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AN INTEGRATED FACILITY MANAGEMENT SYSTEM (IFMS), SUPPORTED BY THE VIRTUAL DESIGN AND CONSTRUCTION FRAMEWORK (VDC), FOR ENGINEERING LABORATORIES

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Álvaro Daniel Bazán Montalto

Código 20172848

Jose Francisco Vidal Quincot

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Asesor

Alexandre Almeida Del Savio

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Jose F. Vidal, BS Civil Engineering
Research Staff
Universidad de Lima
josevidalquincot@gmail.com

Alvaro D. Bazan, BS Civil Engineering
Research Staff
Universidad de Lima
alvbazan@gmail.com

Alexandre A. Del Savio, Director of Scientific Research Institute (IDIC)
Research Advisor
Universidad de Lima
delsavio@gmail.com

Martin Fisher, Director of the Center for Integrated Facility Engineering (CIFE)
Research Advisor
Stanford University
fischer@stanford.edu

SUMMARY: Construction has always been characterized as a fragmented, complex, and challenging industry. This has been reflected throughout the life cycle of construction projects, whether in design, construction, or operation and maintenance (O&M). Although efforts have been made to identify and solve problems in design and construction, there is a high degree of disconnection and lack of consensus in the O&M stage, represented by Facility Management (FM). This paper carries out a bibliographic review of the challenges and problems faced by facility management and the methods and technologies proposed for their solution. Moreover, an introduction to Virtual Design and Construction is made as an emerging methodology showing interesting results in the design and construction stages. The hypothesis is that the same positive results can be obtained if VDC were applied to an O&M stage. Finally, an Integrated Facility Management System (IFMS) is proposed based on the VDC methodology applied to O&M to integrate the building product, organization, and processes of an engineering laboratory facility in Lima, Peru.

KEYWORDS: Facility Management, VDC, ICE, BIM, PPM.

1. INTRODUCTION

Beyond all its limitations in terms of innovation, flexibility, and cost, construction products are complex (Nam & Tatum, 1988). This complexity can be seen in terms of the organization, the product, and the process. Construction projects involve many stakeholders with different objectives and interests, leading to fragmentation issues among the professionals and organizations (Nawi et al., 2014), (Esa et al., 2014). On the other hand, construction products are characterized by a large number of interdependent elements, equipment, and complex systems that make up a building (Nam & Tatum, 1988), with an arduous, lengthy supply chain composed of many internal and external suppliers (Ashworth & Perera, 2015) (Perera et al., 2017).

Some authors correlate this complexity to the heterogeneity and project-based nature of construction (Gálvez-Martos et al., 2018), which complicates the implementation of information and communication technology solutions compared with process-based industries, such as manufacturing and automotive (Nanayakkara et al., 2015). Compared to these, construction processes are less standardized and automated and exploit less technological innovation (Dave et al., 2008). As a result, construction is ranked the second lowest sector to adopt information technology (McKinsey Global Institute, 2016). Furthermore, this project-based nature of construction is seen as a hurdle for innovation and improvement because projects are usually short and of small scope in most firms or the industry (Taylor & Levitt, 2004).

Complexity and fragmentation of projects is an intrinsic aspect of buildings (in the construction industry in general) (Nam & Tatum, 1988), and it is present throughout the entire project life cycle: design, construction, and operation and maintenance (Dainty et al., 2001) (Love et al., 2002).

The design process grows in complexity as more disciplines come into the project (Moum, 2010) as the number of parts into which the work is divided increases, thus requiring a better and greater interaction among the specialties (Ng & Tang, 2010). Although this topic is widely recognized in the industry, little is known about the true factors that may impact the integration of design teams. Galaz-Delgado et al. (2021) validated in an in-depth bibliometric study that the main challenges in design team interactions arise indeed in communication, collaboration, coordination, trust, and role identification.

