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Consultancy-Based Interdisciplinary Project-Based Learning in Engineering Education: Integrating Technical Design and Production Planning

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Abstract

Background: Engineering education often separates technical design from production planning, although professional product development requires these forms of reasoning to evolve together.

Aim: This article analyses a consultancy-based interdisciplinary project-based learning model implemented between the "Introduction to Electromechanical Project" (IEP) and the "Introduction to Industrial Project" (IIP) courses.

Method: The study follows an implementation-oriented qualitative descriptive case-study design, supported by documentary analysis of project briefs, milestone criteria, student presentations, meeting minutes, consultant reports, photographs, and an anonymous satisfaction questionnaire.

Findings: The documentary evidence shows how two IEP groups developed rover-based project concepts while six IIP consultant groups translated those concepts into production-planning, manufacturability, quality-control, logistics, and cost scenarios. Questionnaire results from 25 of 32 students indicated favourable perceptions, especially for skills development, teamwork, communication, and problem-solving, while also identifying coordination between courses as the main operational challenge.

Contribution: The article provides a transferable implementation framework for integrating technical design and production planning through structured inter-course consultancy.

Keywords: consultancy-based learning; interdisciplinary engineering education; project-based learning; production planning; documentary analysis

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1. Introduction

Engineering education frequently places technical design and production planning in neighbouring, but weakly connected curricular spaces. Students may learn to size a system, select components, or reason about functional performance in one course, while learning process planning, organisation, and quality control in another. Yet industry rarely separates these logics. Product definition, manufacturability, cost, maintenance, supply, and risk evolve together, especially in electromechanical systems where structural, electrical, electronic, and control decisions interact from the outset (Jamnia, 2016, 2023; Magleby et al., 1996).

This paper addresses that problem through a consultancy-based inter-course pedagogical practice linking two third-year undergraduate courses at the University of Beira Interior: "Introduction to Electromechanical Project" (IEP), attended by students in Electromechanical Engineering (EME), and "Introduction to Industrial Project" (IIP), attended by students in Industrial Engineering and Management (IEM). In the local design, IEP students developed the technical design and sizing of the electromechanical products or systems, while IIP students worked on the associated production process, decentralised production logic, organisation, and industrial planning. IIP groups were positioned as consultants to IEP groups, so that the same product would be discussed simultaneously from technical and production perspectives.

The paper brings together four complementary layers of analysis. First, it explains the pedagogical architecture of the intervention and its literature-informed rationale. Second, it details the semester project brief and the periodic milestone structure that organises student work. Third, it incorporates documentary and visual evidence from two IEP groups, created and named by student groups as "Advanced Logistics Mobile Assets" (ALMA) and "Engineering for Protection and Advanced Mobility" (EPAM), to illustrate how students interpreted the brief, generated concepts, documented decisions, and publicly defended their evolving projects in mixed sessions. Fourth, it incorporates IIP consultant presentations to show how industrial-project students translated those same concepts into proposals for production architecture, equipment selection, routing, testing, bottleneck management, and economic structuring.

The article presents the design and implementation of an inter-course pedagogical model rather than a controlled impact study. Its value lies in making the local pedagogical architecture explicit, evidencing how the work unfolded over time, and showing how authentic project artefacts can be mobilized as scholarly evidence in engineering education. The foundation is that the consultancy-based model becomes more pedagogically credible when its internal evidentiary chain is visible: not only the intended learning design, but also the project brief, the periodic criteria, the evolving concepts, the meeting records, and the milestone artefacts produced by students. In addition to exposing EME students to industrial engineering and management concepts, and IEM students to mechanical, electrical, and electronic design concepts, the model also supported the development of transversal competencies, including multidisciplinary communication, team building, discussion, and work organisation.

The study was guided by three research questions:

RQ1. Can a consultancy-based inter-course pedagogical model be structured to connect technical design and production planning?

RQ2. How can students produce evidence of the evolution of technical and industrial reasoning during the semester?

RQ3. How did students perceive the pedagogical value and operational difficulties of the interdisciplinary consultancy model?

2. Literature-informed rationale

2.1. Interdisciplinary project-based learning in engineering

Project-based learning is widely used to connect engineering theory with application. In electromechanical and adjacent engineering fields, recent work associates project-based formats with stronger engagement, improved problem framing, and better alignment with professional practice. However, the literature also stresses that project-based approaches are demanding to sustain: they require curriculum coordination, explicit assessment structures, and clear milestones if students are to move beyond unstructured enthusiasm toward defensible engineering decisions (Graham & Crawley, 2010; Shekar, 2014; Kunicina et al., 2024; Mahtani et al., 2026). This caution is especially important when work is distributed across more than one course. Inter-course initiatives can strengthen systems thinking because students must understand how technical and organisational decisions influence each other, but they also increase the demands on coordination. Students need explicit opportunities to negotiate interfaces, clarify roles, and understand stakeholders beyond their own disciplinary comfort zone. The value of such interaction is repeatedly emphasised in engineering education literature that links teamwork, stakeholder analysis, and authentic project work, although there are several difficulties when putting this model in practice (Savage et al., 2007; Howcroft et al., 2023; Todd et al., 1993).

2.2. Integrating design and production reasoning

The need to connect technical design with manufacturing-oriented reasoning is well established in systems approaches to product development. Electromechanical products require the coordinated treatment of mechanics, electricity, electronics, sensing, control, manufacturing, and maintenance. A design that looks satisfactory from a purely technical point of view may still fail in assembly logic, procurement feasibility, lifecycle cost, or serviceability. Educationally, this means that students should learn to treat requirement definition, concept selection, subsystem integration, and production planning as mutually shaping activities rather than isolated steps (Jamnia, 2016, 2023; Magleby et al., 1996; Todd et al., 1993).

Agile and iterative approaches reinforce this perspective. The literature on engineering design education suggests that recurrent review cycles, sprint-like planning, and visible task decomposition help students manage complexity and time pressure. These methods are not a substitute for rigorous engineering reasoning, but they can support it by creating a cadence of documentation, feedback, and revision. For an inter-course model positioned near the end of the curriculum, where students are expected to integrate prior knowledge and apply complementary concepts, such iteration is especially useful because students must repeatedly return to their assumptions after receiving input from another curricular perspective (Edwards, 2017; Jamnia, 2023).

2.3. Feedback, documentation, and experiential structuring

Integrated learning also requires integrated feedback. Research on peer assessment and engineering group work shows that structured rubrics, public review, and documented team processes can support both accountability and reflection. This is relevant at this point because the local pedagogical design did not rely only on the final report. It distributed evaluation across periodic presentations, peer questions, internal group roles, external review by other groups, and cumulative evidence kept in shared digital folders and minutes of the meetings (MoM) (Bailey, 2013; Tien, 2019; Shishavan & Jalili, 2020; Triantafyllou & Timcenko, 2014).

