taken, complemented, depending on the nature of the study, with observational or experimental types of research in the behavioral areas. The selection of the analysis plan (**) is modifiable and changeable according to the nature of the data and the objectives set. It is only at the moment of processing the information that the behavior of the data is certain and decisions are made about the presentation formats and statistical tests to be carried out.

In the fourth stage of prototype development, it is the moment in which the professionals of the engineering area are put in charge of the research. It is here when the design treatments, engineering processes, and validation of the artifacts, software, intervention, etc., are executed. With the guarantee that conceptually the purpose of the solution is supported by the behavior and a specific problem shared between both areas.

The last stage, customization and implementation, is the moment in which the relevant technical and conceptual adjustments are made, the intervention or interaction is applied, and its effect is evaluated with the idea of adjusting the findings and needs of the participants. As generally occurs in research, new enigmas, questions, and research needs are opened so that, when this cycle is completed, the first stage begins again.

It is recommended that the interdisciplinary research team maintain parity and equity in both disciplinary and gender aspects. This approach promotes diversity of perspectives, enriches problem analysis, and ensures that the research remains inclusive, representative, and socially responsible.

In the proposed framework, which brings together different perspectives and processes, it can be seen that in the stages of the MIR (Interdisciplinary Research Method), there is the conceptual design with the identification of the solution need with the conceptualization and correlation of research; the technical design is part of the research execution with data collection and consultations; and, finally, the integration in which the scientific products and artifacts proposed are crystallized, without losing sight of the validation and evaluation of the instruments, research, and results.

It is essential that, for research to be of quality, each stage of the process be regulated and executed around the interests of the stakeholders, understood as the public interest, health personnel, teachers, psychologists, and all those involved in the behavioral area, while also fulfilling technological requirements and ensuring a good user experience.

Table 3 contrasts the main characteristics of behavioral science research, Wieringa's design cycle as part of engineering sciences, and the MIR. It incorporates an updated interdisciplinary proposal that integrates behavioral and engineering sciences to address complex problems requiring both conceptual understanding and technical solutions. The comparison emphasizes methodological orientation, types of problems addressed, and the dynamic interaction between theory and practice, encompassing both the understanding of human phenomena and the development of prototypes, systems, or technological interventions.

1.4 Expert evaluation and illustrative case of the proposed framework

A hypothetical pilot case is presented that simulates the application of the proposed interdisciplinary approach in a university context. Although the case has not yet been implemented, it serves to illustrate how the framework could function in practice.

For validation, a template was used to assess sufficiency, clarity, coherence, and relevance, using a Likert scale from 1 to 4, where 1 = does not meet the criterion, 2 = low level of compliance, 3 = moderate level of compliance, and 4 = high level of compliance [36].

For the expert evaluation, the template was used to assess content validity through expert judgment [36]. This template includes four items and evaluates the criteria of sufficiency, clarity, coherence, and relevance [29] using a 4-point Likert scale, where 1 = does not meet the criterion, 2 = low level of compliance, 3 = moderate level of compliance, and 4 = high level of compliance. Although initially designed to evaluate construct items in questionnaires, the template demonstrates sufficient flexibility for its application in the validation of frameworks, whose content requires systematic and well-founded expert judgment [29, 37].

Four experts participated in the evaluation process, which represents an adequate number according to methodological recommendations for expert judgment procedures [37]. Two held PhDs in behavioral sciences (one male and one female), with 22 and 23 years of academic and scientific experience, respectively. The other two were female professionals from the field of engineering, both holding master's degrees and currently pursuing doctoral studies, with 25 and 12 years of professional experience in academia and research. This composition ensured a multidisciplinary perspective that integrated behavioral sciences and engineering, aligning with the interdisciplinary nature of the evaluated framework.

All experts agreed that, overall, the framework was valid and demonstrated a high level of compliance with the criteria of sufficiency, coherence, and relevance. The criterion of clarity received a moderate level of compliance, which, according to the reviewers' comments, was primarily due to the use of technical terminology. This observation was addressed by including a glossary at the end of this study Table 4.

The experts also highlighted the importance of assigning greater responsibility to professionals in the behavioral sciences for managing the theoretical framework, sample selection, and the design and selection of measurement instruments. They also emphasized the need for training aimed at facilitating the integration of interdisciplinary research within scientific training environments.