During the construction stage, the greatest challenges arise from coordinating all elements, processes, and actors interacting simultaneously. In this case, fragmentation and supply chain management (SCM) are the key factors to control the abovementioned complexity during this part of the project. Fragmentation's cause and effect are represented by the inefficient and ineffective exchange of information in projects, being also the consequence of poor collaboration and integration between construction actors and partners (Fischer, 1989) (Fischer et al., 2017). On the other hand, SCM is the management of all the processes required to deliver a customer service or product through a network of organizations with minimum waste and maximum value (Arbulu and Tommelein, 2002). Therefore, it plays a pivotal role in providing improvement opportunities for all problematic issues in construction (Vrijhoef, 1998), with defined roles and objectives in the industry (O'Brien & Fischer, 1993) (Vrijhoef & Koskela, 2000). Still, it is strongly affected by poor communication and commitment between the parts (Vrijhoef and Koskela, 2002).

The challenges facing design and construction in terms of industry fragmentation and complexity have been widely studied. Likewise, many efforts have been made to solve these problems. However, there is a gap in the operation and maintenance (O&M) stage, represented by Facility Management (FM). The latter is a concept that has been studied for 35 years, but until now, it continues to find contradictions and lack of standardization in practice (Roper, 2017).

This research will focus on presenting a background study on the challenges and problems faced by facility management and the methods and technologies proposed for their solution. Moreover, an introduction to Virtual Design and Construction will be made as an emerging methodology showing interesting results in the design and construction stages. The hypothesis is that the same positive results can be obtained if VDC were applied to an O&M stage. Finally, an Integrated Facility Management System (IFMS) is proposed based on the VDC methodology applied to O&M to integrate the building product, the organization, and processes under a single goal and get the best results in this stage of the project life cycle.

2. BACKGROUND

2.1. Facilities Management

The concept of Facility Management (or Facilities Management) has been around for 50 years when it began as a simple sanitary and cleaning service during the 1970s. Since then, it has constantly been evolving to what is known today as the occupational profession, with millions worldwide involved in managing organizations, their facilities, and services (Drion & Melissen, 2012).

There is no global consensus on the services or processes that Facility Management should cover since the natural diversity of buildings leads to managing in multiple ways based on what is required. However, a definition proposed by the European Committee for Standardization (CEN) states that Facilities Management is "the integration of processes within an organization to maintain and develop agreed services that support and improve the effectiveness of its main activities" (CEN, 2022). This definition is promoted by the European Facility Management Network (EuroFM), including the institutions of the British Standards Institute (BSI) and the British Institute of Facility Management (BIFM) (Euro FM, 2020). Moreover, the International Facility Management Association (IFMA, 2022), while establishing that facility management is a profession, also recognizes the definition provided by ISO 41011:2017, which defines Facility Management as "an organizational function that integrates people, places, and processes within the built environment to improve people's quality of life and productivity of the core business" (ISO, 2017).

Based on the above, there is a notable discrepancy in what is known as facility management within institutions. Most of the literature, on the other hand, defines FM as an industry (Grimshaw, 2003) (Then, 2004), (Atkin and Brooks, 2001) (Banyani & Then, 2016) (Roper, 2017) but with no real support behind the such claim. Only in 2010, Banyani and Then (2010) conducted a study to validate facility management's current functions and status and conclude that it is indeed an industry. Based on their observations, they stated that unlike in the past, where the functions of the Facilities Manager were to ensure the availability of workspace, today's challenges lie in the provision and management of strategic infrastructure and support services that enable business continuity. The Facility Manager is required to anticipate changes in demand and act swiftly while considering adding value to the core business. Moreover, FM organizations must pay attention to strategic issues while considering tactical and operational matters (Banyani & Then, 2010).

Following the line of the academy, the efforts that have been made in research seem to be inconsistent with the results obtained in practice. A bibliometric study that analyzed 724 academic articles referring to Facility Management from 1995 to 2018 showed that the average number of publications per year had doubled (Li et al., 2019). However, according to an IFMA (2017) report, the costs of repairing and maintaining buildings have increased by 72% between 2007 and 2017. Likewise, the most cited FM academic articles are between 10 and 15 years old, reflecting that the current body of knowledge is not as relevant as before (Atkin & Bildsten, 2016) (Li et al., 2019). Although the expansion and research of Facility Management gained quite a bit during its early years as a new field of interdisciplinary study, the academy's current perception is more inclined toward an empirical phenomenon (Alfalah & Zayed, 2020).

