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PAPER

Applying Project-Based Learning (PBL) for Teaching Virtual Design Construction (VDC)

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ABSTRACT

Learning-centered models, which rely on active methodologies such as Project-Based Learning (PBL), should be adopted in undergraduate programs to potentiate the development of collaboration skills within future professionals. This study reports the implementation of PBL in two successive Virtual Design and Construction (VDC) courses from an undergraduate civil engineering program: 1) VDC I, in which the VDC methodology implementation was applied theoretically in an already-built project, and 2) VDC II, in which the VDC methodology implementation was applied in a currently-under-construction project. The study aims to identify students' perceptions of PBL influence on their overall learning experience, degree of acquisition of generic competencies, and project development under the VDC methodology. To assess the PBL and VDC implementation, a survey was applied. Results show more than a third increase in students' perceptions about the benefits of implementing VDC and PBL for the generic competencies acquisition process, compared with other studies which implemented Building Information Modelling (BIM) with PBL. Besides, VDC II students' perceptions of the generic competencies' development process, degree of learning, and project development improved by 6.13%, 7.15%, and 3.44%, respectively, compared with VDC I students' perceptions.

KEYWORDS

Virtual Design and Construction, Project-Based Learning, undergraduate civil engineering program, generic competencies

1 INTRODUCTION

The success of construction projects depends on the planning effort during the early stages of their life cycle [1]. Decisions made during this stage may positively impact their successful execution [2]. Due to the multidisciplinary nature of construction projects, decisions should be taken collaboratively with every relevant stakeholder. However, traditional construction does not provide this work environment, as Architecture, Engineering, and Construction (AEC) project organizations are

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highly fragmented into subgroups. These subgroups include designer(s), contractor, and owner, which may work as independent entities (i.e., design, supply, or general contractor companies) [3]. The AEC industry's fragmented nature creates barriers to effective integration and interoperability, resulting in significant financial losses [4]. Since the early aughts, multiple stakeholders in the AEC industry have signaled the need to further technical, managerial, and generic competencies. Research indicates that the most relevant competencies are effective communication, team leadership, and multi-disciplinary interaction [5,6].

Over the past few decades, collaborative methodologies have increased, improving productivity in the AEC industry, with Virtual Design and Construction (VDC) prominent among them. VDC is defined as the "use of integrated, multidisciplinary performance models of design-construction projects to support explicit and public business objectives" [7]. VDC has been taught and implemented in various projects globally since 2001. The perception of project teams toward VDC has been highly positive, as it supports trustworthy relationships and commitments, improves workflows, and integrates the generated information [7,8]. VDC has been applied as a support methodology in courses across the AEC industry, including sustainability and construction management [9–11]. Moreover, professionals using the VDC approach have better perceived their generic competencies, especially their collaborative skills [12].

Training processes must contemplate addressing generic competencies to produce competent professionals in the AEC industry who can overcome the ubiquitous low levels of collaboration [13]. Thus, a collaborative learning environment based on discussion and cooperative team experiences should be encouraged within classrooms. This approach promotes the development of critical thinking, effective communication, and leadership among students [14]. These generic competencies are central to developing current collaborative methodologies, including VDC. Experience shows that theoretical concepts within the VDC methodology are better understood and put into practice with the Project-Based Learning (PBL) methodology. PBL is an active learning methodology that allows students to explore different ways of dealing with unexpected problems when developing real projects [15].

Therefore, developing generic competencies in future AEC professionals is essential to improve the team and individual performance in projects because they support collaborative relationships, conflict-resolving processes, and decision-making [16,17]. There is a causal relationship between the degree of development of generic competencies and project success, with conflict management and teamwork as the most critical variables [18]. However, there are concerns regarding training other generic competencies in the new generations, such as leadership, self-confidence, and the ability to deal with criticism [19]. Within this context, the learning of VDC should consider generic competencies as a fundamental pillar [20].

Furthermore, with PBL, VDC is beneficial for developing student competencies. This research effort presents a literature review of active learning methodologies. Next, PBL is applied for VDC methodology teaching-learning within an undergraduate civil engineering program. Then, a survey is proposed to evaluate the effectiveness of both PBL and VDC implementations. Results are compared using four case studies of PBL and BIM implementations worldwide. Finally, the discussion and conclusions are presented, focusing on how the combination of VDC and PBL can bolster the development of generic competencies and positively influence both the learning process and the projects' development.

In this context, the research questions were formulated as follows: How do students' perceptions about PBL influence their learning experience? What are students' perceptions about PBL influence on their generic competencies' development process? What are students' perceptions about PBL influence on project development under the VDC methodology? These perceptions are measured within a group from VDC I and VDC II courses.

2 LITERATURE REVIEW

2.1 Learning methodologies

Teaching-centered models, which are related to traditional learning environments and are most common within the civil engineers' training process, encourage students to reproduce information rather than develop competencies [21]. However, when engineering graduates start their professional lives and must solve real-world issues, they may need to relate concepts and processes [22]. Hence, changes must be made in AEC-related degrees training to achieve deeper learning and develop critical and reflective thinking [23].

Different learning methodologies have been implemented in undergraduate and graduate programs. This review focused on research, problem-solving, project management, and teamwork competencies within the civil engineer training process [24–27]. Table 1 presents four learning-centered, or active, methodologies: problem, project, research, and team-based learning. Although these methodologies support better developing teamwork and communication skills [26, 28–30], applying them can generate additional academic stress for students if not properly planned.