The theoretical framework was reviewed and evaluated by experts, and their judgment was used to calculate the content validity index [48]. Inter-rater agreement was assessed

Table 3 Comparative analysis of methodological approaches in behavioral science, engineering, interdisciplinary research and proposed framework

Research aspect	Behavioral science	Engineering science	MIR	Proposed framework
Main purpose	To understand, explain, and predict human behavior, decisions, and interactions	To solve design or knowledge problems through structured cycles	To integrate knowledge and methods from different disciplines to address a common research problem	To integrate the theoretical and methodological approaches of engineering and behavioral sciences to solve complex problems that require both conceptual understanding and technical solutions. It seeks to generate applicable knowledge and functional artifacts supported by solid theoretical foundations
Nature and approach	Theoretical and empirical: aims for explanatory and predictive models	Practical and applied: predictive models focused on the creation and evaluation of artifacts	Process-oriented; combines theory and practice	Interdisciplinary approach based on the action-research model, process-oriented. It combines theoretical, empirical, and design activities in three phases: input, development, and output. Developed through five stages and fourteen substages. It promotes equitable participation of professionals from both areas and fosters disciplinary and gender diversity
Type of problem addressed	Knowledge problems regarding behavior, cognition, and social processes	1. Design problems (creating solutions) – Design cycle 2. Knowledge problems (understanding phenomena) – Empirical cycle	Complex problems requiring integration of knowledge and methods from diverse disciplines	Knowledge problems (led by behavioral sciences) and design problems (led by engineering) converge in the formulation of theoretical–practical solutions
Process structure	1. Problem formulation and theoretical framework 2. Study design and instrument selection 3. Data collection (observation, survey, experiment) 4. Data analysis and interpretation	1. Definition of experiment objectives 2. Experiment design 3. Experiment execution 4. Result analysis	1. Conceptual design (what and why to investigate) 2. Technical design (how) 3. Integration (synthesis in final report)	1. Research conceptualization and correlation: theoretical formulation and definition of research questions and objectives 2. Data collection and consultations: use of parallel empirical methods 3. Results report: interdisciplinary analysis and synthesis 4. Prototype development: creation and validation of artifacts 5. Personalization and implementation: adjustment, application, and evaluation of the intervention
Unit of analysis	Individuals, groups, or social and cultural contexts	Artifacts (models, systems, processes) within application contexts	Complex phenomena lacking explicit definition of the interdisciplinary scope	Phenomena integrating human, social, and technological variables. The unit of analysis may vary between individuals, groups, application contexts, or developed artifacts, depending on the problem's nature

Table 3 (continued)

Research aspect	Behavioral science	Engineering science	MIR	Proposed framework
Validation	Psychometric validation, demonstration of theories through statistical and theoretical analysis, and generalization based on samples	Evaluation of artifact performance and impact; contextual generalization	Interdisciplinary synthesis of obtained knowledge; coherence across disciplines	Validation occurs at three levels: 1. Conceptual: ensuring theoretical coherence 2. Empirical: through data collection and analysis 3. Applied: functional evaluation of prototypes or artifacts
Theory–practice	Theory predominates; empirical results strengthen or refute theoretical models	Practice predominates; theory serves as a basis for design and evaluation	General integration of theory and practice, occasionally leading to practical applications	Theory guides the initial stages: conceptualization and correlation, while practice dominates the development and application phases. Both dimensions are mutually reinforcing: behavioral theories inform technical design, and technological outcomes refine theoretical explanations, closing a continuous cycle of interdisciplinary learning

MIR (Methodology for Interdisciplinary Research)

Table 4 Expert evaluation results

Variable	Level	Frequency
<i>Sufficiency</i> Includes all key components to adequately guide an interdisciplinary investigation	High level of compliance	4
<i>Clarity</i> The stages and functions are easily understood	Moderate level of compliance	1
	High level of compliance	3
<i>Coherence</i> There is a logical and clear relationship among all components	High level of compliance	4
<i>Relevance</i> The framework is relevant and applicable to interdisciplinary studies between behavioral sciences and engineering	High level of compliance	4

3 subjects/items and 4 rates

using Krippendorff's Kappa coefficient for ordinal data with 3 subsects and 4 rates, computed using the open-source statistics program Jasp 0.95.1.0 from the University of Amsterdam. A measure of reliability that facilitates triangulated evaluations among judges and reinforces the robustness of decisions based on expert judgment through a statistical method [48, 63].