2.2. Proposed solutions

The day-to-day work of facility managers is focused on responsibilities they must fulfill, such as real estate management or capital projects and building planning (IBM, 2022). The range of functions and objectives in operation and maintenance of a building becomes quite wide, so the solutions to the problems that may arise must have the same characteristics of adaptability and macro-management. For this, the solutions proposed to the problems in the facility management industry should be more focused on integrating the facility, the organization, the processes, the technology, the information, and the collaborative spaces that can be used to achieve this goal.

Technology in facility management includes both software and systems. Built environments generate vast amounts of data through Internet of Things (IoT) sensors, Wi-Fi, meters, and smart devices. The most effective solutions are directed to an Integrated Workplace Management System

(IWMS), which allows facility management departments to use this data through the infusion of analysis and artificial intelligence (IBM, 2022).

Integrated Workplace Management Systems (IWMS) are software solutions that enable executives and managers to significantly reduce real estate and facility costs while increasing business productivity. The main benefits of IWMS systems are increased efficiency, transparency, flexibility, and customer satisfaction in an organization's facilities management processes (Planon, 2022). In fact, according to studies, the IWMS leads to a reduction in facility maintenance costs of 14%, an improvement in workspace management of up to 40%, and an increase in the efficiency of the use of facilities by 42 % (Research & Markets, 2018).

2.3. Virtual Design and Construction

Virtual Design and Construction is a management methodology that integrates product, process, and organization models (Kunz and Fischer, 2004). The latter is one of his greatest contributions since his approach is strongly focused on integrating a certain work team to achieve the proposed objectives and, ultimately, the client's objectives. VDC was founded by the Center for Integrated Facility Engineering at Stanford University in 2001 (CIFE, 2020). Since then, it has evolved into what is known today, with its main components: Client Objective, Project Objective, Integrated Concurrent Engineering (ICE), Building Information Modeling (BIM), and Project Production Management (PPM).

Within the VDC framework, BIM is the component related to the product. This research will be used merely as a tool (in conjunction with the COBie standard) to achieve the proposed objectives. Several benefits have been identified in the collaboration of BIM-COBie for the operation and maintenance stage. Although it is still considered that COBie presents challenges concerning visual management and transmission of information (Yalcinkaya & Singh, 2016), examples of useful frameworks for correctly implementing the standard have already been made (Alnaggar & Pitt, 2018).

On the other hand, Project Production Management (PPM) is the component of the process, which is based on the application of operational sciences in construction projects, to visualize and analyze them as production systems (Project Production Institute, 2013). This approach was founded by the Project Production Institute (PPI) in 2013. Since then, it has greatly promoted its implementation, relying on mathematical formulas and separating itself from other methods such as Lean, Project Management, and the Last Planner System, among others (Shenoy, 2017). Likewise, PPM works considerably on the reduction of variability, which is defined as "a gap in the quality and quantity of the flows (information, materials, tasks, equipment, workspaces) necessary to carry out a sequence of construction activities" (Garcia-Lopez & Fischer, 2016). The variability present in the work processes will be responsible for the expansion of the buffers used, whether they are of the 3 types: inventory (or work on hold), time, and capacity; which will ultimately result in additional waste and losses for the project (Shenoy, 2017).

Finally, the ICE component is one of the most outstanding of the methodology since it represents the organizational model that, until then, had been little discussed within the opportunities for improvement in the industry. The concept of ICE lies in the co-location of a work team in a highly collaborative workspace to solve problems of concern to all stakeholders. (Chachere, Kunz, and Levitt, 2004).

This article proposes a standard method to optimize the management of a building (Facility Management) through implementing an integrated system. The implementation of this integrated system will be carried out collaboratively through the application of Virtual Design and Construction focused on the Operation and Maintenance stage.