The pedagogical model also incorporates selected elements commonly associated with experiential and game-based learning approaches. It does not transform the courses into a full game. Nevertheless, recurring roles, bounded periodic challenges, visible artefacts, public comparison between groups, and documentary traces of progress create a structured experience in which engagement depends on iteration, communication, and progressive decision-making. These are not superficial motivational additions; they shape how students externalise and defend engineering reasoning (Ahmad, 2024; Bunt et al., 2024; Monteiro & Sousa, 2024).

2.4. Responsible use of generative AI in project-based engineering education

Generative artificial intelligence and large language models are increasingly relevant to engineering education because they can support ideation, documentation, visual communication, and early exploration of design alternatives. However, their pedagogical value depends on how they are introduced and controlled. In project-based learning, AI tools should not replace disciplinary reasoning, technical justification, creativity or engineering judgement. Instead, they can be used as complementary instruments that help students expand initial ideas, compare alternatives, improve communication artefacts, and reflect on the quality of their own decisions.

In the present pedagogical model, AI was therefore introduced as a supervised support tool rather than as an autonomous source of project solutions. This aimed to preserve human-led problem framing while also exposing students to the productive use of emerging digital tools in engineering work.

The use of AI was also extended to visual and communication tasks, such as early concept sketches, group logos, and scenario-based mock-ups of CAD concepts. These artefacts were not accepted as substitutes for technical drawings, CAD modelling, calculations, or manufacturability analysis. Instead, they were treated as complementary communication resources that could support concept explanation, stakeholder discussion, and project identity. The pedagogical emphasis was placed on critical use: students were required to explain the reasoning behind AI-supported outputs, identify sources and assumptions when relevant, and defend the technical content of their presentations during public discussion.

For example, the ALMA and EPAM groups used generative AI tools to create early concept images and scenario mock-ups for their weekly presentations, while IIP consultant groups used AI-generated images to illustrate possible production spaces, packaging, and layout concepts. These images supported communication and discussion, but the technical basis of the projects had to be provided through CAD models, calculations, decision matrices, bills of materials, routing proposals, and cost estimates. During presentations, students were required to distinguish between AI-supported visualisation and validated engineering content.

3. Methodology: qualitative descriptive case study

This study follows an implementation-oriented qualitative descriptive case-study design. The case is the consultancy-based inter-course intervention implemented during one semester between Introduction to Electromechanical Project (IEP), attended by students from Electromechanical Engineering (EME), and Introduction to Industrial Project (IIP), attended by students from Industrial Engineering and Management (IEM). The study combines documentary analysis (educational presentations and reports delivered throughout the semester) with descriptive analysis (anonymous student satisfaction questionnaire). This design allowed to document how the model was implemented and experienced.

3.1. Educational context

The pedagogical intervention was implemented during one semester in two 3rd-year undergraduate engineering courses, IEP and IIP at the University of Beira Interior. The intervention involved the voluntary participation of student groups organised around interdisciplinary project clusters. The documented intervention comprised two IEP groups, ALMA and EPAM, and six IIP consultant groups. Each IEP group was supported by three IIP groups. Therefore, the two IEP cases and six consultant groups analysed in the article represent the complete documented set of participating project clusters.

3.2. Pedagogical intervention

The pedagogical model was structured around consultancy-based interdisciplinary project-based learning. IEP students were responsible for the technical design and sizing of electromechanical systems, while IIP students acted as industrial consultants responsible for production-process planning, manufacturability analysis, layout definition, logistics, quality control, and economic assessment.

The semester combined theoretical-practical classes dedicated to project-management concepts with practical tutorial classes centred on project development, periodic milestone presentations, and inter-group discussion. Periodic presentations followed the project Gantt schedule and were evaluated through professor assessment, peer assessment, and self-assessment.

3.3. Documentary sources

The model application adopts a documentary-analysis approach based on educational documents produced during the semester. The analysed sources included:

(a) project briefs;
(b) semester schedules;
(c) periodic evaluation criteria;
(d) student presentations produced by IEP groups;
(e) consultant presentations produced by IIP groups;
(f) MoM;
(g) photographic records of mixed presentation sessions; and
(h) questionnaire responses regarding student satisfaction with the pedagogical model.

These documents were selected because they provide evidence of project evolution, interdisciplinary interaction, decision-making processes, and industrial interpretation of technical concepts.

3.4. Analytical approach

The analysis focused on identifying how the consultancy-based structure influenced:

(a) interdisciplinary interaction;
(b) technical and industrial reasoning;
(c) project evolution;
(d) public communication;
(e) collaborative problem-solving;
(f) manufacturability awareness; and
(g) systems thinking.

The study does not aim to establish causal educational effects through controlled experimentation. Instead, it documents and analyses the pedagogical architecture and its implementation through authentic educational evidence generated during the semester.

3.5. Ethical considerations

All students involved in the pedagogical intervention authorised the use of photographs, presentations, and project materials for academic and scientific dissemination purposes. No individual performance data are reported in this article. The questionnaire was anonymous, participation was voluntary, and responses were analysed only in aggregated form. The authors were also involved as instructors and implementers of the pedagogical model. To mitigate the potential source of interpretative bias, the analysis relies on multiple documentary sources produced by students and anonymous aggregated questionnaire data. The photographs included in the manuscript were selected only from materials for which students had authorised academic and scientific use.

4. Local curricular context and project theme

The model application joined two 3rd-year undergraduate courses with complementary responsibilities. In IEP, students in EME were expected to define what the system should do and how it should function technically. In IIP, students in IEM were expected to define how that system should be produced, organised, quality-controlled, and industrially planned. This inter-course relationship was operationalised through the project clusters described in the Methodology section. Figure 1 shows the students and professors involved in implementing the pedagogical model. All students authorised the use of photographs and project materials for academic and scientific dissemination.

Figure 1. Students and professors involved in the application of the model proposal.

The semester project theme for the IEP students focused on peace and security. Students were challenged to design cost-effective, modular, dual-use (both civilian and military purposes) autonomous or remotely operated unmanned ground vehicles (UGVs), that is, rovers, for severe environments, using components and equipment made in Europe. The theme was intentionally broad enough to allow different technical interpretations, while sufficiently constrained to require electromechanical design, decision-making, production planning, quality control, and industrial organisation.

In parallel, the challenge for the IIP students was to design the production system required to manufacture the products proposed by the IEP groups. This involved the conception of modular, rapidly deployable, flexible, and compact production units or production plants capable of supporting decentralised manufacturing in operational contexts. The IIP groups were expected to define suitable manufacturing and assembly processes, select machines and equipment, estimate energy and manpower requirements, assess sustainability and life-cycle implications, propose deployment and logistics methods, and calculate expected production outputs and costs. This complementary challenge ensured that each technical product concept was examined not only as an electromechanical system, but also as an industrial proposition with associated requirements for production feasibility, resource allocation, operational deployment, and manufacturability.

