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BIM QA/QC PROCEDURES BASED ON LESSONS LEARNED FROM CONSTRUCTABILITY ISSUES

BIM-
PROCEDURE ZAGOTAVLJANJA IN NADZORA KAKOVOST I NA OSNOVI IZKUŠENJ S TEŽAVAMI PRI IZVEDLJIVOSTI

BIM A+ European Master in Building Information Modelling

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Supervisor:
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Izvleček:

Arhitekturna, inženirska in gradbena industrija je konkurenčen trg, kjer je strategija za izboljšanje kakovosti gradbenih objektov dragocena naložba. Kakovost je obsežen koncept, ki obravnava skladnost in zadovoljstvo med zahtevano izvedbo ter izvedenim projektom.

Ta študija se osredotoča na uporabo izvedljivosti kot tehnike za zagotavljanje kakovosti, ki izboljšuje sodelovanje med projektantskimi in izvajalskimi skupinami podjetij *angl. Design-Build* s ciljem navzkrižnega učenja med projekti. Naloga predlaga uporabo informacijskega modeliranja zgradb (BIM) za lažje vključevanje gradbenega znanja med napredovanjem gradbenega projekta.

Magistrsko delo vključuje zasnovo in podrobnosti ogrodja z uporabo BIM za zbiranje, analizo, shranjevanje, komuniciranje in uporabo / ponovno uporabo gradbenega znanja, vsebovanega v zahtevkih za informacije (*angl. RFI*) in označevanju načrtov pri sodelovanju med projektanti in izvajalci.

Pri študiji primera je bila uporabljena vrsta orodij, kot so digitalizirani formati RFI in oznak načrtov, sistem klasifikacije izvedljivosti, diagram relacijske zbirke podatkov za znanje o izvedljivosti projektov, kontrolni seznami za zagotavljanje kakovosti izvedbe, ki jih je mogoče enostavno vključiti v obstoječe postopke zagotavljanja in nadzora kakovosti (*angl. QA / QC*) gradbenih podjetij.

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BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

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Abstract:

The Architecture, Engineering, and Construction Industry is a competitive market where having strategies that improve the quality of the construction buildings is a valuable investment. Quality is an extensive concept that addresses the compliance and satisfaction between the requested job and the delivered project.

This study focuses on applying constructability as a quality technique that improves the deliverables between the construction and the design teams in a Design-Build company with the objective of cross-learning between projects. It proposes the use of Building Information Modelling (BIM) to facilitate the integration of the construction knowledge while developing a construction project.

The thesis includes the design and detail of a framework using BIM to collect, analyse, store, communicate, and use/reuse the construction knowledge contained in the Request for Information (RFI) and the Redlines of a project when the construction team and the design team interacts.

While performing the case study, a series of tools were implemented, such as a digitalized RFI and Redlines formats, constructability classification system, constructability knowledge database relational diagram, and constructability quality checklists that can be easily integrated in the existing QA/QC procedures of a construction company.

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I would like to express my gratitude to my supervisor, Professor Tomo Cerovšek, for his guidance in the process of doing research, for the challenging questions, and for his knowledge expressed throughout the development of this master's thesis.

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AEC – Architecture, Engineering, and Construction

BDAS – Buildable Design Appraisal System

BEP – BIM Execution Plan

BIM – Building Information Modelling - Management

CAD – Computer Aided Design

CDE – Common Data Environment

CII – Construction Industry Institute

CKDB – Constructability Knowledge Database

CPPMM – Conceptual Product/Process Matrix Model

FM – Facility Management

IFC – Industry Foundation Classes

IPD – Integrated Project Delivery

KM – Knowledge Management

LL – Lessons Learned

LOD – Level of Development

PDCA – Plan-Do-Check-Act Cycle

QMP – Quality Management Principles

QMS – Quality Management System

RFI – Request for Information

TQM – Total Quality Management

VR – Virtual Reality

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1 INTRODUCTION

"*Knowledge is power? No. Knowledge on its own is nothing, but the application of useful knowledge, now that is powerful*." – Rob Liano

1.1 What makes a quality project?

Defining quality of a project is not a straighforward task to do. Quality in general is strongly connected with the relationship between the providers and the customers, the market and competitive advantage, strategies, and commitment [1]; but quality in a construction project has different facets and point of views, since it involves a robust supply chain. At some point in the life cycle of the project one entity can be the customer and in the next one be the provider. Integrating the stakeholders of a project in to fulfil with quality requires clarity, ownership, collaboration, and sharing.

Relationships are created in the AEC industry almost differently in every project, they follow a set of conditions from a variety of contracts and agreements. The thesis is going to focus on a constructioon firm that in almost all their project's develops design and built of their construction project; this means that the structure of the company includes a department for designing, estimating, procuring, and construction processes including those related to managerial supporting business areas.

Therefore there is a great opportunity to share knowledge inside the company and make it a competitive advantage and quality improvement strategy. In order to do so, the study is going to define the quality in terms of quality improvement using constructability as the main baseline of principles to review, check, control, and assure the building projects will not only comply with constructability but they will create a net of learning and sharing knowledge, especially to learn from savings, hits, and misses from previous experiences.

The study is going to propose the use of Building Information Modelling (BIM) to gather the most valuable insights while the project is been developed and make it accesible for future projects.

1.2 Problem statement

It is well known that, although the AEC Industry is one of the most important sectors of our society, the same errors, and cost-time overruns are repeated from one project to another, affecting the general quality of what is produced. If during the development of a project using Building Information Modeling the models were understood as containers of valuable construction knowledge and were available and ready to use during the lifecycle of the project, then the quality would be assured.

1.3 Aim and objectives

The aim of this thesis is to identify if a BIM process can improve the quality of a construction project by reusing the construction knowledge within the construction company.

For achieving the aim above, the objectives are:

1. Define the concept of quality aligned with the strategy of a construction company.
2. Describe the constructability implementation plan to obtain reusable knowledge.
3. Analyse two knowledge containers from a construction company: RFI and redlines.
4. Develop a BIM framework to incorporate the contained knowledge of a construction project.
5. Apply the framework in a case study to develop the needed BIM tools for integrating the construction knowledge.
6. Evaluate the resultd of the case study implementation.