Table 1. Selected learning-centered methodologies

Methodology	Definition	Outcomes
Problem-based learning [28]	Learning through problem-solving from real world	Improvement of problem-solving and teamworking skills by posing problems that occur in the real world according to the teacher's experiences
Project-based learning [29]	Learning organized around projects and their management	Simulation of collaborative environment work and how co-workers relate between them
Research-based learning [30]	Research development based on society's requirements	Promotion of scientific knowledge in different topics by proposing solutions to society's main problems
Team-based learning [26]	Achievement of goals through individual and cooperative activities for students	Promotion of self-learning and preparation to integrate a collaborative learning environment

Research- and team-based learning can be used as a support methodology in problem- and project-based learning. In the former, the team is challenged to find a solution to a problem based on questions made by the teacher. In the latter, the team analyzes potential issues in the project development to generate solutions. While both are active learning methodologies, project-based learning mirrors better actual work in the AEC industry [31].

Notwithstanding the adopted learning methodology, current training processes must include technological tools to improve students' competencies. The PBL Lab at Stanford University developed the P5BL methodology, which considers five aspects (problem, project, product, process, and people), further explained in Table 2, including their relationship with Information Technology (IT) [32].

Table 2. Problem-, project-, product-, process-, and people-based learning

Aspect	Objective	Relation with IT
Problem	Define the objectives and constraints of the problem in collaboration with different stakeholders (e.g., owner, contractor, and architect).	Support with tools to determine, express, visualize, manipulate, and communicate.
Project	Avoid disjunctions between students and AEC workers and simulate multidisciplinary teamwork.	Improve cross-discipline communication, collaboration, and coordination over time and space.
Product	Motivate to look for new knowledge and skills due to the engagement in the product to create.	Design with a 3D shared-model product.
Process	Identify and adopt communication protocols and organizational structures to the most efficient and effective ones.	Develop information assessment technologies.
People	Internalize a new culture where students, teachers, and industry representatives interact with each other.	Provide shared workspaces for distance-learning lectures or meetings.

Source: Adapted from [32].

P5BL has been implemented in the AEC Global Teamwork course offered at Stanford University since 1993. The course targets creating a multidisciplinary team with students from different programs, departments, universities, and countries, implementing IT to fulfill the project's objectives and produce more effective and efficient products. This course aims to create an interdisciplinary learning experience, integrating one architect, one structural engineer, one construction management student from a graduate program, and one or two supporting students from an undergraduate program. Participants are expected to evolve from mastering only their discipline to becoming aware of other disciplines' goals and associated constraints, and becoming capable of cooperating and providing alternatives to solutions, even before their colleagues request them [33–34].

2.2 Project-based learning

As mentioned before, the PBL methodology supports learning experiences that allow students to be part of real-world problems and develop self-directed learning and critical thinking. It also helps them to develop competencies in a collaborative environment by applying theoretical knowledge [35]. PBL within civil engineering training implies that students are encouraged to propose solutions to significant problems related to the design or constructive processes through research and collaboration [36].

There are several advantages that PBL offers to bolster the teaching and learning processes. Students who learn through PBL develop better self-learning competencies, such as critical thinking, problem-solving, and multidisciplinary work. Moreover, they experience increased motivation compared with students who have access to learning only through teaching-centered models [37, 38]. Students are likely to have fewer theoretical problems because they are more involved in class development [39], and therefore, they get higher scores than students learning through teaching-centered models [40]. At the same time, teachers are more motivated and find their work fulfilling, as they explore different projects with each new group of students every teaching cycle. Teachers become lifelong learners as they continually receive student feedback [41].

Literature reports successful implementations of PBL methodology in construction management courses worldwide, engineering and architecture programs, with case studies from countries such as the USA, China, and Spain [26, 44]. In these courses, students were required to adopt a role (architect, engineer, facility manager, estimator, among others) within a team of subcontractors who managed the project based on BIM. According to the results of the surveys applied, the students were satisfied with the methodology of the courses. At the same time, they considered generic competencies such as effective communication, critical thinking, and teamwork to improve notably and felt more prepared to work on real-world projects.

3 METHODOLOGY

The research uses a quantitative approach to describe, explain, verify, and predict phenomena [45]. Given the deliberate manipulation of the independent variables (PBL and VDC), this research uses a quasi-experimental design to observe effects on dependent variables (degree of acquisition of generic competencies, learning improvement and project development improvement). The survey presents intact groups of undergraduate civil engineering students at a private university enrolled in VDC courses, meaning no selection or random allocation. The two groups are experimental. The research is oriented toward studying implementation cases of PBL for teaching-learning VDC. Then, a literature review of project management courses that apply BIM and PBL was developed to observe and compare the effects on dependent variables, as shown in Figure 1.

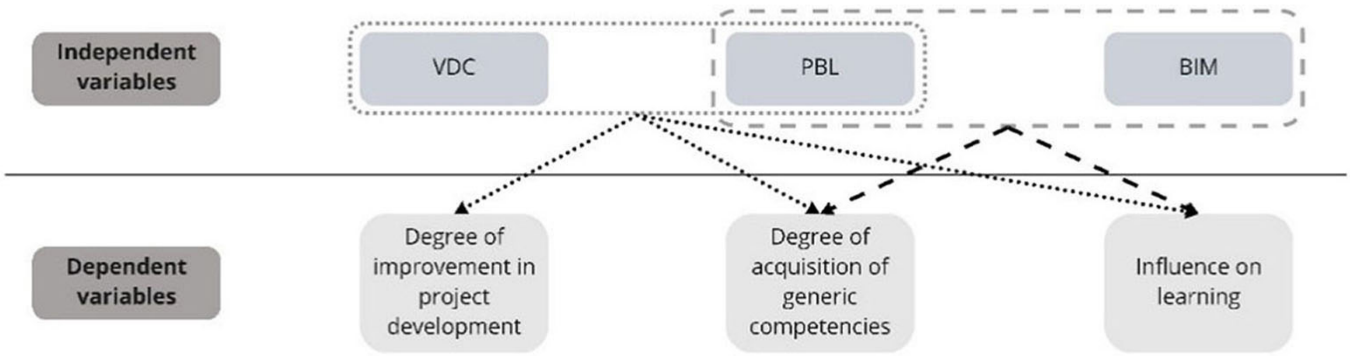

Fig. 1. Relation between independent and dependent variables

The methodology consists of two sections: 1) the proposed VDC courses methodology, where the main characteristics of VDC are explained, and 2) the data collection approach.