The project brief required students to define functional and operational requirements, study the market and compare alternative concepts, justify design decisions using formal methods, propose electrical and control architectures, and consider energy autonomy, electromagnetic compatibility, manufacturability, production feasibility, and cost-effectiveness. It also required a traceability chain from requirements to decisions and expected effects. This structure encouraged students to move beyond isolated prototype design and to consider future integration, production, maintenance, and operational use. Table 1 summarises the main documentary sources produced during the semester and used to support the analysis of the pedagogical intervention.

Table 1. Documentary sources prepared during the model application.

Document type	Evidence used in this article	Analytical purpose
Project brief and course slides	Semester theme, UGV brief, role structure, and schedule	Establish the intended pedagogical and technical design
Periodic evaluation criteria	Presentation requirements	Reconstruct milestone expectations and assessment logic
IEP presentations and MoM	Mobility-support rover concept, cost/specification iterations, documentation practices	Illustrate one pathway of project development under the brief
IIP consultant presentations	Three presentations linked to each IEP concepts	Document manufacturing, logistics, quality, equipment, and cost interpretations
Mixed-session photographic report	Photographs of IEP and IIP presentations during joint classes	Document the public, inter-course ecology in which concepts were defended and revised

The available documentary record included IEP and IIP presentations, MoM, and the semester photo-report. These sources do not constitute a complete outcome dataset for the whole semester. However, they are sufficiently rich to reconstruct how students interpreted the project brief, how their designs and industrial responses evolved, and how the pedagogical structure made the work publicly legible. Table 1 summarises the documents prepared by students throughout the semester.

5. Pedagogical architecture: semester design, milestones, documents, and consultancy logic

The periodic schedule converted a broad inter-course project into a sequence of bound design tasks. Early weeks focused on concept, market, team organisation, and project planning. Middle stages required three design versions, a complete assembly drawing, dimensioning work, command and power circuits. The final stages moved toward execution drawings, manufacturing processes, economic analysis, and final reporting.

Figure 2 shows the semester schedule used in both courses. The semester combines two complementary class formats. Theoretical-practical classes introduced project management concepts relevant to planning, coordination, and monitoring, while practical classes were dedicated to project development with tutoring. In those practical sessions, each group presented the periodic evolution of its project against the Gantt diagram, followed by a discussion of the different project options adopted by the groups. This alternation between conceptual framing and tutored project work helped students connect management tools with concrete engineering decisions. Additionally, groups evaluate other groups, and inside each group, students evaluate colleagues.

Assessment also followed a course-unit teaching-learning classification (CTC) that formally balanced test performance, project development, professionalism, and individual contribution within the group. Equation 1 shows the formula for calculating the CTC grade.

$$CTC = 0.9 \times [(0.25 \times TG) + (0.75 \times PG)] + PPV + PV \qquad [1]$$

In this formula, TG is the test grade [0, 20], PG is the project grade [0, 20], PPV is a posture and professionalism value [0, 1], and PV is a performance value within the group [0, 1].

PG aggregated periodic project presentations with professor evaluation, evaluation by other groups, self-evaluation, and the final report, including the project specifications document and the project video. The periodic evaluation sheets clarified what counted as progress. In the opening stage, students were asked to propose a Gantt plan, identify the competencies of each team member, structure their digital dossier, define the concept clearly, identify target markets, estimate (broadly) costs and selling price, and present early evidence of external contact, and team building. In subsequent weeks, the criteria became more demanding: SWOT analysis, three project versions, weighted decision matrices, sketches, assembly drawings, subsystem dimensioning, instrumentation, control simulation, execution drawings, manufacturing processes, economic analysis, and draft video/report development. Thus, the assessment system made the semester legible as a cumulative engineering process rather than a series of disconnected presentations.

The consultancy-based relation with the IIP course was reinforced by cluster formation and by rubric items that explicitly required evidence of interaction with IEM groups. In other words, the inter-course relation was not left to goodwill alone; it was partially built into the semester schedule and the periodic public accountability structure.

Introduction to Electromechanical Project (IEP) presentations	Week01	Week02	Week03	Week04	Week05	Week06	Week07	Week08	Week09	Week10	Week11	Week12	Week13	Week14	Introduction to Industrial Project (IIP) presentations
Product + target market + Gantt plan + group organisation and organisation of the group folder in Microsoft Teams.	▪	▪													
Project specifications for three different versions of the project.			▪												Presentation of the production process Selection of production equipment
Assembly drawing of one concept, supplier contacts. Alternative technical solutions for the same internal machine problem.				▪											Presentation of product specifications, production process and production equipment
Justification of the contribution of each group member. Work progress (free topic on subsystems).					F	F	▪								
Assembly drawing of the overall system, including mechanical and electrical elements.								▪							Analysis and presentation of material flow Presentation of layout and implementation study
Mechanical sizing (kinematics and dynamics). Sizing of joining elements.									▪						Presentation of the stock-control model Presentation of cost estimates and total cost
Design and simulation of control and power circuits. Control programs.										▪					Presentation of industrial facility implementation, production model, stock control and cost estimate
Assembly drawing + final project specifications + production + manufacturing drawings of two parts + bill of materials + manufacturing processes											▪				
Economic analysis + free topic on subsystems. Submission of the draft final report and project video												▪			Presentation of the production and quality control model
Final presentation. Submission of the final report, specification document and project video													▪	T	Final presentation

▪ IEP presentation ▪ IEP + IIP presentation F Holidays/public holidays T Test

Figure 2. Semester schedule used in IEP/IIP.

6. Results from documentary evidence

The documentary material from the IEP groups, ALMA and EPAM, provides evidence of the work developed and of how students engaged with the pedagogical structure. The two cases are useful because they exhibit different trajectories. The ALMA group developed the MobiKing concept, which stayed close to a field-support rover narrative aligned with the broad security frame of the brief, whereas EPAM developed the DuctRover concept, which progressively redirected its concept toward duct inspection, showing how students used the open structure of the semester to redefine a project in a more precise niche.

6.1. ALMA group: a mobility-support rover framed around field assistance - MobiKing

The group defined its concept, MobiKing, as a rover for military terrain support, with functions in reconnaissance, victim detection, and the transport of supplies, first-aid kits, and radios. The early presentations also included target segments such as the armed forces and civil protection, competitor references, an initial cost table, a selling-price estimate, a Gantt plan, team organisation, and external contacts. These elements suggest that the students quickly understood the performative logic of the periodic criteria: to be credible, the project had to be framed not only as a technical idea but also as an organised engineering initiative.