3. METHODOLOGY

This project aims to carry out an explanatory investigation related to the proposal for implementing an Integrated Facility Management System, supported by quantitative information, based on the Virtual Design and Construction methodology.

Firstly, a preliminary hypothesis of the integration of VDC and FM was proposed to achieve the client's objectives during the operation and maintenance stage of a building. Based on this premise, a bibliographic review was carried out in indexed databases, such as Scopus, Mendeley, and Web of Science, as well as regulations and standards of good practice, using the following keywords: "Facility Management," "Virtual Design and Construction," "Integrated Workplace Management System" and "Information System."

From the study of the information collected and semi-structured interviews with those in charge of the laboratories, a VDC framework is proposed with suggested production objectives and controllable factors, which were reviewed and validated by the stakeholders related to the operation and maintenance of the establishment.

4. RESULTS AND DISCUSSIONS

4.1. Project Introduction

Laboratories have always been considered one of the most important establishments for the progress of society, generating a great impact in sectors such as medicine, engineering, and education (Lippi & Mario, 2020) (Asiksoy & Islek, 2017). Being the cradle of research, science, and progress, laboratories have always represented a high investment cost. The need to have precise measurements in various atypical scenarios leads to having equipment of the highest quality and caliber, which is generally not cheap. This has increased over the years as new needs arise, and technological progress allows us to evaluate much more adverse situations. In that sense, the cost of the laboratories is generally justified based on the objective and need for research and teaching. (Malaviya & Sanjiv, 2014) (Amihud & Mordechai, 1993).

The facility studied in this article is the Laboratories of the Civil Engineering Department (Figure 1) at the University of Lima, located in Lima, Perú. When the Civil Engineering Program of the University of Lima began in 2017, the need arose to implement laboratories to provide: (i.) technical and academic support to the subjects taught; (ii.) research support; and (iii.) support for the construction industry through collaborative agreements. In this sense, the direction of the Civil Engineering Department defined a gradual procedure for implementing the laboratories to meet those goals.

Figure 1 – Overall view of the Laboratories of the Civil Engineering Department.

The implementation of the laboratories is in line with the progress of an academic program and the different branches of research. The following laboratories were identified and implemented: Laboratory of Materials, Soils, Rocks, Topography, Geomatics, Structures, Environmental Engineering, Pavements, Sanitary Engineering, Hydraulics, and Hydrology. The results obtained in this chapter will reflect the method proposed to implement the IFMS under a VDC approach applied to the Operation and Maintenance stage in said establishments.

4.2. Analysis of the Problem based on primary information

Interviews were conducted with those in charge of the Laboratories of the Civil Engineering Department. This made it possible to clarify the objectives, identify the critical equipment, map the equipment maintenance process, identify problems or sources of variability, and propose improvements in the effectiveness of the maintenance process. The results of these interviews are presented below.

One hundred percent (100%) of the managers interviewed agree that the laboratories meet 3 main objectives: support in the practical development of the subjects taught in the Civil Engineering Program, development of research by students and teachers, and support to the industry through research agreements. In this sense, the value of the investment made for the implementation of the laboratories is measured in the degree of use of the equipment in academic courses, research, and collaborative research agreements (not from an economic/investment point of view).

The laboratory managers interviewed agreed on 11 key pieces of equipment, presented in Table 1, organized by the laboratory disciplines.

Table 1. Key equipment.

Laboratory	Technical Name and Characteristics	Tests	Image
Materials	Uniaxial compression machine "AUTOMAX". 2000 kN capacity.	• Rocks, • Bricks, • Adobes, • Among other materials.	
	Multi-testing machine. 600 kN capacity.	• Free testing, • Cyclic fatigue, • CBR, • MARSHALL, • Cementitious Flexure, • Penetration, • Compression by position, • Compression by force, • Tensile stress by position, • Tensile strength, • Tile adhesives, • Shear strength.	