As for the VDC courses methodology, contents and scenarios for learning were proposed. Two courses were considered: VDC I and VDC II. As for the data collection, a survey was conducted to explore students' perceptions of PBL influence on their generic competencies' development process and their overall learning experience. Students' perceptions of PBL influence on project development under the VDC methodology were also measured.

3.1 Project-based learning

The proposed VDC courses, I and II, for undergraduate civil engineering programs introduced this methodology with the following sequence: introduction to the VDC framework, Process-Organization-Product (POP) Matrix, Integrated Concurrent Engineering (ICE), Production Objectives and Controllable Factors, Building Information Model (BIM), Project Production Management (PPM), Integrating Project Delivery (IPD), High-Performing Buildings, Lean Construction, and Collaborative Contract Management. The courses included different assignments per week, according to the content sequence.

PBL was implemented in these VDC courses, where two scenarios were designed to develop the VDC framework (Figure 2). In Scenario 1, each group selected a unique project and created its own VDC framework with Production Metrics and Controllable Factors. In Scenario 2, multiple subprojects derived from a single project were chosen by each group. Each group developed a VDC framework with their Production Metrics and Controllable Factors aligned with a general VDC framework.

Students could select two real-world projects for each scenario: 1) an already-built project or 2) a currently-under-construction project. The first type of project would allow students to propose and simulate a solution to the real problem presented in the project. In contrast, the second type would allow them to apply their proposals and evaluate results with professional criteria. The second type of project is associated with a higher autonomy level in the project by students since the teacher acts as an advisor rather than a lecturer [46].

As the courses were held virtually, online-collaborative platforms such as Miro, an online virtual whiteboard, and BIM 360, software for information and deliverable centralization, were used. BIM 360 helped to manage the project information within the work teams. Previous research found that students perceived BIM 360 as an easy platform to coordinate the project they were working on [48].

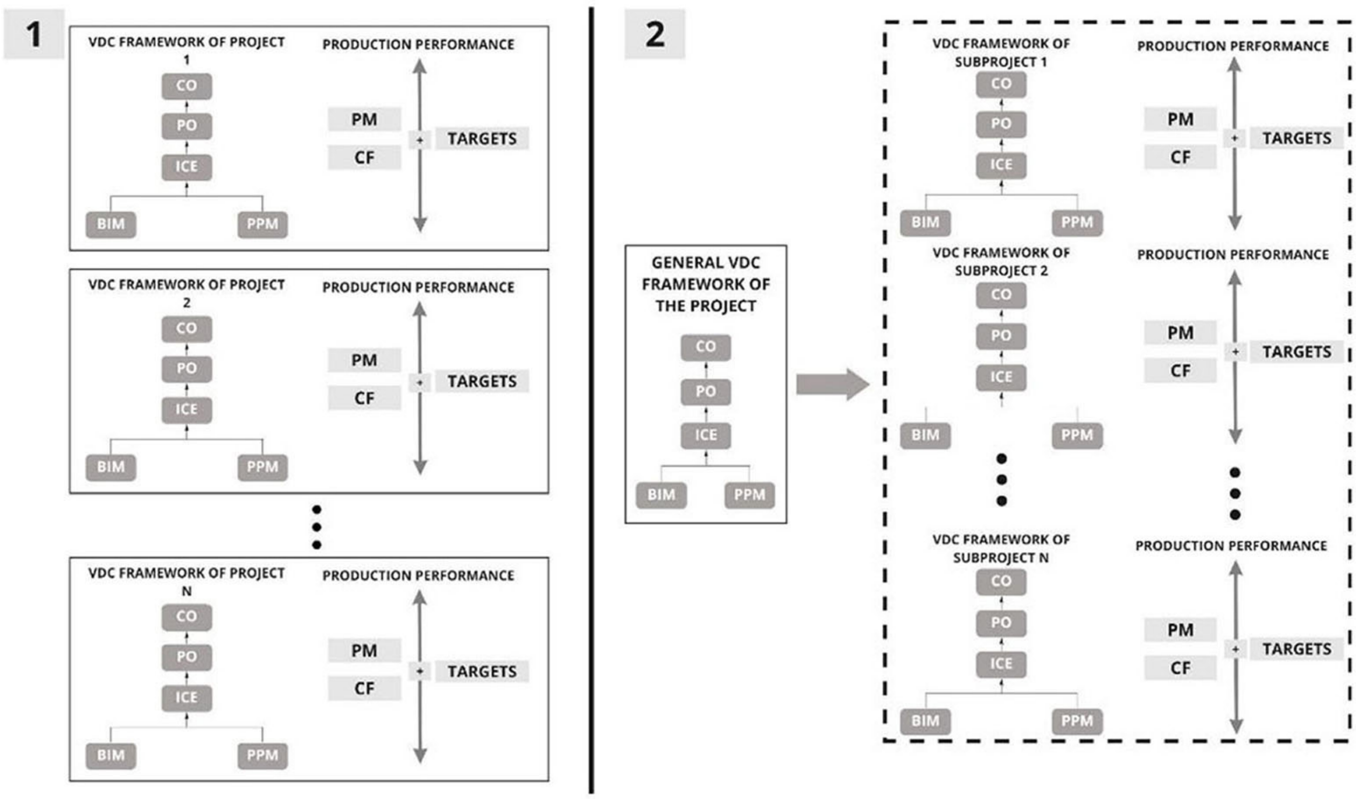

Fig. 2. The two scenarios of VDC framework development for VDC courses

The present work proposes two VDC courses within the PBL framework, considering the five aspects of the P5BL approach from Stanford University, and promoting the use of IT, as presented in Table 3. Since the "people" aspect is oriented to engage team members from different disciplines and countries, the interaction of students with professionals who are not involved with the courses was encouraged.