As the semester progressed, ALMA/MobiKing moved from a broad dual-use statement to more structured concept-development work. The group produced a SWOT analysis, a Why-Why chain focused on limited energy autonomy, three concept versions with differentiated materials and functionalities, and competitive comparisons against commercial systems. Added version-by-version specification tables and explicit competitor benchmarking were developed, indicating that students were beginning to transform a general idea into a comparative engineering proposition. The ALMA/MobiKing artefacts also show the influence of the semester criteria on student behaviour. The move toward three formal versions, the inclusion of competitor specifications side by side with local assumptions, and the explicit division of tasks by named team members all mirror the evaluative expectations of the periodic sheets. The project evolved towards a more detailed subsystem-level analysis.

Another point concerns the inter-course logic. ALMA/MobiKing's public presentations included evidence of team building with IIP groups and the periodic criteria explicitly required interaction with the cluster, as shown in Figure 3. Even when the technical work shown remained largely within the IEP domain, students were being socialised into an expectation that production, supply, maintenance, and quality would need to be discussed with another curricular community rather than imagined in isolation. By itself, this interaction extends learning beyond the scope of the IEP syllabus.

(a) Example of a periodic public presentation. *(b) Example of a team-building activity.*

Figure 3. ALMA and its consultant groups' involvement.

Figure 4 shows the evolution of the CAD MobiKing rover concept and the computational tools used for mechanical analysis along the semester, considering Professors, stakeholders and other groups' suggestions.

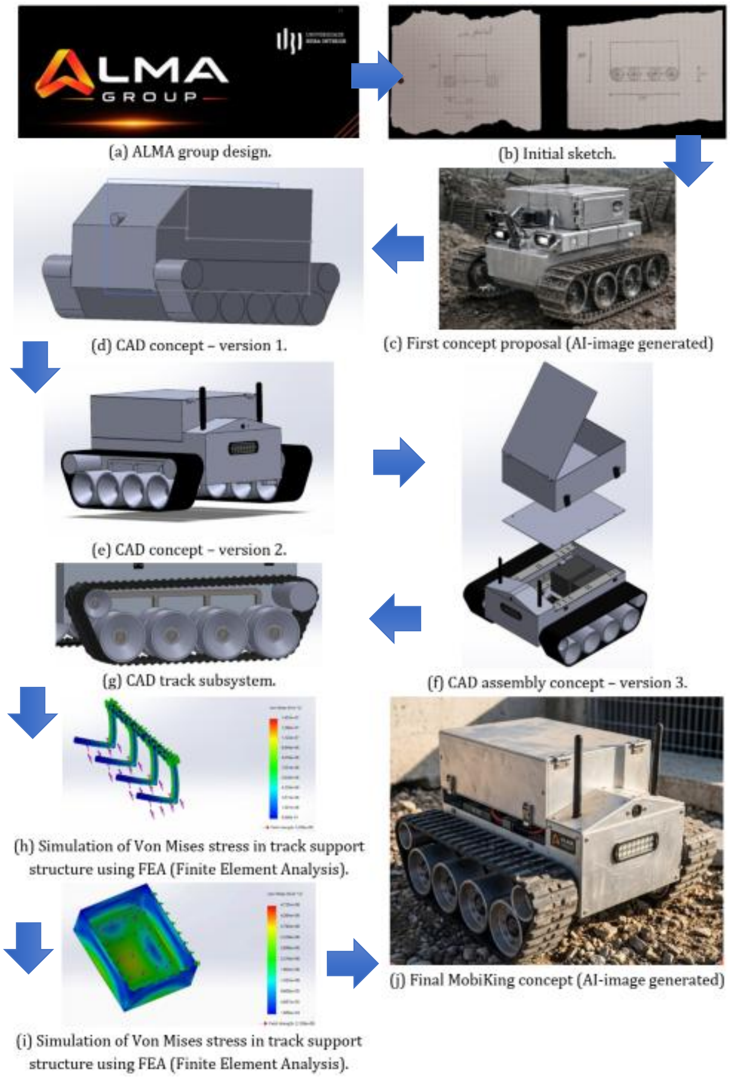


Figure 4. ALMA/MobiKing concept development.

6.2. EPAM: concept redirection and the emergence of DuctRover

EPAM group offers a particularly instructive case because it did not remain attached to its initial broad interpretation of the brief. In the first presentation, EPAM still framed the product as a general-purpose intelligent mobile platform capable of transporting materials and re-establishing communications in disaster-affected areas. This reading fit the original "peace and security" frame, and the group identified both civil and defense-related uses. However, in the following iterations, EPAM showed a deliberate concept-selection process in which several ideas were compared. The selected direction became a compact inspection robot for ventilation ducts, named DuctRover. In this sense, the dual-use orientation of the original brief was preserved. This redirection is pedagogically important. It shows that the course did not force students to remain locked into a first idea simply because it matched the generic project theme. Instead, the periodic structure rewarded increasingly specific design reasoning. Once the group identified inspection in confined spaces as a more coherent niche, the project acquired a clearer operational problem, a narrower target market, and more tractable technical questions concerning locomotion, size, communication, and energy autonomy.

EPAM's next presentations make visible a rich technical decision process. The group identified a central problem around inspection inside confined conduits, listed geometric and operational limitations, differentiated functional, technical, and economic requirements, and generated three alternative configurations for locomotion. It then presented a weighted comparison and justified the selection of one version based on simplicity, adaptability, maintenance, and low cost. Thus, EPAM moved toward assembly-level reasoning. The group presented an overall assembly drawing, variants for an internal arm, a Duncker diagram, and a product tree.

That decision is itself educationally relevant: it indicates that the students were judging feasibility and scope, not simply accumulating tasks. In other words, the documentary record captures an important engineering lesson-knowing when a concept can be specified rigorously without overcommitting to construction.

The MoM reinforce the same picture. They first documented the moment of concept selection and the beginning of external contact with potential clients. Then, it records further clarification of technical requirements, work on the Gantt schedule, continuation of market research, online meetings for coordination, and team-building activity. Together, these records show how students inhabited the project not only as designers but also as coordinators, documenters, and prospective technical entrepreneurs.