Geotechnics	Triaxial soil system. Measures inlet and outlet water volume, friction angles, cohesion, and porosity. It consists of: a cutting frame, pressure control frame, and snubber tank.	• Saturation, • Consolidation.	
	Direct cutting. Measures cohesion and friction angles. Performs shear and vertical deformation cuts.	• Direct shear tests on fine-grained soils (clays, silts, sands).	
Pavements	Hamburg Wheel. Variable wheel speed from 20 to 30 cycles/min. Power: 4,6 kW. Wheel Load: 700 N. Weight: 600 kg.	• Asphalt molds and compacted soils. • Simulates pavement wear by vehicular traffic.	
	Servo-hydraulic universal testing machines. 30 kN capacity, rigid two-column load frame, sealed rod actuator. High-precision, double-acting labyrinth-bearing actuator. High-performance servo valve allows sinusoidal load frequencies up to 70 Hz. Climatic chambers for temperature ranges from -25 to +70 °C or -50 to +80 °C.	• Resilient modulus test measures the amount of soil deformation when small loads are applied. • Simulates vehicular traffic.	
Structures	Single-ended hydraulic actuator. Model: MTS DuraGlide 201.60. Dimensions: 400 x 400 x 2550 mm. Tension load capacity: 650 kN (145 kip). Compression load capacity: 1015 kN (230 kip). It comprises FlexTest 60 Controller, the Hydraulic Power Unit, and Hydraulic Service Manifold.	• Spot testing. • It works vertically for static movements and horizontally for cyclic movements. • Beam, columns, and slabs, among other structural elements.	
	Uniaxial compression machine "AUTOMAX" of 3000 kN. Power: 700 W. Weight: 100 kg. It comprises a flexural frame for beams and control console.	• Compression testing of specimens of different dimensions. • Tests in Barcelona • Compression tests in masonry. • Tensile tests. • Adhesion tests.	

Sanitary, Hydraulic, and Hydrology Engineering	Compact fluid mechanics basic module HM250. Power: 1.1 kW. Voltage: 220 V. Phase: Single phase. Pump Power: 50 W. Flow sensor: 0 -15 L/min.	• Demonstrate the effect of various obstacles on the energy level in the open-channel flow.	
	Flow and Sediment transport channel. Digital flow meter: 10 to 200 liters per minute. Pump flow rate: 0 to 180 liters per minute. Power: 0.5 kW Phase: Single Phase. Voltage:220 – 240 V.	• Mechanics of sediment transport. • Investigations in fixed and smooth bedform.	
Environmental	Spectrophotometer Infrared FTIR. Power: 160 W. Voltage: 220 V. Phase: Single Phase. Wavenumber: 600 – 4000 cm-1.	• Characterization by infrared spectra. • Identify structural alterations of material molecules.	

A piece of equipment is considered key when it meets the following requirements: (1) its operation is essential due to its high demand (academic courses, research, and collaborative research agreements), (2) its maintenance is complex and laborious or with much variability in the correction period, or (3) that it does not have a replacement available in the local market.

Next, the current maintenance process of the equipment in the laboratories is presented in Figure 2, using the Business Process Model and Notation (BPMN) standard, as well as its duration analysis:

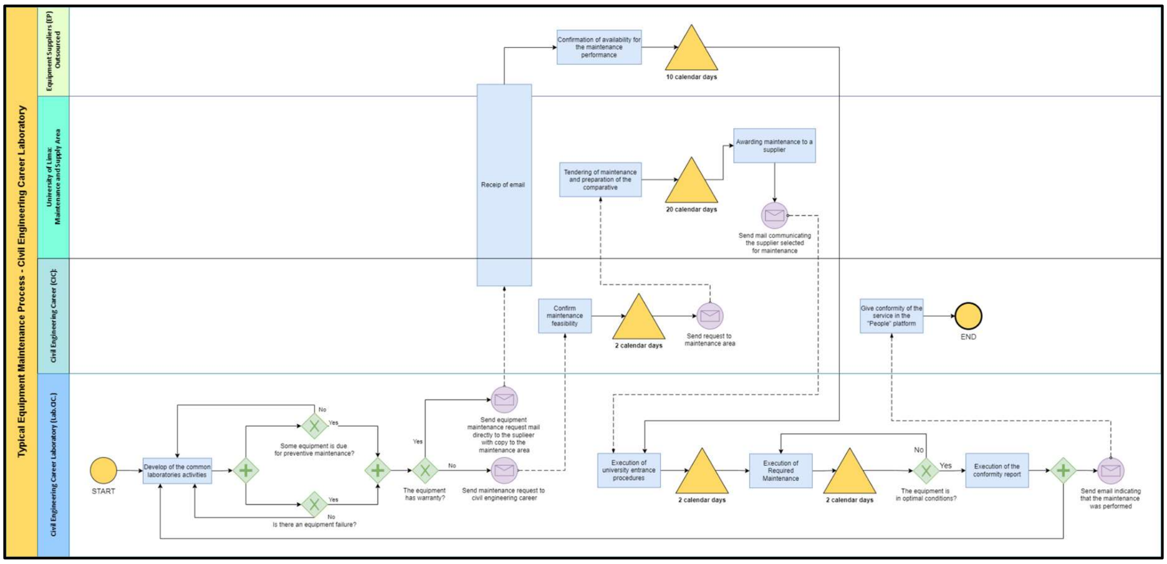

Figure 2 - Current maintenance flow.

The average duration of the equipment maintenance process depends on 2 variables: type of maintenance (corrective or preventive) and the existence of equipment warranty. As can be seen in Table 2, the days of equipment inoperability increased from 2 days (duration with preventive maintenance and warranty) to 26 days if corrective maintenance without equipment warranty is performed. In this sense, it is necessary to seek to develop the maintenance of the equipment preventively and seek extended guarantees for the equipment to reduce the risk of inoperability.

Table 2. Current maintenance flow time analysis.

Type of Maintenance	Warranty	Total Process Duration (Days)	Duration of Inoperability (Days)
Preventive Maintenance	Yes	14	2
	No	26	2
Corrective Maintenance	Yes	14	14
	No	26	26

The interviewees indicated that the main problems in terms of the maintenance process are the following: (1) Latency in communications and deficiencies in the follow-up of maintenance requests, (2) lack of technical knowledge of the suppliers awarded to carry out the maintenance of the equipment and (3) the lack of extended warranties. In addition, as seen in the process presented in Figure 2, those in charge of the laboratories do not participate in the choice of the provider that will carry out the maintenance service. Therefore, no feedback is given from the chosen providers, and it isn't easy to track the status of the requests. In this sense, the award process's duration and the chosen supplier's reliability are the greatest sources of variability within this process.

Consequently, 60% of the managers interviewed indicate that they have had some equipment in their laboratory inoperative due to maintenance and that the average repair time (corrective maintenance) of critical equipment is 130 calendar days (historical value). In addition, it is indicated that 2 pieces of equipment (1 of them critical) are not working in their optimal state due to maintenance issues. Based on this, those in charge of the laboratories suggest improving the process by doing the following: participate in the selection of the suppliers that provide the maintenance service, develop a supplier evaluation system, use maintenance software, improve programming maintenance and request extended warranties.

4.3. Elaboration of Virtual Design and Construction Framework

Based on the information from interviews with laboratory managers, the VDC framework was developed. Subsequently, this framework was validated by the laboratory team. The proposed VDC framework is presented in Table 3.

Table 3. Proposed VDC Framework.

<table>
<tr><th colspan="4">VDC FRAME</th></tr>
<tr><td>CO</td><td colspan="3">Guarantee a 95% operability of the critical equipment.</td></tr>
<tr><td>OP</td><td colspan="3">Develop and implement an Integrated Facility Management System (IFMS), which manages the 11 critical equipment of the laboratories.</td></tr>
<tr><td>ICE</td><td colspan="3">Guarantee a 90% attendance of stakeholders.
Have 100% compliance with the agenda in the sessions (% Agenda Compliance).</td></tr>
<tr><td>BIM</td><td>Have a 100% of the critical information for the operation and maintenance of the equipment included in the BIM model (% Critical information available).</td><td>PPM</td><td>Have operability of 95% in the 11 critical equipment.</td></tr>
</table>

The client's objective is to guarantee the continuity of the use of the equipment that the laboratory has. In this sense, it is desired to avoid any inoperability of the equipment due to corrective maintenance. For this reason, the project team's objective is to develop an integrated Facility management system to manage the 11 critical pieces of equipment. The production objectives and controllable factors for the ICE, BIM, and PPM components are presented in Table 4.