Table 3. Problem-, project-, product-, process-, people-based learning adapted to VDC courses

Aspect	Implementation	IT Use
Problem	Define measurable objectives in the VDC framework, the constraints, and the project's challenges with different stakeholders.	Collaborative platform to coordinate teammates and key stakeholders.
Project	Select and study an actual project in which to implement VDC.	Internet to obtain information and plan meetings with stakeholders via a communication platform.
Product	Use BIM objectives and High-Performing Building concepts to give value to the final client's product.	BIM and Common Data Environment to share model updates.
Process	Adapt and adopt PPM and Lean concepts to project workflows.	Collaborative platform to develop optimized workflows.
People	Hold ICE sessions with stakeholders to plan activities and set optimization alternatives.	Communication platform to coordinate stakeholders.

3.2 Data collection technique

Figure 3 shows the steps to develop the data-collection approach implemented in the present research, with a survey as the final product. To measure students' perceptions of VDC and PBL, Scopus and Web of Science databases were reviewed to select relevant questions for the survey. As seen in Table 4, information related to VDC and PBL is null, while there are papers associated with BIM and PBL. Therefore, studies focused on implementing active learning methodologies for BIM teaching, such as PBL, were analyzed. The reviewed papers correspond to the past 10 years. The described implementations were conducted among project management courses within engineering programs. They were chosen to compare this research's results with students' perceptions about their generic competencies' development process and overall learning experience.

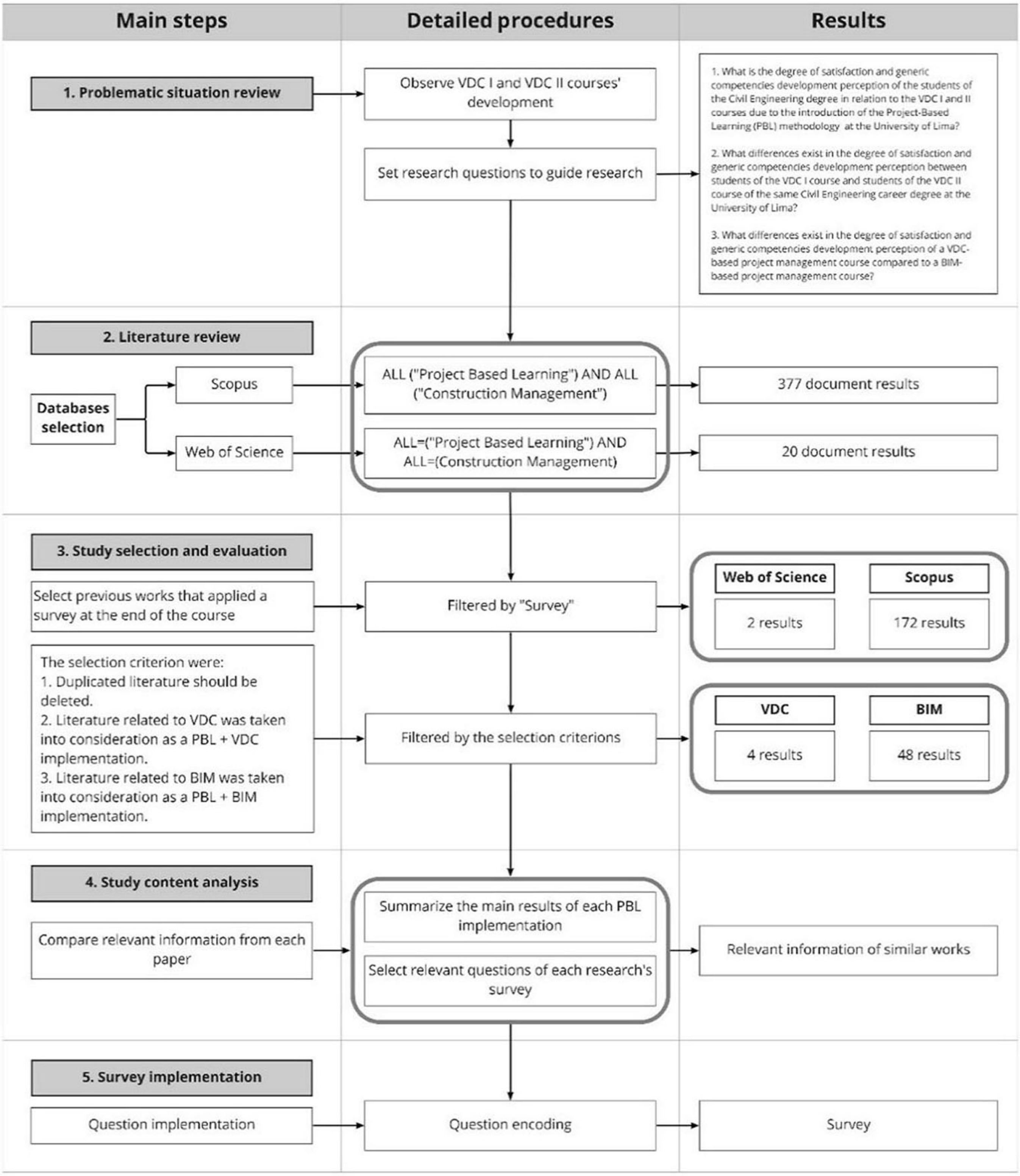

Fig. 3. Research methodology framework

Table 4. Papers are found in Scopus and Web of Science databases

Aspect	Scopus	Web of Science
ALL („Project-Based Learning") AND ALL („Construction Management") AND ALL („VDC") AND ALL (survey)	4	0
ALL („Project Based Learning") AND ALL („Construction Management") AND ALL („BIM") AND ALL (survey)	48	0

Survey questions were categorized into four sections based on the objectives and the dependent and independent variables mentioned above (Table 5). Section 1 aims to measure whether the resources used in the proposed VDC courses were appropriate and gauge students' perceptions of the virtual environment. Sections 2 and 3 focused on calculating students' perceptions of VDC and PBL methodologies. Section 4 was presented as the course methodology to avoid explaining the definition of PBL to the students. Section 4 gathers feedback from the students' learning experience. Each question had a unique ID representing the section it belonged to.