1.4 Methodology

To achieve the research aim and objectives, a qualitative methodology is going to be followed with the shown process [**Figure 1-1**]:

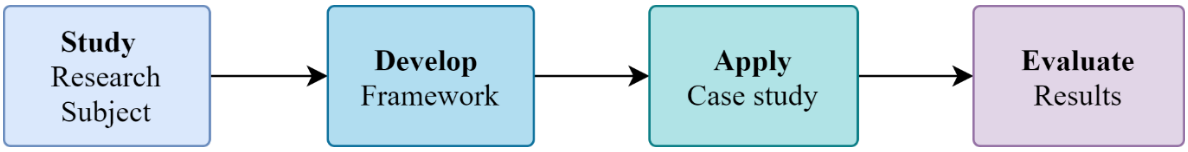


Figure 1-1. Research process.
Source: own elaboration

1.5 Thesis structure

Chapter 1: INTRODUCTION. The first chapter will give the context of the thesis topic, explaining the basic definitions that will introduce the Quality improvement, Constructability, and Building Information Modelling (BIM) topics, stating the thesis problem, and addressing the relevance of its research for the Construction Industry. The author will highlight the aims and objectives of the dissertation work with an explanation about the thesis structure that will be followed.

Chapter 2: LITERATURE REVIEW.

- AEC QUALITY IMPROVEMENT. The first section will address state of the art about the Quality Improvement in the Architecture, Engineer, and Construction (AEC) Industry. The author will highlight the key elements that define quality in a construction project, how it affects the success of the project execution, and how the AEC Industry depends on a quality improvement culture for constant growth and competitiveness.

- CONSTRUCTABILITY. The second section will explain Constructability as the selected technique for quality improvement. It will give an overview of the topic, explaining the benefits of considering it in the life-cycle of a construction project, the principles that frame the technique, the implementation of experts' construction knowledge, and the current barriers faced when a Constructability program is applied.

- CONSTRUCTION KNOWLEDGE. The third section will focus on the core of Constructability, explaining the process that manages Construction Knowledge. In this chapter, it would be described the knowledge in the AEC industry, who and what contains it, and how to obtain value from it. The section will also address an overview of the lessons learned system in a construction company as a knowledge container.

- THE ROLE OF BIM IN CONSTRUCTABILITY. The fourth section connects the previous topics of Quality improvement, Constructability, and Construction Knowledge with the methodology of Building Information Modelling (BIM); it will explain the current use of BIM addressing the problem stated in the first chapter. This chapter will take into account an overview of the model as a knowledge container.

Chapter 3: PROPOSED FRAMEWORK. The author will design the workflows needed for employing BIM for obtaining the contained knowledge and using it in future projects. An explanation of the workflows and filters for extracting knowledge of existing containers would be stated.

Chapter 4: CASE STUDY. The fourth chapter will apply the proposed framework of the previous section in a case study. The author is working with a design-build company that has more than fifty years in the Mexican Construction Market and will select an industrial project for the case study. An overview of step by step process will show the applicability of the proposed workflow.

Chapter 5: FINDINGS AND DISCUSSIONS. The fifth chapter will go into the analysis of the findings of the applied case study; it will identify the strengths, weaknesses, opportunities, and threats of its implementation, and discuss the results obtained in the case study.

Chapter 6: CONCLUSIONS. The sixth chapter will conclude the thesis project with an overview of the research in the dissertation work.

2 LITERATURE REVIEW

The literature review is structured to build up the theoretical background of the thesis topic; as explained before, it is divided from general concepts and definitions to the specific supporting information about the different subjects. The design and selection of the subjects to review are related to the aim and objectives stated in Chapter 1. The literature is divided into two main topics: Quality and Building Information Modelling.

2.1 Key definitions

Quality Definition

Quality is a broad concept considered when providing products and services; it can be defined as the ability to identify customer's expectations and fulfil or exceed them; taking in mind the competitive aspect of the market. The International Organization for Standardization (ISO) in the ISO 1994a [1] norm define quality as "*the totality of characteristics of an entity that bears on its ability to satisfy stated or implied needs*". For the AEC industry, a simplified definition is the fulfilment of the project scope in the agreed cost and time[1].

Constructability Definition

The definition of Constructability has evolved [2], and it is differently defined depending on each construction institute; they all have a different extent and point of view of the concept; either from the project management perspective or purely on the influence of constructability in the design phase of a project[3].

The Construction Industry Institute (CII) of the United States established in 1983 to promote the practice of Constructability, defines it as "*the optimum integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives*."[4].

The CII of Australia [2] defines Constructability as the "*system for achieving optimum integration of construction knowledge in the building process and balancing the various project and environmental constraints to achieve maximisation of project goals and building performance*."

The Business Roundtable from the United States defined it as "*the planned involvement of construction in the engineering process*" and the Construction Management Committee of the Construction Division of ASCE as "*the application of a disciplined, systematic optimization of the procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team*" [5].

Samimpey and Saghatforoush [6] defined it as *a technique that analyses construction logic from the beginning to the end of a project with the purpose of detecting obstacles, restrictions and potentials* and for Hancher and Goodrum [7] it is "*the integration of design and construction knowledge during the early stages of a project development process to insure the project is buildable, cost effective, biddable, and maintainable.*"

Fischer *et al*. [8] defined it as "*the extent to which the design of the building facilitates ease of construction, subject to the requirements of construction methods*."

Building Information Modelling Definition

Building Information Modelling (BIM) is defined by the National BIM Standard Committee (NBIMS) [9] as "*a digital representation of the physical and functional characteristics of a facility (...) It serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward*" BIM can be seen in three different categories: As a product, as a collaborative process and as a facility life-cycle management tool.

2.2 Overview of Quality

The subjective definition of quality is related to the perception of who is acquiring the good or the service, which is going to give a value to it; this value will be rating its relationship with the cost, presentation, usability, convenience, and the fulfilment of various personal preferences [10].

At the beginning of the last century, a control system was required for the industries standardisation [11]. It was encouraged by the International Standard for Quality Management System (QMS) a process approach that systematises the procedures and clarifies the elements involved in it [12], understanding that a process is "a set of interrelated or interacting activities that transforms inputs into outputs" [13].

There are five activities related to quality [**Figure 2-1**]:

- Inspection of human error, instrument tolerances and completeness.
- Control by standards, measurement tools, comparison performance and improvement plans.
- Assurance through confidence and consistency.
- Engineering business by defining policies and strategies.
- Manage through process schemas.