The interpretation scale was applied to categorize the degree of agreement between observers. Values below 0.01 indicate no agreement, while values ranging from 0.01 to 0.20 represent slight to minimal agreement. A value between 0.21 and 0.40 denotes fair or reasonable agreement, with moderate agreement indicated by values between 0.41 and 0.60. Substantial agreement is observed in values ranging from 0.61 to 0.80, and values between 0.81 and 1 reflect almost perfect agreement [62, 63]. A value of 0.92 (95% CI Lower = 0.84; 95% CI Upper = 1.00) was obtained, reflecting almost perfect agreement. This indicates consensus in the scoring process among the evaluators. It also reflects the interchangeability of the measurement instruments and the reproducibility of the measure [37].

Below, the hypothetical case evaluated in conjunction with the proposed framework will be presented.

Title: Optimization of statistics education based on learning style diversity: Hypothetical case.

Objective: The aim of this pilot study is to evaluate the academic performance of university students following the application of adaptive learning technologies.

Methodology: The project has a quantitative approach that will be carried out in a university statistics course, combining educational knowledge about teaching methods and statistics with process engineering techniques to personalize learning according to the individual characteristics of students. Technologies such as adaptive learning management systems (LMS) will be used to collect data on students' preferences to adjust the content and pace of instruction.

The roles within the validation plan are recognized as behavioral sciences (BS) and engineering (E), and participation is identified as secondary (sec), significant (sig), and predominant (pre) Table 5.

2 Discussion

2.1 Theoretical implications

Science depends on its intended purpose; when the goal is purely cognitive, it results in pure science, whereas applied science (technology) builds upon pure science but is directed toward practical applications [34, 42, 71]. Interdisciplinary research spaces often aim to translate and mediate between these distinct perspectives and stakeholder demands (Kryzstoforska et al., 2023).

Scientific research is a complex and dynamic process that requires constant interaction between theory and empirical practice [19]. Its goal is to interpret phenomena, formulate, verify, and refine theories to generate knowledge and solve various types of problems [52]. This process involves cognitive changes that occur when scientific findings are made publicly available, allowing individuals to expand their knowledge [24].

The proposed framework creates opportunities for integrating theoretical and practical approaches. It provides an organized process that fosters effective interdisciplinary collaboration. This supports the translation of scientific knowledge into applied solutions that address the need for positive impact in developing societies, aligning with the abductive theory of method (ATOM) in behavioral sciences [41].

2.2 Human-centered design

Interdisciplinary research focused on humans includes studies related to well-being, climate, health, and education ([23], Kryzstoforska et al., 2023; [57, 61]).

The proposed framework addresses the need for human-centered engineering that adapts to emerging tasks, as media technologies enable the emergence and evolution of new patterns of knowledge and experience [11, 16, 88, 89].

The proposed framework fosters interdisciplinary collaboration through its organized structure. It promotes a holistic approach that enhances research efficiency. By centering on human beings and their contexts, the framework drives scientific and technological advancements. It also supports human-centered development, focusing on improving well-being and quality of life.

Table 5 Illustrative case for the proposed framework for integration between engineering and behavioral sciences: Optimization of statistics education based on learning style diversity—procedure and intervention participation

MIR	Stage	Procedure of the overall process		Participation	
		Substage	Task	BS	E
GP = Identification of the need for a solution					
Conceptual design	1. Conceptualization and correlation of research	Constructs and concepts	Literature review, justification, and definitions about learning style diversity, optimization of education of adaptative learning technologies, etc.	pre	sec
		Problem formulation	The lack of personalization in the teaching of statistics may lead to poor academic performance and learning difficulties.	sig	sig
		Research objectives	Identify predominant learning styles and relate the learning methodology to academic performance. And the definition of technical objectives for the adaptive system—to be used in the design cycle.	sig	sig
GP = Research execution (Empirical cycle)				BS	E
Technical design	2. Data collection and consultations	Sample selection	Students from a university statistics course. Inclusion and exclusion criteria are based on the needs, access to the study population, and elements found in the conceptualization of the research.	pre	sec
		Research design selection	Longitudinal quasi-experimental research with experimental and control groups. With the assignment of Hofman's categorization (integrative modeling—level medium)	sig	sig
		Instrument selection	Selection of learning style questionnaires, monitoring tools within the LMS, and Academic performance records	pre	sec
		Analysis plan selection	Parametric or non-parametric tests will be used depending on the behavior of the data, preferably using repeated measures ANOVA, post hoc tests, and a 5% significance level. The open-source software JASP version 0.19.3.0 will be used.	sig	sig
GP = Scientific products and artifacts				BS	E

Table 5 (continued)