Table 5. Survey sections

Section Number	Section Name	Section ID	Number of Questions
1	Course design	CD	12
2	Virtual Design and Construction methodology	VDC	14
3	Course methodology	PBL	19
4	Course feedback	FB	13

Questions in sections 1 and 4 are based on the resources, tools, and objectives implemented in the VDC courses proposed. The first ten questions of section 2 focus on the benefits reported by the authors in the literature review [7, 8, 49]. In comparison, the last four questions are based on the suggestion to measure how the learning of a methodology can influence the students' professional life [50]. For section 3, the questions proposed by [44] were utilized because the generic competencies evaluated were considered analogous to the objectives of this research. These questions assessed the opinions of the VDC and PBL implementation in the surveyed students. Even though the case studies from the literature review and the present research employ different methodologies (BIM and VDC), questions regarding the students' perceptions of their generic competencies' development are compared in the discussion section. The final survey is presented in Table 6.

Table 6. Survey developed

ID	Question
Course Design Section	
	Regarding the course design...
CD-1	The Miro platform helped to coordinate and limit the scope of each team.
CD-2	The Miro platform helped to coordinate and develop the deliverables of each team.
CD-3	The virtual environment did not impede the development of the classes.
CD-4	The virtual environment did not impede the development of my project.
CD-5	The virtual environment was fine for communication within my work team.
CD-6	The university gave me different support (licenses, platforms, software, books, etc.) to develop my project.
CD-7	The hours allocated to the course are appropriate.
CD-8	The BIM 360 platform helped centralize project information.
CD-9	The BIM 360 platform helped meet my project objectives.
CD-10	I agree with the involvement of a teaching assistant.
	Regarding virtual class sessions...
CD-11	They positively affected my learning.
CD-12	It was very beneficial to have multiple experts in the field.
VDC Section	
	VDC helped to...
VDC-1	Generate reliable information.
VDC-2	Identify all the complexities of the project.
VDC-3	Analyze all the complexities of the project.
VDC-4	Solve all the complexities of the project.
VDC-5	Develop an optimal workflow.
VDC-6	Improve work-team collaboration.
VDC-7	Define the project objectives.
VDC-8	Improve the productivity of work teams.
VDC-9	Improve the personal preparation of each student.
VDC-10	Define a reliable work plan.
	Studying the VDC methodology...
VDC-11	It will offer me better job opportunities in the national market.
VDC-12	It will offer me better job opportunities in the international market.
VDC-13	It will help solve the problems of the construction sector at the national level.
VDC-14	It will help solve the problems of the construction sector internationally.
Project-Based Learning Section	
	The learning methodology helped me develop my skills in...
PBL-1	Critical thinking.
PBL-2	Self-learning and independent thinking.

(Continued)

Table 6. Survey developed *(Continued)*

ID	Question
PBL-3	Interpersonal communication.
PBL-4	Decision making.
PBL-5	Problem resolution.
PBL-6	Leadership.
PBL-7	Teamwork.
PBL-8	Information management.
PBL-9	Planning.
PBL-10	Analysis.
	It helped improve my awareness of...
PBL-11	Teamwork.
PBL-12	Leadership.
	It motivated me to...
PBL-13	Learn.
PBL-14	Prepare before class so I can participate in the development of the class.
PBL-15	Collaborate in teamwork.
	Thanks to the course methodology...
PBL-16	I could understand theoretical concepts better.
PBL-17	I was able to meet the learning objectives of the course.
PBL-18	I feel able to apply my knowledge in practice.
PBL-19	I feel prepared to work in the architecture, engineering, and construction industry.
Feedback Section	
	About the course...
FB-1	There is a good balance between theoretical content and practical activities.
FB-2	Presentations (PPTs) have good-quality content.
FB-3	The bibliography used in the course is adequate.
FB-4	The Miro platform was helpful as a virtual whiteboard.
FB-5	The teacher is competent to teach the course.
FB-6	The teacher's support was key to meeting the course's learning objectives.
FB-7	The development of project-based learning would benefit other courses in the Civil Engineering program.
FB-8	Keeping the cameras on during the development of the classes allowed a greater involvement of the students.
FB-9	The Zoom platform is suitable for teaching the course.
FB-10	How satisfied were you with the course?
FB-11	How likely are you to recommend the course to other students?
FB-12	Were the objectives of the course clear?
FB-13	Were the objectives of the course met?

The survey used five-point Likert-type scales to analyze students' learning experiences to guide the next steps and future improvement efforts. The values for this survey are: 1 = totally disagree; 2 = disagree; 3 = undecided; 4 = agree; 5 = totally agree.

4 RESULTS

4.1 VDC courses

The VDC methodology is taught in two semester-long courses from an undergraduate civil engineering program at a private university. The methodology is divided into two classes: VDC I, introduced in the eighth semester, and VDC II, in the ninth. For the first semester of 2021, both VDC I and VDC II courses were taught in a virtual environment. Thus, a video chat platform for the lecture sessions and an online virtual whiteboard for developing the group assignments were utilized.

In VDC I, VDC is presented theoretically. Throughout the course, the following thematic axes are developed: introduction to the VDC framework, POP Matrix, Production Metrics, Controllable Factors, IPD, ICE, BIM, and PPM. Based on the proposed course methodology, VDC I adopts the first project type, in which students develop collaborative assignments applied to the real world. These are already-built projects targeting each thematic axis, so that students can develop a VDC framework at the end of the course.