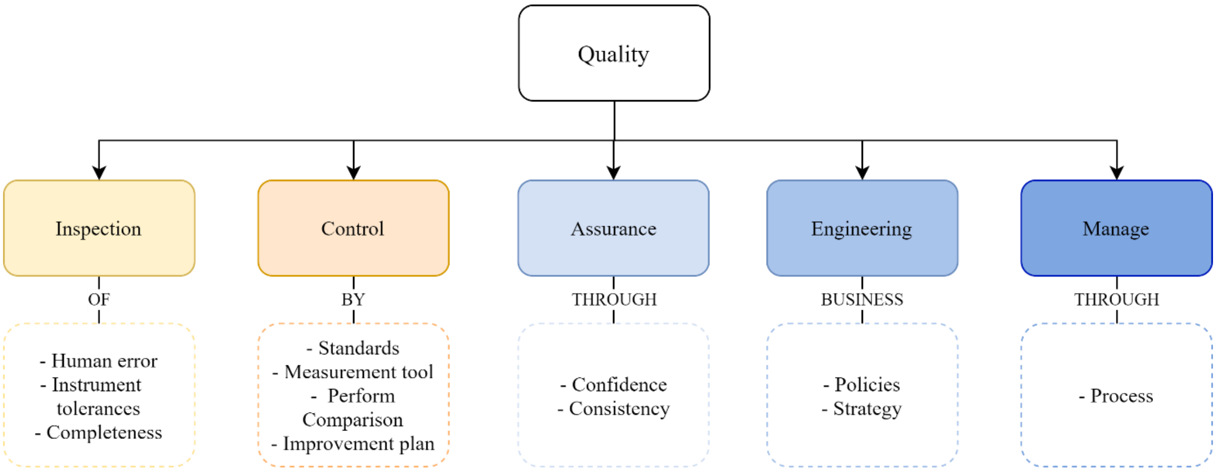


Figure 2-1. Quality activities.
Source: own elaboration from [1].

Quality management refers to the action of "establishing quality policies and quality objectives, and processes to achieve these quality objectives through quality planning, quality assurance, quality control and quality improvement" [14]. Each of the previously described concepts supports the quality management system starting by focusing on the processes and resources to accomplish them.

2.3 Quality in the AEC Industry

The literature indicates that it is complicated to interpret the relationship between quality and the AEC Industry: from its definition to its measurement; this vagueness needs to be clarified to forestall confusions and misunderstandings in the construction projects [10].

The construction industry requires an extraordinary effort of coordinating the different stakeholders with needs, opinions, perspectives, workload, contractual relationship, degree of involvement, among other activities of a project[15] and the project delivery is positively related to the quality management program because of the relationships it creates between the stakeholders of the facility[11].

2.4 Quality Improvement Program

Total Quality Management (TQM) was adopted as a management philosophy to have a strategic goal towards quality in the companies with mainly two objectives: Customer satisfaction and continuous improvement [5].

Continuous improvement involves discovering and solving problems; actively searching different and efficient ways to complete a task with the purpose of having more productivity [16]. In the construction industry quality improvement refers to the formal process to notice the problems before the construction stage and to point out methods that can increase productivity and innovation [5].

There are similarities in the TQM and Constructability: (1) Measurement system to track costs and schedule savings from the quantitative aspect and customer satisfaction, and quality from the qualitative side. (2) The commitment of the people in the project, the teamwork, training, capabilities and resources to accomplish the project objectives [5].

A general understanding of how to analyse and apply a quality management system with the focus on improvement is based on the PDCA cycle shown in [**Figure 2-2**]. The International Standard representation shows not only the cycle but its relationship with the context of the application, customer requirements, needs, and expectations with the wanted result, and satisfaction from it [12].

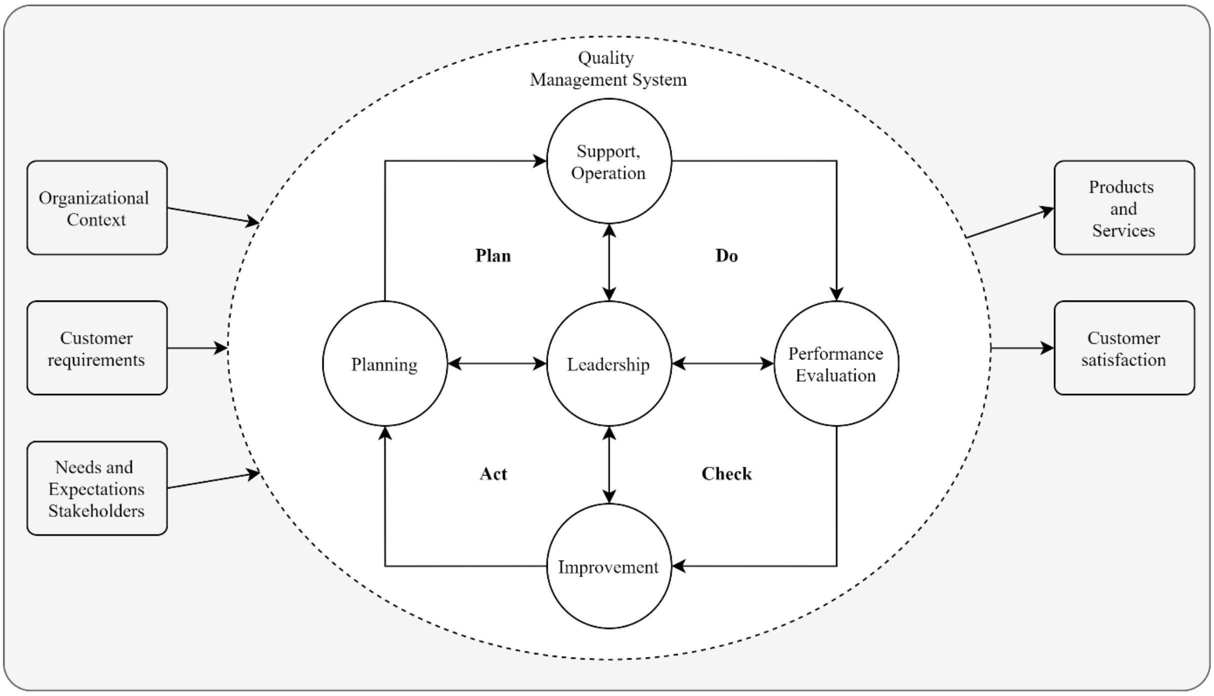


Figure 2-2. PDCA cycle. International Standard Representation
Source: Adapted from [14]

2.5 Overview on Constructability

The complexity of the construction projects and competitiveness of the market influenced the need of specialization which affected the segregation of the design and construction departments' tasks [5] creating an isolated culture among the Construction Industry's professionals [17] especially between the design and engineering team, but also with the procurement and construction team [6].