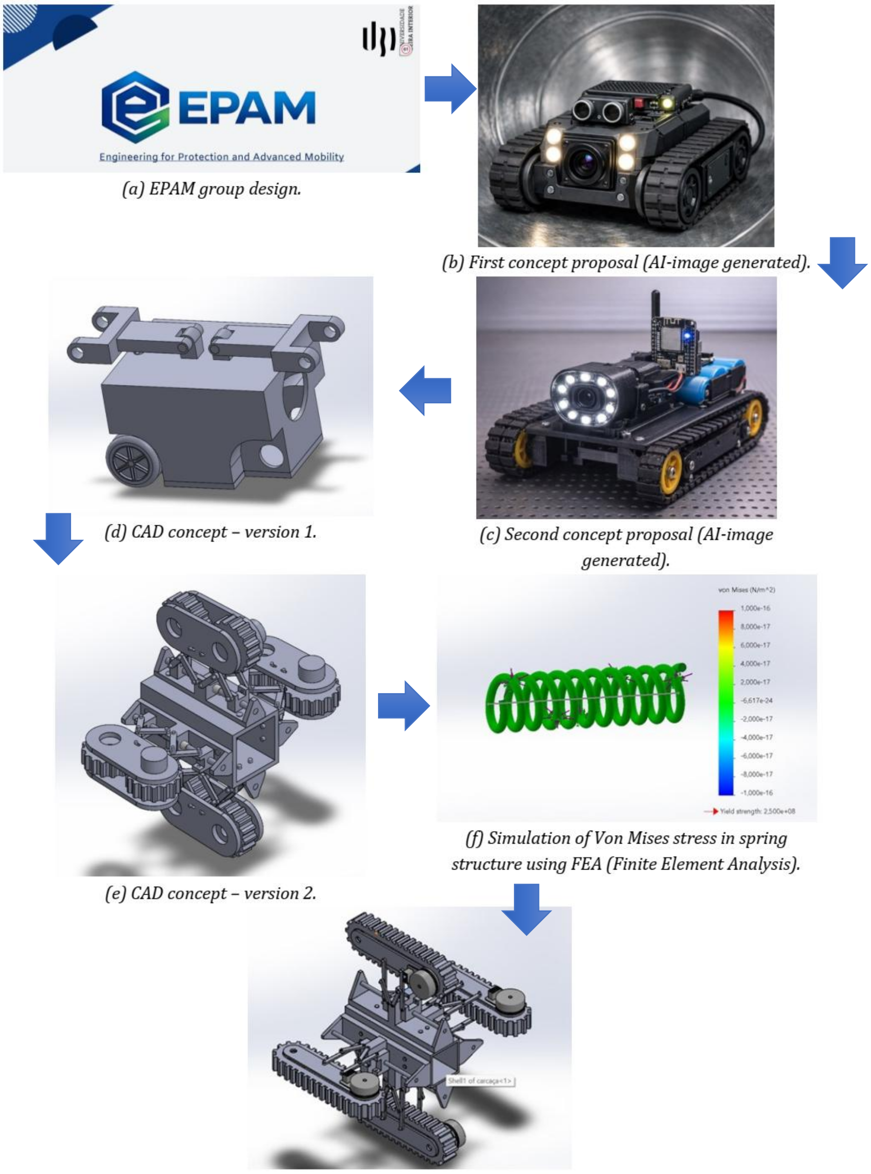
The presentation also documented the cluster with IIP groups, which signals that the consultancy logic had become part of the project narrative. The public presentation and interaction with IIP consultant groups are shown in Figure 5.

(a) Example of a periodic public presentation.

(b) Example of a team-building activity.

Figure 5. EPAM and its consultant groups' involvement.

Figure 6 shows the evolution of the CAD DuctRover concept and the computational tools used for mechanical analysis throughout the semester, considering Professors, stakeholders and other groups' suggestions.



(a) EPAM group design.

(b) First concept proposal (AI-image generated).

(c) Second concept proposal (AI-image generated).

(d) CAD concept – version 1.

(e) CAD concept – version 2.

(f) Simulation of Von Mises stress in spring structure using FEA (Finite Element Analysis).

(g) CAD assembly concept – Final DuctRover concept (AI-image generated).

Figure 6. EPAM/DuctRover concept development.

6.3. Consultancy contributions from IIP student groups

The six IIP groups were distributed across the two IEP projects: AXIS, GPAC and MobileForge Robotics supported ALMA/MobiKing, while ATLAS 4, G4 and PolyCorte supported EPAM/DuctRover. The IIP consultant groups proposed production architectures, make-or-buy distributions, materials, equipment portfolios, quality checkpoints, timing estimates, bottleneck analyses, and amortisation scenarios tailored to the IEP concepts. In that sense, the consultants did not merely validate design ideas after the fact. They generated parallel industrial interpretations of those ideas and, in some cases, reframed what would count as a feasible product and production system.

6.3.1. Support to the ALMA group – MobiKing concept

The ALMA IEP group was supported by three IIP consultant groups: AXIS, GPAC, and MobileForge Robotics. Together, these groups translated the MobiKing rover from an electromechanical product concept into industrialisation scenarios involving production planning, logistics, quality control, manufacturability assessment, layout organisation, and economic analysis. This consultancy work is central to the inter-course pedagogical model because it demonstrates how IEM students applied industrial-engineering reasoning to a product under development by EME students.

AXIS group focused on decentralised and mobile production concepts for MobiKing. The group analysed how the rover could be manufactured or assembled near military, disaster-response, and civil-protection contexts through a mobile production unit. Their proposal included production-flow organisation, quality-control logic, layout planning, and support infrastructure for field production. The group also explored production-capacity estimation and proposed an indicative selling price of approximately €3,000/rover.

The GPAC group developed a complementary production-process analysis focused on manufacturability and process organisation. The group defined production routes, quality-control stages, production-flow diagrams, and assembly logic associated with the MobiKing chassis and cargo compartment. It also integrated technical specifications into the industrial plan and proposed recyclable packaging solutions. The estimated material and component cost was approximately €987/rover and a selling price of €2,000/rover. The production-capacity analysis estimated approximately 8 rovers/day.

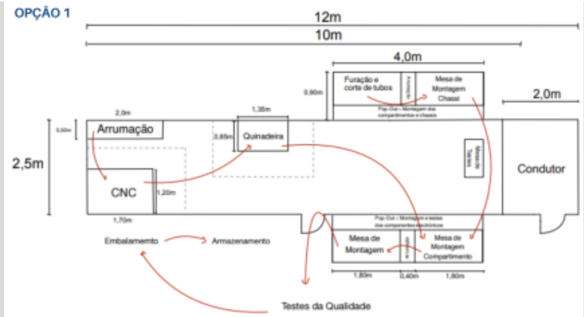
MobileForge Robotics group proposed a containerised mobile-factory concept based on modular production units. The consultancy work included make-or-buy analysis, production-process organisation, material-flow analysis, transport considerations, packaging alternatives, and layout proposals. The estimated material and component cost was approximately €1,470/rover and a selling price of €4,500/rover. The production-capacity analysis estimated approximately 6 rovers/day.

Taken together, the three consultant groups illustrate how the consultancy-based structure expanded the ALMA/MobiKing project beyond technical design alone. The industrial-engineering students introduced manufacturability analysis, production scalability, logistics, quality assurance, economic feasibility, and operational deployment considerations into the design discussion. Educationally, this interaction encouraged interdisciplinary communication, systems thinking, iterative decision-making, and earlier exposure to production-oriented constraints during the engineering-design process.

Figure 7 summarises representative industrial-engineering outputs developed by the consultant groups for the MobiKing concept.

(a1) AXIS presentation.

(a2) Truck com pop-outs

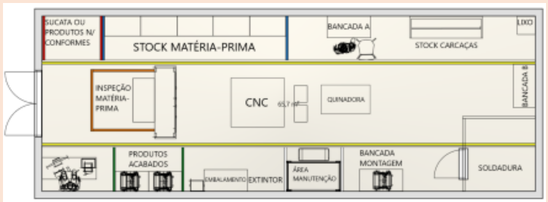


(a3) Production layout and flow.