For this study, each group selected a national interest project, which included wastewater treatment plants, telecommunications infrastructure, dams, and railways. To achieve the course objectives, students had to seek information on the project's scope and involved stakeholders. Each group developed a VDC framework for each unique project, in line with the first scenario presented in the VDC course methodology. Assignments designed through the VDC I course were: set relationships between the objectives of the project and the client; propose and classify metrics targeting those objectives; identify workflows that govern the project based on the types studied in lectures; establish production metrics and controllable factors for each VDC component (ICE, BIM, PPM) and the relationship between the objectives for each element with the motivation or expected effect for the project; propose IPD applications for the project; and define the interrelation of the VDC framework with its respective reflection.

In VDC II, students put into practice all the theoretical knowledge gained in VDC I to develop a VDC implementation in a real-world project currently under construction, based on the second type of project presented in the course methodology. To bolster the VDC implementation, aspects reinforced in the lectures include: IPD, Lean Construction, High Performing Buildings, and collaborative contract management. The projects adopted for the first semester of 2021 were the design and construction of a set of laboratories and buildings for a university in Lima, Peru. Students had access to the project BIM shared in the collaborative BIM 360 platform.

For this study, each project of the VDC II course was divided into sub-projects, depending on the number of students and their affinities (structural, electrical, sanitary, earthworks, foundation, and implementation of the prefabricated beam). After establishing the general VDC framework, each group started developing their VDC framework with Production Metrics and Controllable Factors, in line with the second scenario established in the course methodology. The next stage was choosing a component workflow that each group commissioned. Students had to decide on the working sequence under a traditional approach without collaboration. Then, students had to develop a proposal for an optimized and improved workflow using the VDC concepts, based on the knowledge previously acquired in VDC I and the introductory part of VDC II. This optimization aimed to reduce the work objectives' variability, which helped to reduce project cost and time. After this deliverable, Production Metrics and Controllable Factors were followed. This was done by involving the students in ICE sessions during the design stage, selecting materials for the construction process, and the simulation of work (BIM 4D).

Since BIM is an implicit and transcendental topic throughout the civil engineering program from this study, students already possessed the required knowledge of BIM 3D (geometry), 4D (project scheduling), and 5D (cost estimation) [47]. Thus, the implementation of BIM was natural for the surveyed students, and they could focus on the VDC components. At the end of the course, each group consolidated their VDC implementation research processes, resulting in a research poster. These posters were presented in an educational event, which presents each academic semester's most outstanding research projects [27].

4.2 Survey results

Students from the courses VDC I and VDC II, corresponding to the first academic semester of 2021, completed the survey presented in Table 6 during July and August and at the end of each course. The total study population comprised 31 students from an undergraduate civil engineering program at a private university in Lima, Peru: 13 from VDC I and 18 from VDC II. The study sample corresponds to 13 students from VDC I (100% completion rate) and 17 from VDC II (94.44%).

The results of the survey are presented in Figures 4–8, which show the consequences related to students' perceptions about the design of the courses, VDC in the courses, the generic competencies' development process in the courses, and the learning methodology, as well as their overall learning experience and the course feedback, respectively.

Of students' perceptions about PBL influence on project development under the VDC methodology, results are shown in Figure 5. In general, students think applying the VDC methodology helped them develop their projects better. Additionally, students perceive their theoretical and practical knowledge about this methodology as an advantage for their future professional development.

Regarding students' perceptions of PBL influencing their generic competencies' development process, Figure 6 reveals that VDC I and VDC II score higher than analogous studies. This implies that students perceive that PBL application has influenced their development of competencies such as critical thinking, effective communication, leadership, and teamwork, among others. However, VDC II students present higher scores than VDC I students.

Students' perceptions of PBL influence on their learning experience results are shown in Figure 7. The obtained scores are close to the analyzed study cases, as the mean from VDC I and VDC II exhibits. In general, students think the PBL application motivated them while helping them achieve the courses' learning outcomes.

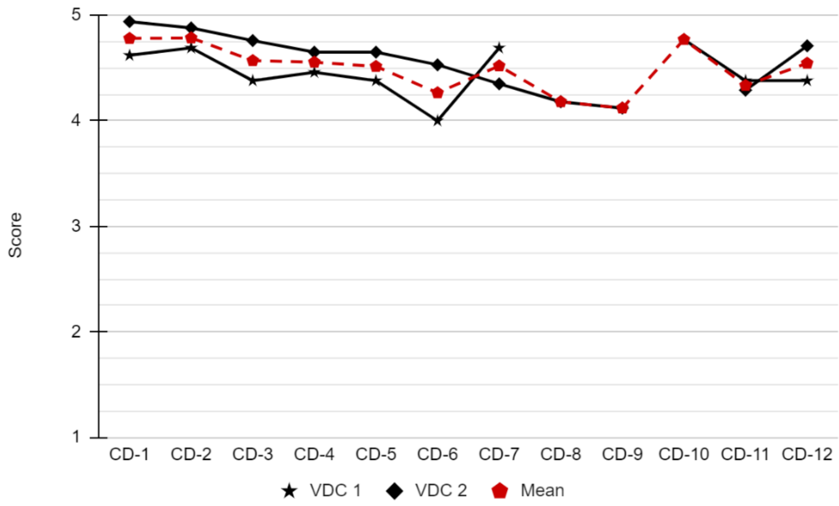

Fig. 4. Survey results on students' perceptions about the design of VDC I and VDC II courses