Over the last forty years, the concept of Constructability has been the subject of research, finding that projects can be enhanced using Constructability as a technique for Quality Improvement [18]. Constructability has also been proposed as a project goal-achieving technique, becoming an essential step in the overall Quality Check and Quality Assurance process [19].

In the Construction Industry, there are different tools proposed to increase the capabilities and competitiveness of the companies, such as Total Quality Management (TQM), Value Engineering, and Lean Management [16] but the difference relies on the objectives of each of the management systems [20]. Improving construction projects through Constructability becomes a responsibility of all; the effort of integrating the Construction knowledge and experience has to be done early on in the project to have the most benefits from it[17].

It has been proven that applying a Constructability program in the project can reduce from ten to twenty per cent the construction cost [20]. The CII of the United States stated that employing the concept in the right time frame of the project can have a positive impact on the cost for around six to twenty-three per cent [4].

Project delivery is one of the most important factors for determining a construction job has been successful. When the handover of the project considers the identification of the construction risks, omissions, and mistakes before it is built, the possibility of reducing going over budget and/or over scheduled increases.

There are four main reasons that determine a project has been successfully executed: (1) duration of the construction (time), (2) cost of the project, (3) quality, and (4) client satisfaction; this could be obtained considering Constructability principles that improve the team performance, surge project limitations, and promote collaboration among the stakeholders of the project during its entire development process [21].

According to Kannan *et al*. [3], performing a Constructability analysis will improve the construction procedures; assuring that the overall project will be executed more smoothly and efficiently; therefore, the more efficient the process runs, the better the quality of the project; and in consequence the best project handover.

When the AEC companies realized the potential benefits of deploying Constructability, such as the trustworthiness of the design information and the simplification of the construction process [22] started to consider Constructability as a strategy to have more outstanding quality in their products and being competitive in the market; however in order to do so, it is essential to understand the concepts and principles of Constructability[23].

2.5.1 Constructability Objectives

In initial studies, the concept of Constructability was focused mainly on productivity, later on as the isolated relationship between design and management principles, and finally as the need of integration of the stakeholders during the overall life cycle of a project[2]. For Russell [5], in the first employment of Constructability, the purpose was to integrate the design and construction teams through different formality levels.

A project that follows a Constructability analysis allows guaranteeing the purpose of Quality Improvement reached through this technique. Among the objectives of implementing Constructability include: (1) Cost reduction, (2) Quality improvement, (3) Efficient construction schedule, (4) Promotion of construction safety, (5) Diminution of change orders, (6) Reviewing the project during the design phase with Constructability objectives [19].

Russell [5] elaborated a framework that determines the quantitative and qualitative benefits of Constructability. Even though the balance is inclined over the qualitative rather than the quantitative benefits.

The quantitative considers:

- the valuable reduction of engineering and construction cost and
- the optimization of the project schedule.

On the other hand, the qualitative benefits take into account:

- having more opportunities to prevent problems,
- having a focused team with the same project objectives,
- each participant has clarity on how it is going to be involved in the project,
- each of its members has created a more significant commitment to the project,
- generates team building and cooperation which happens by having increased communication,
- a better understanding of the site layout and accessibility,
- increased comprehension of production logistics which makes fewer interruptions of the work schedule,
- improves safety measures,
- lowers the volume of work that needs to be done again,
- enhances construction flexibility,
- reduces facility management cost,
- initiates the project more steadily and continuously,
- has a just-in-time mindset which lessens the inventories sizes,
- has an effective and efficient production,
- considers the asset's future expansion constraints and
- it is a marketing point for the contractor.

The benefits of applying a Constructability program involves not only those related to the construction process but to the overall project life-cycle such as planning, procurement, client satisfaction, and the integration of project stakeholders; the benefits have an impact in the budget, schedule, quality, safety and other domains [24].

Constructability is a strategic, creative and analytical way to improve in the most important factor for building a project [23]. An analysed method is needed in order to document, share, and apply the Constructability knowledge into future projects [25].

Nevertheless, each project has its own objectives; the Constructability assessment needs to reflect it as measurements of the project; it will be aligned with the Owner's Quality expectations and satisfaction [26] and company's performance.

2.5.2 Constructability Principles

Similar to the definition of Constructability, different institutions have developed Constructability principles that have served as guidelines for their implementation of Constructability reviews. There are at least three institutions and a handful of researchers that have worked with Constructability principles for more than four decades; CII from the United States introduced seventeen with a significant role of the owners into the decision making; CIRIA from the United Kingdom has seven principles dedicated to Constructability in the sixteen principles of the Construction Industry; CIIA from Australia developed twelve constructability principles including where, in the timeframe of the project, to use them [6].

The CII of the United States invested in research about Constructability focused on construction knowledge during the different stages of a project; with this studies, they were able to identify problems, develop Constructability concepts, and structure Constructability principles that will help promote it as a system that achieves savings mainly in terms of cost and time of the project execution [2].

In Singapore, a Constructability score system called Buildable Design Appraisal System (BDAS) is required for building plans since 2001; they have three core principles for buildability: Standardisation, Simplicity, and Single Integrated Elements [27]. The principle of standardisation refers to the repetition of project variables such as bay spacing, elements sizing, and details; simplicity is about having non-complicated construction methods and avoiding complex details; the single integrated element is the principle that considers the combination of different elements to form one single one [28].

In their research about Constructability at an organizational level, Bakti and Trigunarsyah [18] set the following six Constructability principles:

(1) Early integration of Constructability knowledge and experience from the experts.

(2) Project schedule considering Constructability.

(3) Modularization and preassembly.

(4) Standardisation.

(5) Streamlined design.

(6) Method and room for construction innovation.

From the management approach of Constructability, these principles are meant to improve the construction process because they are arranged by categories based on how the principle is approached and what kind of procedure is being implemented. Samimpey [6] analysed the literature review and identified the Constructability needs of a project elaborating a list of Constructability prerequisites [**Table 8-3**] grouped in three different factors: Managerial, Technical and Environmental.

Okon *et al.*[15] researched an analysis between the Constructability principles and the level of impact they have in the project and overall work scope [15].

There are different concepts related to Constructability, and its principles, Kifokeris and Xenidis [21] identified them and described them in the following table [**Table 2-1**].