(a4) Packaging option.

(a) Industrial engineering proposal from the AXIS group.

(b1) Expandable trail.

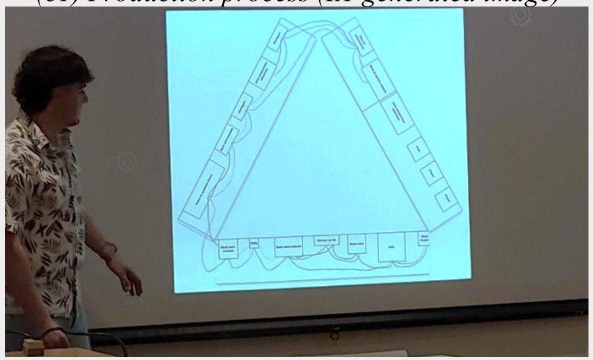


(b2) Production layout.

(b3) GPAC presentation.

(b) Industrial engineering proposal from the GPAC group.

(c1) Production process (IA-generated image)



(c2) Production layout and spaghetti diagram (3 connected containers)

(c) Industrial engineering proposal from MobileForge Robotics group.

Figure 7. Main outputs in terms of industrial engineering for the MobiKing concept from the three-consultant teams.

6.3.2. Support to EPAM group – DuctRover concept

The EPAM IEP group was supported by three IIP consultant groups: ATLAS 4, G4, and PolyCorte, each contributing to the industrialisation of the DuctRover concept from a different production-planning perspective. Together, the consultant groups translated the electromechanical design into manufacturing strategies, layout proposals, production-flow organisation, quality-control procedures, packaging concepts, stock-management approaches, and economic scenarios.

ATLAS 4 focused on the production-system architecture for DuctRover. The group developed process-flow proposals involving additive manufacturing, assembly, quality testing, packaging, and dispatch, together with layout and warehouse-organisation concepts. The consultancy work also included stock-control principles and production-capacity analysis. Their final economic scenario estimated a production cost of approximately €420/rover and a selling price of €1,200/rover.

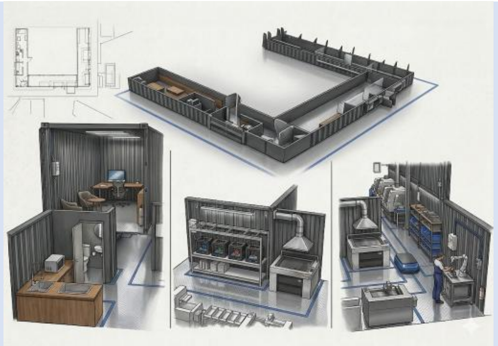
G4 developed a complementary production and material-planning proposal. The group analysed the main structural, mobility, and electronic components of DuctRover and proposed a hybrid manufacturing approach combining composite manufacturing and additive manufacturing. The consultancy work also addressed sustainability-oriented packaging solutions, production planning, and material-cost analysis. Their final economic scenario estimated a production cost of approximately €767/rover and a selling price of €1,180/rover.

PolyCorte contributed a third industrialisation pathway focused on material selection, subtractive manufacturing, production layout based on mobile houses, warehouse organisation, and economic analysis. The group proposed CNC-based manufacturing approaches, modular production concepts, quality-control procedures, and stock-management strategies. The final economic analysis estimated a production capacity of approximately 18 rovers/day, with a variable production cost of approximately €942/rover and a proposed selling price of €2,250/rover.

Overall, the three consultant groups demonstrate how the consultancy-based model expanded the DuctRover concept beyond electromechanical design into industrial reasoning and manufacturability analysis. The interdisciplinary interaction exposed students to production planning, logistics, economic feasibility, material selection, quality control, and operational constraints during early design stages. Educationally, this interaction reinforced systems thinking, collaborative problem-solving, and the integration between technical and industrial perspectives.

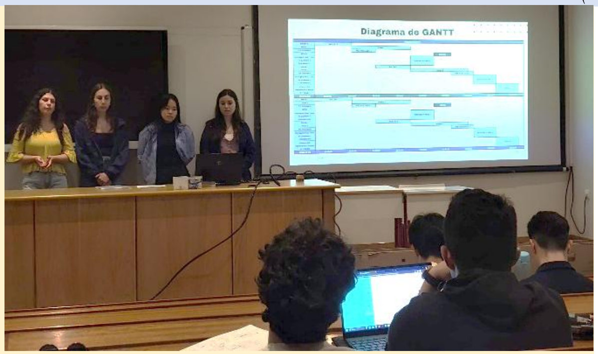
Figure 8 summarises representative industrial-engineering outputs developed by the consultant groups for the DuctRover concept.

(a1) ATLAS 4 presentation.


(a2) Production layout and common sections.

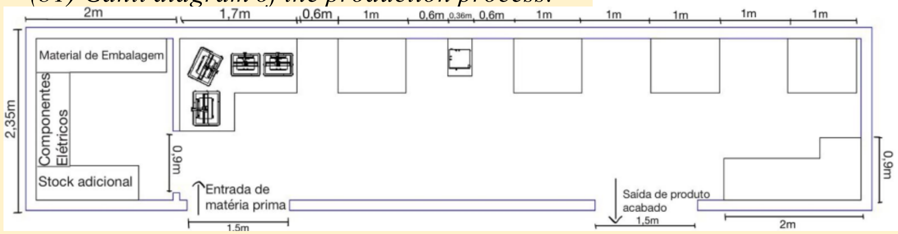

(a3) Raw material warehouse.

(a) Industrial engineering proposal from the ATLAS 4 group.



(b1) Gantt diagram of the production process.

(c1) Production layout.



(b2) Production layout and section.


(c2) Production layout.

(b) Industrial engineering proposal from the G4 group.

(c) Industrial engineering proposal from PolyCorte group.

Figure 8. Main outputs in terms of industrial engineering for the DuctRover concept from the three-consultant teams.