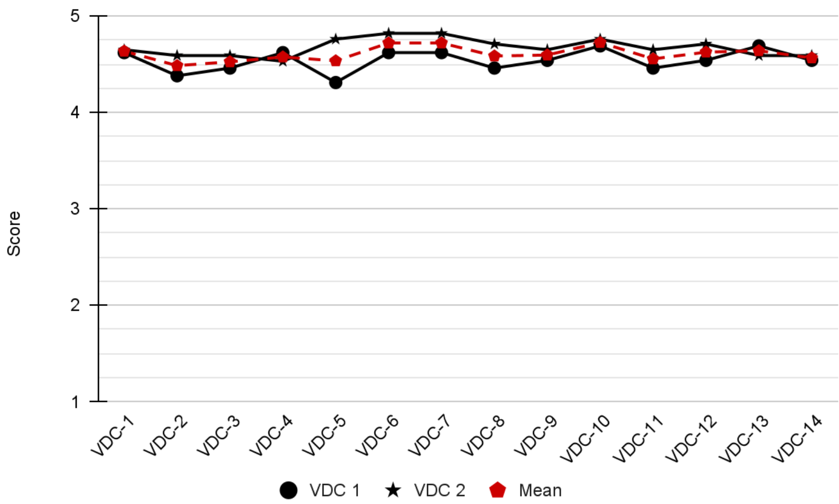

Fig. 5. Survey results on students' perceptions of VDC methodology in VDC I and VDC II courses

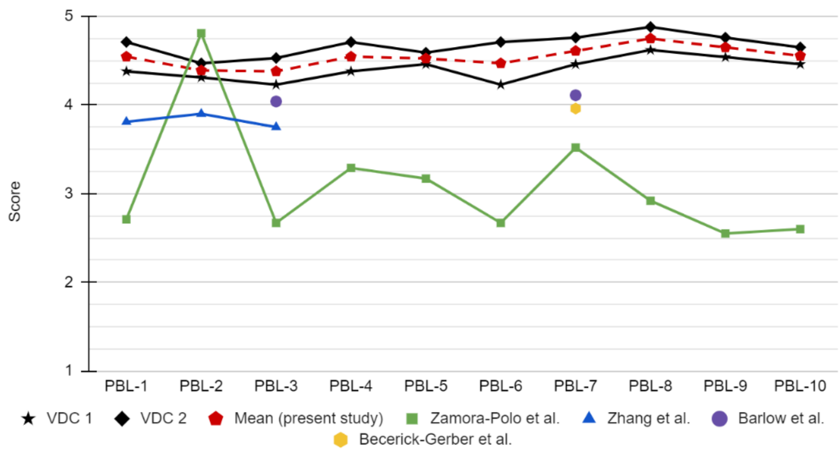

Fig. 6. Survey results on students' perceptions of the generic competencies development in VDC I and VDC II courses and study cases

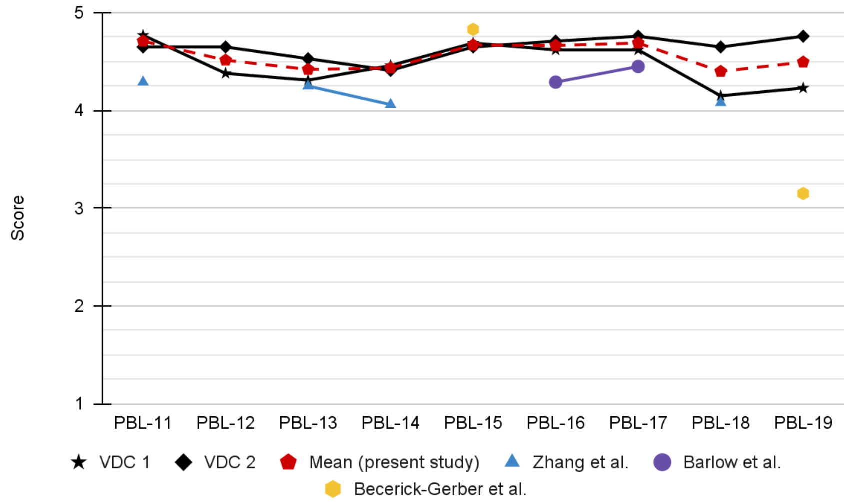

Fig. 7. Survey results on students' perceptions of the learning methodology in VDC I and VDC II courses and study cases

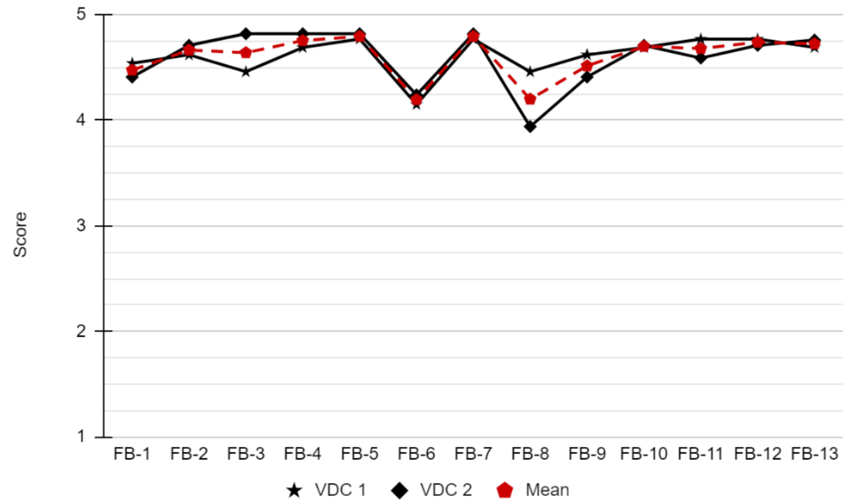

Fig. 8. Survey results on feedback from VDC I and VDC II courses

5 DISCUSSION

In general, scores from VDC II (4.62) were higher than those from VDC I (4.52). This is likely due to the possibility of getting involved in a currently-under-construction project since it involves a more practical than theoretical dynamic. In VDC II, students accessed ICE sessions with the designers, constructors, and clients and interacted with stakeholders, reinforcing engagement with their VDC implementation. Moreover, VDC II students appreciated having the technical specification documents, plans, and models of the projects available in BIM 360, where the information was updated as the project was developed. Additionally, VDC II students could download the central model and work with local models to fulfill the objectives of their VDC implementation. These facts were considered for the VDC II students as a closer experience of real-work dynamics. VDC I students did not have these learning experiences and opportunities. VDC I students had to develop their VDC implementation with information from projects already built without access to the stakeholders. For these reasons, VDC II students believe they can put theoretical knowledge into practice and are better prepared to work in the AEC industry than VDC I students.