Table 2-1. Constructability Concepts

Constructability Concepts		
#	Concept	**Description**
01	**Constructability program**	Planning for Constructability purposes is the main aspect of the involvement of all parties in the project.
02	**Project Team**	It is identifying the key team members that will contribute to the implementation of Constructability.
03	**Project Integration**	Integrating the design and construction team to bring expertise early in the development of the project.
04	**Contractual alignment**	Alignment of the construction methodology with the contractual responsibilities in the project.
05	**Schedule**	Construction priorities are reflected in the programming of the execution of the project, and responsibilities are clear since the beginning of the project.
06	**Construction Methods**	The selection of the leading construction methods should be the baseline for the design development of the project.
07	**Construction Site**	The construction plan should consider the analysis of the site of the project to have a smoother work.

08	**Construction Sequence**	The sequence of the construction needs to be aligned with the design and procurement process.
09	**Technologies**	Communication and cooperation between the participants of the project should be enhanced using collaborative platforms and technology.
10	**Design simplification**	Construction knowledge should help simplify the intended design of the project to have a smooth construction.
11	**Standardization**	Having standard elements in the project without compromising the result of the project.
12	**Technical Specifications**	The specification of the project elements must be clear and simplified for construction.
13	**Modularization**	Having the project modularized will help with the fabrication, transportation, and assembly, which will make the construction process more efficient.
14	**Resources**	The inventory for construction should be taken into consideration of the site layout.
15	**Weather**	The construction schedule should reflect the climate conditions of the construction site.
16	**Prevention**	The planning of the construction must consider the use of resource and the prevention of clashes in productivity.
17	**Innovation**	Used to solve problems during the construction.
18		Needed to increase the productivity of the construction workers during the construction in terms of health and safety, and manoeuvrability.
19		In the selection and use of equipment.
20		Building the temporary site offices.
21	**Contractors**	The evaluation and selection process for contractors and sub-contractors should be standardized and documented accordingly.
22	**Constructability Program**	The constructability implementation plan should be established and documented to maintain and continuously improve.

Source: own elaboration from [21].

2.5.3 Constructability Implementation

Wong [27] study indicated that quantified assessment of designs, Constructability review, and Constructability programmes are the most common deployment of Constructability; for some the implementation performed during the design stage, others during the whole process of the project, or only applied at specific phases of the project.

The application of a Constructability program has to be done in a disciplined and systematic way; including the optimization of the construction knowledge of a project during each of its development stages; the information has to come from the adequate personnel with the appropriate knowledge and experience in the project's typology to contribute reaching the project goals and objectives [18].

Both formal and informal Constructability activities are held during the construction projects; according to Russell [5] the informal approach usually can be confused with management procedures and frequently formal Constructability analysis are supported by company philosophy and programs of implementation such as the track of lessons learned, team building and construction team involved in the planning stage of the project with better possibilities to obtain their benefits.

The application of an informal Constructability analysis, such as the use of a checklist to find errors and omissions is less effective since the relationship between the designer-engineer and the Contractor is in a reactive tone [16] which affects the overall environment required for a productive review.

Gugel *et al*. [26] studied, created, and tested a framework related to the elements and variables that play in the decision of applying a formal or informal Constructability program; it is proposed to help determine the amount of effort is going to be invested in a project in terms of Constructability since it is often not recognized as a complete process [**Figure 2-3**, **Figure 8-1**].

The framework consists of three steps: Variables, Combination, and Selection.

> The first step analyses the work based on two main aspects: Owner or Contractor, and Project; each of the aspects has different categories in which the project will be analysed [**Figure 2-4**, **Figure 8-2**]; depending on the majority of the variables recommendations or when there is no majority the set priority, a formal Constructability program is selected.
>
> The second step combines the main aspects of the formality results: when the Owner and the Project are both informal, or when the Owner is formal, but the project does not require a formal review then the final recommendation is to approach it in an informal way; but when the Owner-Contractor and the Project recommendation is to follow a formal assessment, or when the Owner-Contractor result is following an informal process, but the Project recommendation is formal, a third step is needed for the final recommendation.
>
> On the final step, the decision is between following a Formal Constructability Program or doing Tracking of a Constructability Program, which is a test of the benefits when applying it in the Company, usually performed before setting in the company policies and processes.

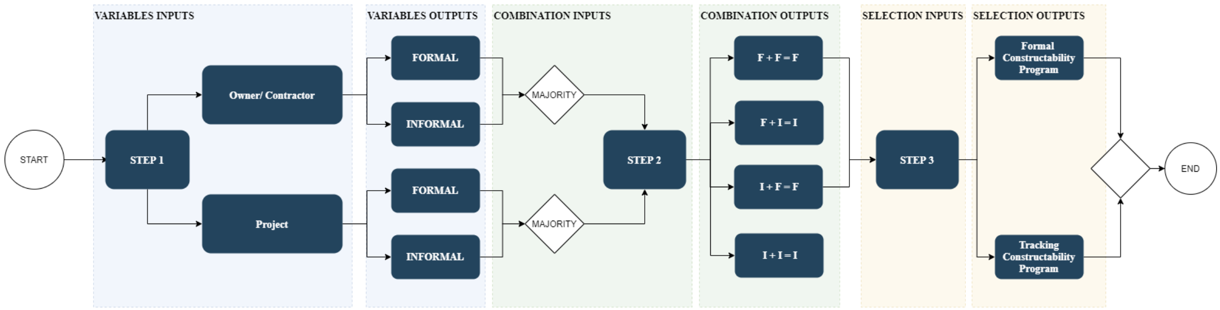


Figure 2-3. Constructability Formality Model.
Source: Own elaboration adapted from [26]. See amplified version in Annexes.

In step 1: Variables, there are two different categories in which the work can be analysed; the first one is the Owner-Contractor [**Figure 2-4**]. The first variable corresponds to the type of owner the project has. This can determine how formal or not is required the project to be; it can either be Public or Private.

The second variable is Project objectives; the author prioritised based on his findings, the Pilot of the project is the most important objective for doing a Constructability assessment in a formal manner, and the Aesthetics of the project is the objective with less formality is needed. The first three objectives the author recommends making a formal approach to the Constructability program.

The third variable is Capability and Expertise where the findings are that the more experienced the Owner is, the less formality tends to have when implementing a Constructability plan.

The fourth factor is referred to the Resources of the Owner-Contractor, there are two variables; the tools and the users, commonly the more tools the Contractor is required for the project, the more formal assessment is recommended.