7. Results from the student questionnaire

To complement the documentary analysis, students were invited to complete an anonymous satisfaction questionnaire regarding the pedagogical model. The questionnaire included Likert-scale items related to course organisation, interdisciplinary interaction, project-based learning, tutorial support, public presentations, competency development, and overall satisfaction with the consultancy-based structure. The questionnaire was structured into six sections:

(a) students characterisation;

(b) course organisation and overall evaluation;

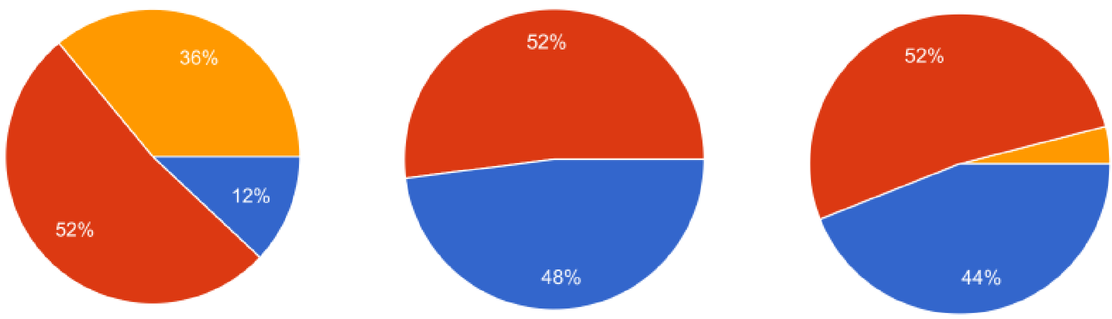
(c) skills development;

(d) interdisciplinary integration between IEP and IIP;

(e) motivation and engagement; and

(f) open qualitative feedback.

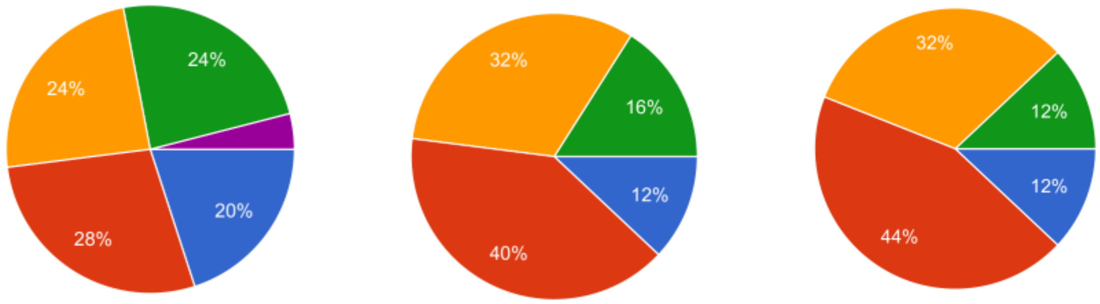
The student satisfaction questionnaire obtained 25 valid responses from a total of 32 students available to participate in the study, corresponding to a response rate of 78.1%. The global evaluation of the pedagogical model was favourable. 12.0% of students classified the model as "Very good", 52.0% as "Good", and 36.0% as "Satisfactory". No students selected the categories "Weak" or "Very weak". On a five-point ordinal scale, the global evaluation obtained a mean score of M = 3.76, with a median of 4 and a standard deviation of SD = 0.66. Details of the most relevant survey results are presented in Figure 9. The results show that the strongest dimension was "skills development" (M = 4.30; SD = 0.66), with 89.7% of responses in the categories "Strongly agree" or "Agree". This dimension included particularly high ratings for problem-solving, technical communication, teamwork, and time-management. "Motivation and engagement" also obtained a strong result (M = 4.15; SD = 0.71), followed by "course organisation" (M = 4.06; SD = 0.80).



(a) Global evaluation. *(b) Helped develop problem-solving skills.* *(c) Improved technical communication skills.*

Figure 9. Questionnaire results related to global satisfaction and highly rated learning outcomes. *Legend: Very Good: ■; Good: ■; Satisfactory: ■; Weak: ■; Very weak: ■.*

As shown in Figure 10, the most moderate results were obtained for the "integration between IEP and IIP" dimension (M = 3.58; SD = 1.02). Although 58.0% of responses in this dimension were positive, it also presented 25.3% neutral responses and 16.7% negative responses. This indicates that students recognised the educational value of the interdisciplinary model but also perceived operational difficulties in its implementation.



(a) Integration between IEP and IIP. *(b) Adequacy of the consultant-group model.* *(c) Usefulness of interaction between students from both courses.*

Figure 10. Questionnaire results related to challenges. *Legend: Strongly agree:* ■; *Agree:* ■; *Neither agree nor disagree:* ■; *Disagree:* ■; *Strongly disagree:* ■.

The open responses reinforce this interpretation. Representative critical comments illustrate these operational difficulties: one student referred to 'difficulty of communication between courses'; another indicated that, for IIP students, 'it would be simpler to have the product with the final specifications from the beginning'; and another suggested 'fewer presentations and more classes to develop the project with teacher support'. These comments do not contradict the positive evaluation of the model but identify the scaffolding required for future iterations. The most frequently reported strengths were "interdisciplinarity", "contact between students from different courses", and "knowledge exchange", representing 60.0% of the responses. However, the main difficulty was "communication and coordination between courses, groups, students, and teachers", representing 56.0% of the responses. The main suggestions for improvement were to "reorganise the articulation between courses", "provide clearer objectives and intermediate deadlines", "increase tutored practical work", and "reduce excessive presentation frequency" when it does not correspond to meaningful project progress.

8. Discussion

These results complement the documentary evidence by showing that students recognised the pedagogical value of the model, especially for skills development, teamwork, communication, and problem-solving. At the same time, the more moderate results for IEP–IIP integration confirm that interdisciplinary collaboration requires explicit coordination mechanisms, stable intermediate deliverables, and dedicated interaction moments. Therefore, the questionnaire does not merely validate the intervention. It also identifies operational conditions required for its improvement.

The documentary and questionnaire evidence supports six main claims about the pedagogical value of the intervention:

1. The semester architecture succeeded in converting broad course intentions into visible periodic engineering artefacts. The groups did not simply "work on the project"; they worked on bounded deliverables-concept slides, SWOT analyses, version tables, sketches, CAD assemblies, cost models, and MoM- which made progression discussable and assessable.
2. The inter-course consultancy logic was not marginal. It was embedded in the schedule and periodic rubrics through explicit references to the IEM cluster, which increased the likelihood that production thinking would enter the design conversation early.
3. The consultant groups did not simply react to finished concepts; they reformulated those concepts industrially through make-or-buy splits, equipment selection, mobile versus fixed production architectures, routing and timing tables, bottleneck identification, quality-test definitions, and amortisation scenarios. This suggests that the consultancy layer can function as a parallel industrial-design studio rather than as a lightweight feedback mechanism, provided that the consultant's work is visible early enough in the semester to influence the design conversation.
4. The supporting documents indicate that students did not merely accumulate slides; they learned to externalise engineering reasoning. SWOT analyses, Why-Why chains, version comparisons, competitive benchmarking, and early cost estimates are all imperfect but important transitional forms between intuition and engineering argument.
5. The two IEP groups demonstrate that the pedagogical model can accommodate distinct trajectories. ALMA elaborated a rover concept within the original field-support frame, whereas EPAM narrowed the problem and pivoted toward duct inspection. The model, therefore, seems compatible with both continuity and redirection if students can justify the change.
6. The documentary record suggests that cross-course consultancy benefits from a strong social infrastructure. Cluster-based interaction, evidence of team building, shared dossiers, role rotation, and public questioning all seem to matter because consultancy is not only an exchange of information; it is also a social permission structure that makes critique and reformulation normal. This resonates with broader literature on stakeholder integration, collaborative design, and participatory structuring in engineering and educational design (Howcroft et al., 2023; Savage et al., 2007).