MIR	Stage	Procedure of the overall process		Participation	
		Substage	Task	BS	E
Integration	3. Results reporting	Empirical	Report direct observations and reflect the results without value judgments.	pre	sec
		Analytical	Connects theory with the data and offers explanatory interpretations based on existing models or theories	sec	pre
	4. Prototype development	Design treatments	Designs technical interventions based on the research objectives according to the users' interests.	sec	pre
		Engineering processes	Implements engineering processes, such as process optimization and technical strategies for the development and enhancement of technological solutions.	sec	pre
		Validation	Validates the instruments, processes, and interventions through rigorous tests and evaluations as outlined.	sec	pre
	5. Customization and implementation	Evaluation treatment	Evaluates the implemented interventions to determine their effectiveness and suitability with ethical principles.	sig	sig
Evaluation		Evaluates the obtained results in a comprehensive manner, considering the established variables and objectives, as well as user interaction and experience, to identify areas for improvement in the prototypes	sig	sig	

The specifications within the general research design and roadmap may change based on the researchers' judgment in the real field. MIR = MIR (Interdisciplinary Research Method) intervention stages. The tasks will be carried out by the research team members with the necessary participation. This will involve ongoing dialogue to meet both the research objectives and the interests of the stakeholders.

2.3 Practical relevance

The methodological framework for interdisciplinary research facilitates research design and fosters interdisciplinary collaboration, promoting research integrity by enhancing critical elements of mutual interest [18, 95]. This approach enables positive experiences in learning and education processes, paving the way for new knowledge and human capital development [14].

The convergence of behavioral sciences and engineering can provide mediation and informed insights to complement design processes with implementation scenarios, supporting data modeling and decision-making with synergistic potential in interdisciplinary research (Kryzstoforska et al., 2023). This approach aligns with the real needs and realities of both science and society.

3 Conclusion

The integration of behavioral sciences into engineering design is fundamental to understanding the behavioral implications of engineering interventions, although it presents challenges due to the dynamic nature of human behavior and social interactions.

The adoption of new technologies transforms habits and relationships, but their impact is difficult to predict, requiring an evaluation beyond technical efficiency, incorporating economic, social, and moral dimensions. In this sense, user feedback is key to improving designs, although their implementation can be slow and costly. Therefore, this study emphasizes the need for an integrated approach that links engineering with behavioral sciences, which has the potential to contribute to the development of more effective solutions adapted to human dynamics.

In this study, a framework for addressing challenges and seizing opportunities in interdisciplinary research is presented. It is a conjunction of methods and perspectives of previous authors and adds a process structure with the distinction of roles and contributions in charge of each area. This proposal offers a solid structure that fosters collaboration between engineering and behavioral sciences, which aims to promote innovation and complex problem-solving by integrating methodologies and regulating participation to significantly contribute to improving the practice of interdisciplinary research in the future.

4 Recommendations

Given the increasing demand for integrated approaches and the inherent complexity of interdisciplinary research in the behavioral sciences and engineering, it is essential that this conceptual framework undergo empirical validation to ensure its robustness. Such validation could be conducted through pilot tests, case studies, and even comparisons with traditional approaches. This process will enable the identification of strengths, limitations, and areas for refinement, ultimately facilitating the optimization of the framework's performance and establishing it as rigorously tested as an empirical tool.

To strengthen the empirical validity of the proposed framework, the following process is recommended:

1. Design a formal validation protocol that includes validation objectives, type of study, target population, data collection and analysis techniques, as well as a clear definition and determination of the framework's success criteria (e.g., effective interdisciplinary integration, process improvement, impact on decision-making, outcomes produced, time performance, among others).
2. Apply the framework in real-world interdisciplinary settings in which the phenomenon under study is addressed, ensuring both disciplinary and gender diversity in alignment with the SAGER (Sex and Gender Equity in Research) guidelines. This ensures a rigorous consideration of sex and gender factors when evaluating the framework's applicability and generalizability across different contexts.
3. Record the performance of the success criteria through a mixed-methods approach, combining quantitative instruments (e.g., scales, rubrics, performance indicators) and qualitative techniques (e.g., semi-structured interviews, focus groups, non-participant observation) to enable triangulation and a deeper understanding of the framework's application.
4. Verify fidelity of implementation, ensuring the framework is applied as designed, through the use of checklists, structured observations, or facilitators'/interveners' logs.