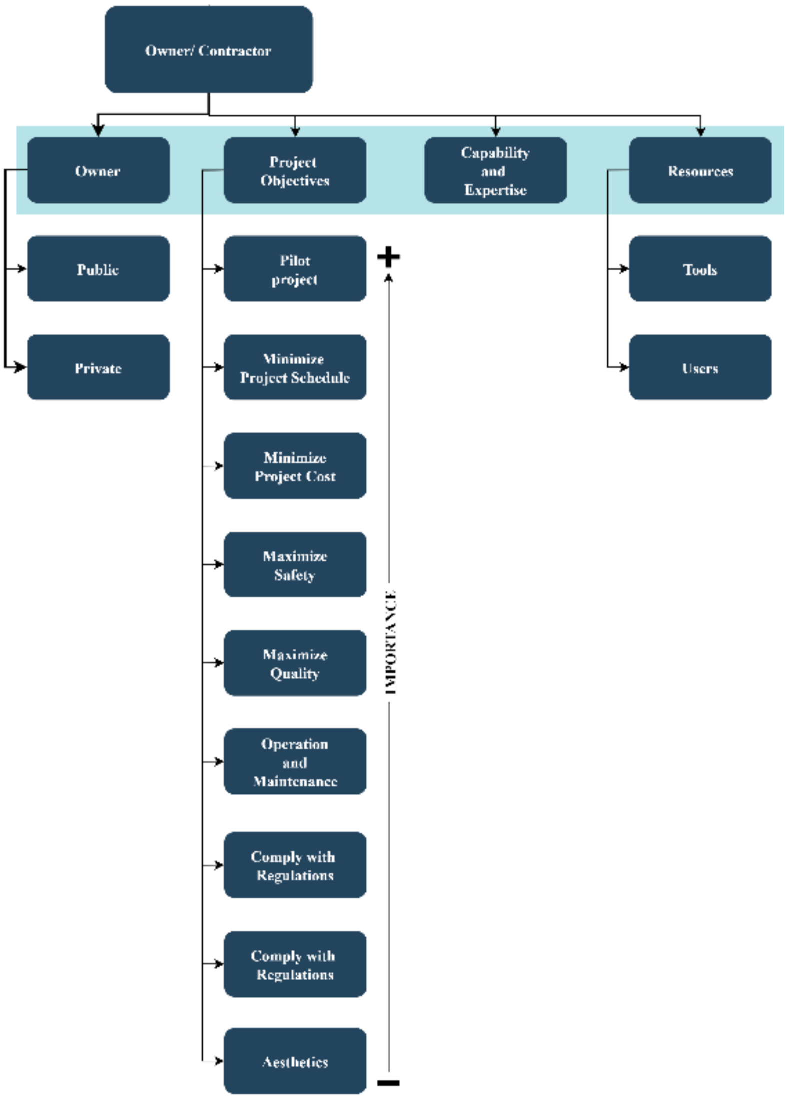


Figure 2-4. Step 1 Owner-Contractor variables in Constructability Formality Model
Source: Own elaboration based on [26]. See amplified version in Annexes **Figure 8-2**.

The second category in the Constructability Formality Model Step 1 is the Project characteristics [**Figure 2-5**]. The first variable has to do with the type of construction, and if it is a new project, retrofit or rehabilitation, this has to do with the uniqueness of the project; the more unique, the more uncertain the project is, therefore; it is recommended to follow a formal approach of the assessment.

The second variable is Contract strategy; this is related to the type of contract the project is and how many stakeholders the project has; this will dictate the recommendation about doing a formal or informal strategy.

The third factor is the project size, which according to the author it is in terms of cost, the greater the cost of the project the formality level is increased, except for the pilot project was the objective is to test and track the Constructability process.

The fourth variable is about the technical difficulties of the project; this has factors that will determine the recommendation of its formality, as a rule of thumb the more complex the project is the more risk; therefore it is suggested to follow a formal approach of the Constructability review; although according to the author, usually it is done informally; when the factors are Design and Construction techniques, usually if it is new it is suggested to do it formally; Labour intensity, which refers to the number of people involved in the project (either on-site or at the office), and miscellaneous, that may add challenges and risks to the project.

The fifth variable is the location which is related to the experience at that particular site the project is which can relate with issues such as permits, regulations, or others that because of its location gives to the project.

Finally, the Peculiarity of the project, which, as stated before, must do as well with the uniqueness of it. The more complex, the more formal review is endorsed.