The evidence also refines the relation between this practice and selected experiential and game-based design principles. Role rotation, bounded challenges, visible progress markers, and public comparison were useful only because they were tied to engineering work produced by students, documented reasoning, and public accountability.

9. Limitations

The study presents methodological limitations. First, it was implemented in a single institution and involved a limited number of student groups. Second, the study does not include a control group or longitudinal measurement of learning outcomes. Third, the evidence relies on documentary materials, student-produced documents, and perception data, which may not capture all learning processes. Fourth, the authors were also implementers of the model, although anonymous questionnaire data and multiple documentary sources were used to mitigate this limitation. Future work should incorporate interviews, competency rubrics, comparative designs, and longitudinal follow-up.

10. Conclusions

This article presents a consultancy-based inter-course model linking technical design and production planning in engineering education and documents its semester implementation through a project brief, a milestone schedule, periodic rubrics, IEP student presentations, IIP consultant presentations, MoM, and a photographic record of mixed sessions. The combined evidence from IEP and IIP consultant groups shows that students used this structure to define concepts, compare alternatives, contact stakeholders, organise work, and progressively transform initial ideas into more explicit technical and industrial propositions.

The study does not claim to measure learning gains causally. It documents how the model was implemented, evidenced through student artefacts, and perceived by participants.

The semester evidence suggests that the educational strength of the model lies in its documentary, iterative, and dialogic character. Students were not only asked to design. They were asked to explain, justify, compare, schedule, record, and expose their decisions to peers and to another curricular community. Meanwhile, the IIP consultant groups were asked to reinterpret the same products through routes, equipment, costs, layouts, testing stages, and decentralised-production concepts. This produced a richer form of project learning in which technical and industrial reasoning could begin to meet before the final stage of the work.

The results indicate that consultancy-based interdisciplinary project-based learning supports a stronger integration between technical design and industrial reasoning. The interaction between IEP and IIP students promoted systems thinking, structured decision-making, and the articulation of design choices with manufacturability, logistics, quality control, and economic feasibility. The use of periodic milestone presentations, documented project evolution, and inter-group consultancy reinforced accountability, communication, and iterative refinement of engineering solutions. Evidence from project documents and student perception data suggests that this model enhances engagement and aligns learning activities with professional engineering practice.

The study contributes an implementation-oriented pedagogical framework for inter-course collaboration in engineering education, demonstrating how complementary disciplinary roles can be structured to reflect real-world product development processes. The results support the integration of technical and industrial perspectives within undergraduate curricula and highlight the value of project documents, as real as possible, as sources of educational evidence. While the findings are context-dependent, the proposed model provides a transferable reference for programs seeking to strengthen interdisciplinarity, applied learning, and the connection between design and production.

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AI use statement

AI-assisted tools were used to support language revision and translation during the manuscript preparation. Within the pedagogical framework, students were allowed to use generative AI only as a supervised support for early ideation, visual mock-ups, and group identity elements. AI-generated outputs were not accepted as substitutes for CAD modelling, engineering calculations, technical drawings, manufacturability analysis, or design justification.

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Appendix A

Student Satisfaction Questionnaire on the Pedagogical Model
Introduction to Electromechanical Project (IEP) / Introduction to Industrial Project (IIP)

Background

This questionnaire aims to evaluate students' perceptions of the interdisciplinary pedagogical model implemented in the course units Introduction to Electromechanical Project (IEP) and Introduction to Industrial Project (IIP).

The model is based on project-based learning, development of real projects in groups, periodic presentations, interaction between students from different degree programmes, continuous tutorial support, and integration between technical design and industrial planning.

Responses are anonymous and are used exclusively to improve the teaching and learning process.

Section A — Student Characterisation

A1. Degree programme

( ) Electromechanical Engineering (IEP)

( ) Industrial Engineering and Management (IIP)

A2. Group

____

Section B — Overall Evaluation and Open Feedback

B1. How do you globally evaluate the pedagogical model implemented? (Response scale: 1 - Very poor; 2 – Poor; 3 – Satisfactory; 4 – Good; 5 - Very good): ___

B2. What do you consider to be the main strength of the pedagogical model? (maximum: 20 words)

____

B3. What do you consider to be the main difficulty encountered? (maximum: 20 words)

____

B4. What suggestions do you have to improve the course unit? (maximum: 20 words)

____

Section C — Course Organisation

Response scale: 1 – Strongly disagree; 2 – Disagree; 3 – Neither agree nor disagree; 4 – Agree; 5 – Strongly agree

C1. Was the weekly organisation of activities adequate? ___
C2. The project schedule helped monitor the development of the work? ___
C3. The periodic presentations contributed to keeping the group focused on the objectives? ___
C4. Was the tutorial support during practical classes useful? ___
C5. Was the workload adequate for the objectives of the course unit? ___
C6. Were the assessment criteria clear? ___
C7. Did the assessment method adequately reflect the work to be developed? ___

Section D — Skills Development

Response scale: 1 – Strongly disagree 2 – Disagree 3 – Neither agree nor disagree 4 – Agree 5 – Strongly agree
D1. The project contributed to improving teamwork skills? ___
D2. The project contributed to improving technical communication skills? ___
D3. The pedagogical model helped develop problem-solving skills? ___
D4. The project contributed to improving time-management and task-management skills? ___
D5. The project allowed theoretical knowledge to be applied in practical situations? ___
D6. The periodic presentations helped develop argumentation and technical-defence skills? ___
D7. The project contributed to increasing autonomy in learning? ___

Section E — Integration between IEP and IIP

Response scale: 1 – Strongly disagree 2 – Disagree 3 – Neither agree nor disagree 4 – Agree 5 – Strongly agree
E1. Was the interaction between students from both degree programmes useful? ___
E2. Collaboration between groups helped improve understanding of the relationship between technical design and industrial production? ___
E3. Was the consultant-group model adequate? ___
E4. Were the contributions from groups in the other degree programme relevant to project development? ___
E5. The interdisciplinary model brought the project closer to real engineering practice? ___
E6. Should the integration between IEP and IIP continue in future academic years? ___

Section F — Motivation and Engagement

Response scale: 1 – Strongly disagree 2 – Disagree 3 – Neither agree nor disagree 4 – Agree 5 – Strongly agree

F1. Did the pedagogical model increase motivation to learn? ___

F2. Did the development of a real project make learning more interesting? ___

F3. Did the public presentations increase engagement with the course unit? ___

F4. Was the work developed more stimulating than traditional methodologies? ___

F5. Do I recommend this pedagogical model for future editions of the course unit? ___