The VDC literature review shows different benefits when applied to construction projects. VDC allows work teams to simulate, understand, and analyze the complexities that a construction project delivery is prone to suffer [49]. Surveys applied to work for teams after ICE sessions show beneficial results in the team member's perception of their preparation and participation and the efficiency of the session. In addition, in support of Lean Construction techniques, pull-planning helps to generate more steadfast commitments, increasing the work teams' confidence in the plan and understanding of the upcoming construction phase [8].

Based on the results obtained from the applied survey in this study, students' perceptions of VDC are aligned with the previous statements, highlighting a greater collaboration between work teams (mean 4.72), solving the complexities of the project (mean 4.58), and generating more reliable information (mean 4.64) and plans (mean 4.73). Therefore, it can be affirmed that students perceive that applying the VDC methodology can support the better development of projects. Furthermore, VDC II students value higher (4.76) than VDC I students (4.31) the fact that the VDC methodology allows the development of optimal workflows, because of the opportunity to study different existing ones and find optimization options, with Lean Construction and PPM focus.

The industry requires civil engineering graduates to possess scientific knowledge and generic competencies, such as problem-solving, creativity, teamwork, decision-making, and effective communication [5, 31, 51]. Results of the present study show that students identified that PBL contributed to developing these competencies. Comparing VDC I and VDC II results, the degree of generic competencies development generally improved by 6.13% in VDC II students, compared with VDC I students, being the generic competencies with more difference leadership (11.35%), decision making (7.53%), critical thinking (7.53%), interpersonal communication (7.09%) and teamwork (6.73%). The learning experience improved by 7.15% in VDC II concerning VDC I. VDC II students' perceptions of the improvement in the project development was 3.44% higher than VDC I students' perceptions. Students also considered that PBL motivated them to collaborate more in teamwork (mean 4.67), be aware of the need for leadership development (mean 4.52), and understand better theoretical concepts (mean 4.67).

Based on the survey results, the implementation of PBL with VDC has had a higher impact on developing generic competencies than implementing PBL with BIM [26, 42–44]. These higher scores are found in the VDC methodology's theoretical background that the BIM methodology lacks, which is reflected by (1) the stakeholders' integration and collaboration (ICE component) for the planning, analysis, and optimization of the workflow (PPM component), and (2) the use of virtual models (BIM component) to manage project information and represent the final product [9, 52]. ICE, BIM, and PPM allowed students to achieve a higher degree of professional development due to the collaborative work required instead of focusing only on learning how to use new software. Thus, students perceive that the PBL application has positively affected their learning experience.

Since VDC I and VDC II courses were held virtually, collaborative platforms were fundamental for students to coordinate their project development. In other studies, students worked on a centralized model, while in the present research, students downloaded the model and worked on that local model. This could be why the perceived value of BIM 360 was lower than expected.

Regarding the limitations of the present research, since the study was cross-sectional, it would be convenient to gather data at other specific points in time, considering new groups of VDC I and VDC II students. Furthermore, since the research was conducted at a single private university, the results are most valuable at an institutional level. However, the presented methodology can be adapted to other civil engineering undergraduate programs, considering each context's particularities, including educational models, curricular proposals, teaching-learning methodologies, and study contents.

6 CONCLUSIONS AND FUTURE WORK

P5BL is the learning methodology that adapts better for teaching the VDC methodology, as VDC components (BIM, ICE, and PPM) are considered in it (Problem-Project-Product-Process-People). In this context, the PBL was applied in an undergraduate civil engineering classroom, considering the five aspects of the P5BL.

It was demonstrated that students from the surveyed undergraduate civil engineering program perceive PBL and VDC methodologies as beneficial for their training and professional development. They believe PBL positively affects their overall learning experience and perceive a more significant acquisition of generic competencies, comparing the application of VDC with BIM by more than a third. Since students scored an average of 4.54 in questions relating to the fact that VDC improves future job opportunities and resolves AEC industry problems, it is concluded that their perceptions of VDC methodology are highly positive. The VDC implementation helped them analyze a variety of complexities and solve them using collaboration, which allowed better project development.

Therefore, implementing PBL and VDC within the civil engineering training process is significant. It supports the training of students who feel more confident about assertively responding to the demands of the AEC industry. Implementing the mentioned methodologies is of interest, not only within civil engineering undergraduate programs but for all programs related to the abovementioned industry, such as architecture or project management.

The higher results of VDC II come from the students' involvement in developing currently-under-construction projects through improvement proposals of the constructive process. This involvement allows application VDC components (ICE, BIM, and PPM) to be developed collaboratively by work teams with stakeholders (the owner, designers, constructors, suppliers, etc.). However, both VDC I and VDC II students perceive a better comprehension of theoretical knowledge, which could give them better job opportunities and help them feel prepared to participate in the AEC industry.

Analyzing PBL implementation in a multidisciplinary classroom is recommended for future works, integrating architecture and electrical and mechanical engineering students, as presented in the study cases. New research may also focus on identifying students' engagement and supporting factors to PBL and the constraining factors in a virtual and physical environment. It is also suggested to measure the perception of those students on the dependent variables who have taken the VDC I course and, subsequently, VDC II course and analyze the impact that taking both courses has had. A similar study in VDC programs offered by the Center for Integrated Facility Engineering (CIFE) at Stanford University is proposed, as they involve students from different countries, study levels, and specialties. Finally, analysis techniques such as PLS-SEM could be used to analyze hierarchical models and quantify the influence of the study variables.

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