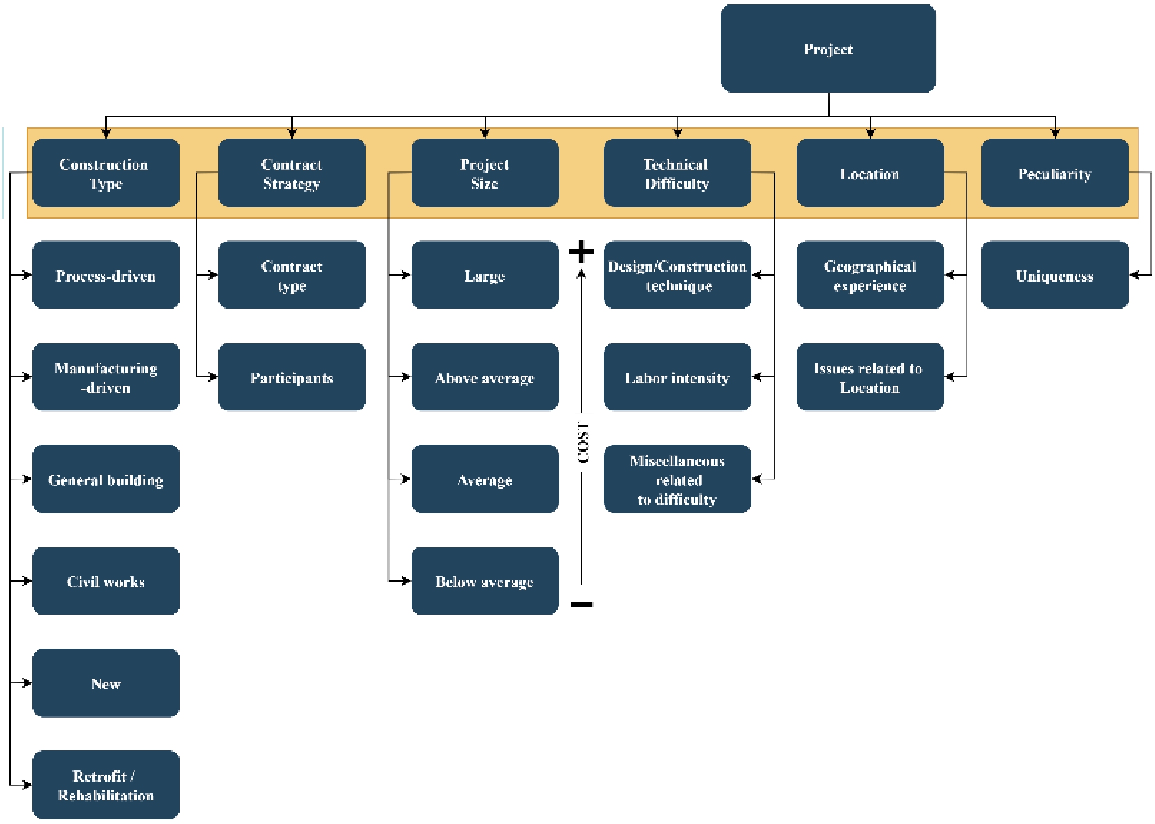


Figure 2-5. Step 1 Project variables in Constructability Formality Model
Source: Own elaboration based on [26]. See amplified version in Annexes **Figure 8-2**.

One of the benefits of applying a formal Constructability program relies on the available resources where the construction knowledge can come from: The most common ones and usually taken into account in an informal Constructability program are: construction reviews, construction coordinator, construction personnel, and trained or experienced engineers; the Constructability knowledge can also come from teamwork, proper use of lessons learned, construction team integration, coordinated project schedules, monitoring, continuous improvement, and innovation[20].

The relationship between the cost and the benefit of the Constructability program effectiveness depends on its maturity [5]. Reducing the cost of a project is probable when applying a Constructability program [29], but it becomes crucial for decision making during the planning stage of the project to have a Constructability review, especially for areas like project planning, site layout and the selection of the construction methods [16].

There are two systems used for Constructability: Knowledge-based and Quantitative analysis. The Knowledge-based systems clearly structure and systematize the knowledge into non-graphical and graphical knowledge; the first one refers to a database that generates rule-sets for the evaluation and decision-making, and the second one utilizes visual tools to help the understanding of Constructability problems and solutions. The Quantitative analysis system measures the Constructability impacts in the project by giving a score [22].

According to Kannan *et al*. [3], an efficient Constructability analysis should consider:

(1) the evaluation of the construction project,

(2) the understanding of the type of contractual work is going to be developed as well as its warranty schema,

(3) the application of quality management and value engineering concepts,

(4) the understanding of prefabrication, assembly, and modulation techniques, and

(5) the consideration of the operation and maintenance phase project during the development of the project.

For Hancher *et al*. [7], there are roles and aspects that the Constructability review program requires:

(1) **Champion**: A responsible for overseeing the Constructability implementation. This role ensures fluidity in cooperation and communication and has the authority to approve solutions.

(2) **Team**: A team is necessary to perform the Constructability review. Due to the multidisciplinary and the variety of the stakeholders of a project, it is vital to have just the essential people involved; including Construction professionals, construction staff, consultants,

regulatory representative, utility representative, material suppliers (if there is an essential element in the project), and maintenance representatives.

(3) **Review frequency**: Constructability review is performed in different stages of the project: Level 1, 2, and 3 correspond to how frequent the reviews are made according to the project complexity; being Level 1 the complex one with the need of more involvement from the stakeholders, and Level 3 the least complex project.

(4) **Resources**: The process should be simple and focused in order to not overload the teams. It should consider manpower, funding, and time.

(5) **Reviewing**: The process needs to define the type and length of the meeting with specific items to review, a guideline and checklist to focus the review, the follow-through plan with the assigned responsibilities of each reviewed item, and the distribution of the review in a systematic way.

(6) **Measuring results and benefits**: Refers to having indicators that measure the Constructability impacts of the reviews.

(7) **Post-construction reviews**: To eliminate any repeated mistakes usually performed at 90% of construction completion, a mechanism to distribute the results is recommended.

The level of implementation of a Constructability program is variable for each company; there are seven categories in which the methods can be grouped [30]:

(1) The company policy statement,

(2) Checklist of procedures, lessons learned, and technical problems,

(3) Company performance indicators,

(4) Contract responsibilities,

(5) Analysis and system modelling,

(6) Revisions,

(7) Technology methods.

Although Construction companies know the advantages of improving the design through the integration construction knowledge doing a Constructability review in their process; the resources, time, reworks, and human effort are still a disadvantage for Constructability implementation [31].

For Okon *et al*. [15], the criteria to decide if a project is buildable is not straightforward, each project is unique, and the Constructability requirements vary from project to project. According to Gugel *et al*. [26], it is common that when a Constructability plan is implemented the procedure formality depends on two factors: Capability and Experience; the more experience an owner has in performing similar projects, the less formality in the implementation of a Constructability program.

As Griffith and Sidwell [2] stated, there are three important factors for a successful implementation of constructability system. The first is the involvement and understanding of the concept by the client; second, the integration of Constructability experts in the early stages of the project; and third, the commitment of the stakeholders. The resources to perform a Constructability review depends on the tools and people available, especially the Construction input that comes from the experts; it cannot be performed without it [26].

2.5.4 Constructability Barriers

Although several authors have proven the benefits of implementing a Constructability plan in the construction projects, usually it is not the case [8]. Applying for a Constructability review, although for Stamatiadis *et al*. [32] the research indicated a decrease in the number of change orders in the project, it does not necessarily indicate a saving in the effort of the team, the changes instead of being made in the construction site they were made in the design phase.

For Rajendran [33] in project and company level is clear that there are barriers for implementing a constructability plan which includes those related to the engagement of the constructors, efficient communication and collaboration, and technology and construction methods efforts.

2.6 Overview of Construction Knowledge

To have an efficient Constructability application, the Construction knowledge must be in an accessible form; there are different ways in which the knowledge is available: (1) Explicit: Easily and precise knowledge relatable to variables and elements in a project, (2) Implicit: Knowledge that needs the combination of different variables in order to relate it to elements in a project [8].

One key element for any strategy of growth is knowledge; managing and enhancing it among the company becomes a challenge in any organization, especially when it is necessary to determine what is known, and who knows it [34]. Each project has the potential to give valuable insights to a company, but this knowledge must be appropriately captured and disseminated [35]. Transforming the information into relevant knowledge is the competency organizations have to promote [36].

Regarding the company knowledge, it is important to put attention on three aspects of quality improvement based on knowledge: Gain, waste, and loss of knowledge [12].