5. Evaluate the experiences of the involved stakeholders using qualitative and/or quantitative methods to assess usability, clarity, and relevance from the users' perspective.
6. Identify contextual enablers and barriers, documenting the conditions that facilitate or hinder the application of the framework. These findings should guide potential structural, operational, or even conceptual adjustments.
7. Thoroughly document and publish the validation process to ensure transparency and replicability of the results.

Additionally, the outcomes obtained through the application of the framework can be compared with other existing research methods or those frequently employed by researchers. This comparative analysis can empirically reveal advantages, limitations, and distinctive contributions. Although the validation process may take several years, it is considered essential for improving research practices and scientific output.

It is recommended that interdisciplinary collaboration networks be fostered to strengthen and continuously improve the proposed framework. Its flexibility allows it to be adapted to different methodological approaches—quantitative, qualitative, and mixed—and to be applied in different areas of knowledge, such as STEM education, the design of digital health technologies, and cognitive engineering, among others. It is also recommended, in line with the experts' comments, that training sessions be conducted with this framework for interdisciplinary teams in scientific environments.

To ensure the effectiveness of this methodological framework, it is crucial to conduct periodic evaluations and implementations that facilitate the evolution of research across various contexts. Furthermore, following the completion of the research, assessments of performance, compatibility, and interaction among the research participants should be conducted to foster improvements not only in the framework but also in the overall research outcomes.

Standardization, through methodological guidelines and specific checklists, will facilitate the adoption of the framework in the scientific community and promote more structured, reproducible, and transparent research. In the generation of reports, several areas, such as health, psychology, and education, widely use formats and checklists, among them STROBE, TREND, SPIRIT, and CONSORT, and their respective extensions, PRISMA-Education, CONSORT-Education, and STROBE-Psychology, as well as Wieringa [102] who proposed a series of checklists adapted to information systems and software engineering.

However, in the absence of a checklist for interdisciplinary research between engineering and behavioral sciences, it is recommended to develop tools and checklists in order to achieve quality interdisciplinary research. These checklists should contemplate key aspects, such as clarity in interdisciplinary integration, definition of stages and roles, exposition of validation criteria, and results from both perspectives.

5 Limitations

This interdisciplinary research framework has some limitations. Validation was conducted with a limited number of experts from specific areas of the behavioral sciences and engineering, and it has not yet been tested with real empirical cases. Therefore, its generalizability across all contexts in behavioral sciences and engineering may be limited, and adaptations might be required for specific research settings.

5.1 Glossary

Framework Structured practical guidance or a tool to guide the user through a process, using stages or a step-by-step approach [66].

Design science A research approach focused on the study of artifacts within a defined context. Its goal is both to design and to investigate technological solutions relevant to real-world problems. The two key components are the artifact in context, which is the object of study, and the two main activities: designing the artifact and investigating it [102].

Engineering science: Engineering science refers to a conglomeration of scientific disciplines that focus on the development and application of technical systems based on the laws of nature and social objectives [9].

Design cycle A structured and iterative process used in engineering to develop and refine solutions through various stages such as problem investigation, treatment design, and treatment validation. This cycle is repeated multiple times throughout the research project to adjust and improve the designed solutions [102].

Empirical cycle A systematic approach to scientific research that consists of several phases, including the observation of phenomena, hypothesis formation, experimentation, and evaluation. The empirical cycle allows for the validation and adjustment of scientific theories through the collection and analysis of data in a real-world context [102].

The methodology for interdisciplinary research (MIR) a type of research that integrates theoretical frameworks, methods, and skills from two or more distinct scientific disciplines through a common conceptual model, applied throughout all phases of the research process [1].

Acknowledgements

Our sincere gratitude SASIORE for their invaluable support and contributions throughout this research.

Author contributions

VP, conceptualized the study, conducted the investigation and formal analysis, and drafted the first draft of the manuscript. JM, critically reviewed the framework and contributed to writing, review, and editing. All authors contributed to the study conception and design, commented on previous versions of the manuscript, and read and approved the final version.

Funding

No funding was received; the researchers conducted the study independently.

Data availability

A small set of data was collected through expert judgment as part of the preliminary validation of the proposed framework. These data are available from: <https://doi.org/10.6084/m9.figshare.30290833.v1>.

Declarations

Ethics approval and consent to participate

Not applicable. This is a methodological article that does not involve human participation or sensitive information; it is exempt from approval by an ethics committee.

Competing interests

The authors declare no competing interests.

Received: 24 April 2025 / Accepted: 13 October 2025

Published online: 17 November 2025

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