Table 4. ICE, BIM, and PPM production objectives and controllable factors.

ICE	Description	Metrics	Goal
Production Objectives	•Guarantee 90% attendance of stakeholders. •Have 100% compliance with the agenda in the sessions.	% Attendance of Stakeholders = #Attendees/Guests * 100 % Fulfillment of Agenda = Points developed / Points Scheduled *100	>90% 100%
Controllable Factors	•Have weekly ICE sessions to review project metrics. •Send a Minutes of the meeting in advance to the meeting. •Involve the laboratory team in choosing equipment maintenance service providers.	Session Frequency # of days % of attendance of the laboratory team in the maintenance supplier selection meeting	Weekly 2 >90%

BIM	Description	Metrics	Goal
Production Objectives	•Have 100% of the critical information for the operation and maintenance of the equipment included in the BIM model.	% Inclusion of critical information in the BIM = Information Included / Information Requested	100%
Controllable Factors	•Define a checklist of information necessary for the maintenance of equipment. •Use BIM displays with the critical equipment information and places them as QRs on the physical equipment.	% Of Checklist definition for critical equipment % Of critical equipment modeled and included in BIM displays	100% 100%

	•Model 100% of critical/key equipment.	% Of critical equipment with visual management in Laboratories % Modeled Critical/Key Equipment = Modeled Equipment / Total Equipment	100% 100%

PPM	Description	Metrics	Goal
Production Objectives	•Have a 95% operability in the 11 critical equipment.	% Equipment operability	95%
Controllable Factors	•Map the current process of Operation and Maintenance of the equipment and propose an optimized one. •Develop an evaluation system for maintenance providers. •Use a platform to manage maintenance dates. •Develop a detailed maintenance schedule for critical/key equipment.	# of mapped processes (Current and optimized process proposal) % of suppliers of the maintenance included in the evaluation system % of critical/key equipment included on the platform to manage the maintenance dates % of critical/key equipment with a detailed maintenance schedule	2 100% 100% 100%

The proposed VDC framework and production objectives aim reducing variability in the problems identified in section 4.2. For the ICE component, having weekly meetings with those in charge of the laboratories could reduce communication latency and enable them to participate in the selection of maintenance providers. The BIM component allow the management and organization of critical information for the maintenance of the 11 selected pieces of equipment and share them with the stakeholders. An optimized process can be obtained from the current process mapped for the PPM component; an evaluation system can be developed for suppliers, and software or a platform can be used to manage maintenance dates related to a general maintenance schedule.

In this way, the proposed VDC framework covers production objectives that allow measuring the operability of critical equipment and controllable factors that directly impact the problem described in point 4.2.

5. **CONCLUSIONS:**

The main objective of this research was to propose an integrated facility management system (IFMS) based on the concepts and practices used in the VDC framework for engineering laboratories.

The bibliographical review denoted a generalized disagreement, lack of standardization, inconsistencies in the Facility Management industry, as well as how the available literature of the academy perceives it. Based on the efforts previously made in the industry, using methodologies and technologies such as BIM, Lean, or IWMS, the application of VDC was proposed due to its high focus on fulfilling clear objectives established by the client and the project.

Within an industry with a low level of standards in the objectives and functions that must be met (due to the great variety of buildings), it was concluded that VDC could contribute to the solution of challenges and problems faced by FM.

Finally, the latter was corroborated through the Integrated Facility Management System (IFMS) proposal for engineering laboratories, which organized the objectives, production objectives, and controllable factors each actor/stakeholder should meet.

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