Each company, based on its own characteristics, must choose their best Knowledge Management approach, making sure they are taking advantage of what was learnt in past projects [34]. If knowledge is perceived as an important element that has to be included in every project, and without it, the project is not complete, the system will warranty the use of its Constructability knowledge [35].

Although it is significant the amount of knowledge it is handle in the AEC industry, it is also acknowledged that the same mistakes keep happening again and again; the research to improve Knowledge Management strategies increase due to the fact that it helps retain the know-how of its employees, enhances continuous improvement, makes more efficient the response to clients, and decreases the amount of rework [34].

The expertise knowledge exists in two different forms: (1) Information in a written form referred to as Explicit knowledge and (2) the information that exists only in the head of the expert referred to as Tacit knowledge, which generally is the most common way the Constructability knowledge is; it is key to transfer all and especially the Tacit knowledge in a way that can be organized and useful for the organization [37].

There are two perspectives on how knowledge can be managed:

(1) Supply-driven: Focused on how the information is moving along the process, usually supported by technological tools, and

(2) Demand-driven: Interested in how the user moves the information in the process, normally needs to think on how to encourage employees' involvement.

There are two knowledge management strategies:

(1) Mechanic: Strategy that relies on technology tools and mostly deals with explicit knowledge,

(2) Organic: Strategy that works with people driven techniques and mainly with tacit knowledge.

Although these two perspectives exist, the developed strategy needs both in order to be successful [35].

Even though projects in the AEC industry are unique, Constructability knowledge helps improve future performance [34]. Constructability does not just depend on the analysis of its concepts but in the experience of executing projects that comes from working on site. Each participant from the construction team has the ability to collect inputs that can be processed as valuable knowledge [3]. The use of construction knowledge applied as Constructability increments the possibility of having a project with a positive outcome [16].

Constructability knowledge is based on the information about the construction process, methods, resources, requirements, and constraints; these elements serve as attributes to the classification system

[25]. It is common to use Constructability tools such as lessons learned, brainstorming sessions, digital or physical mock-ups, review sessions, etc.; but it is relevant knowing the project development process and what information is required for the application of it [37].

Although the benefits and importance of the Constructability knowledge explained in chapter 2.3, the way is brought in the project life cycle is generally with methods that are inefficient, unsophisticated and contribute to rework; "To effectively utilize Constructability knowledge (…), the right information must be available at the right time, in the right level of detail, and from/to the right entity" [37]. A system that can check the design at the right moment with formal documented Constructability knowledge is needed, the organization of this knowledge should be considering how the design and construction decisions are made [8].

In order to have a proactive feedback, it is recommended to perform the Constructability assessment during the development of the specific stage of impact, so the input is delivered in a just-in-time philosophy and becomes valuable and useful [22].

Fischer *et al*. [8] found that having direct communication between the construction expert and the knowledge manager through interviews is a better way to collect Constructability knowledge; they classified the source of expert knowledge in four characters:

(1) General Contractor: which have a broader knowledge of the Industry,

(2) Designers: which have the design knowledge and the doubts they generally have about Constructability,

(3) Subcontractors: Their knowledge is based on construction methods, equipment, and workforce personnel, and

(4) Suppliers: which have knowledge about market availability in terms of systems and methods.

Lessons Learned

Although in the CII Constructability Guidelines were tracking lessons learned, they made an exclusion about how these were impacting different aspects of a project [25]. Unfortunately, issues during construction are documented but are barely stored as lessons learned [37].

A lessons learned database is one helpful tool to do the Constructability review; it is a formal system of organized Construction knowledge and experience [7].

There are different definitions of Lessons Learned; the concept has changed over time, it has been considered as recommendations and protocols to a system that recollects and promotes the knowledge gained during a process or activity; according to Weber *et al*. [38] a complete definition would be the one used by the America, European, and Japanese Space Agencies:

"*A lesson learned is a knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. Successes are also considered sources of lessons learned. A lesson must be significant in that it has a real or assumed impact on operations; valid in that is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or eliminates the potential for failures and mishaps, or reinforces a positive result*."

In this definition, there are three characteristics of a lesson learned; it must be significant, validated, and applicable.

One of the organizations' strategies to manage knowledge is to safeguard the one acquired by its employees in a systematic way and with a specific scheme. The format for the lessons learned must include the description of the experience from its source, the process application, the magnitude, and the results (either positive or negative); this needs to be done so are not confused by other knowledge sources such as incident reports, alerts, best practices, and memories [**Table 2-2**] [38].

Knowledge Management Artifacts					
Knowledge Artefacts	**Experience source**	**Process Application**	**Magnitude**	**Results**	
				Positive	Negative
Lessons learned	YES	NO	ORG	YES	YES
Incident reports	YES	NO	ORG	NO	YES
Alerts	YES	NO	IND	NO	YES
Best practices	YES/NO	YES/NO	ORG	YES	YES
Memories	YES/NO	YES	IND	YES	NO

ORG: Organizational level
IND: Industry-level

Table 2-2. Difference among Knowledge Management Artefacts.
Source: Adapted from [38].

The organization of Constructability information is essential; it is part of the strategy of implementation, considering when it is relevant for the phase and the level of detail the project is at [37]. The use of the most valuable form of construction knowledge formalized as Lessons Learned, gives a more significant advantage of the construction company over its competitors[39]. When the collection and dissemination of lessons learned are standardized, the more likely it is to be reused in future projects [26].

The lessons learned of completed projects usually are integrated into a final report and added in a database that is used to communicate them [17]. It is essential that this documented system grants, shares, and captures the knowledge and experience of a project to be able to use it in the future; Taking into account that Constructability implementation encourage the innovation and general project performance, without excluding either positive or negative experiences [16].

A lesson learned process requires five main activities [**Figure 2-6**]:

(1) **Collection**: there are different strategies to compile the experts' knowledge:

1. Passive: The experts in the company will submit the lessons learned during the project using a form.
2. Reactive: The experts will be interviewed to gather the knowledge acquired in the project.
3. After action: The knowledge is collected during or close to the end of the project.
4. Proactive: The collection is done while the situation is being solved.
5. Active: The recollection of the lesson learnt is done by carefully analysing the project process and finding essential lessons along with the execution of the work.
6. Interactive: The communication with the authors of the collected knowledge is open for a dynamic problem-solving strategy.

(2) **Verification**: There are assigned professionals responsible for validating the collected information in terms of accuracy, repetition, consistency, applicability, and importance.

(3) **Storage**: During this process, the main target is to express the knowledge in the needed format for its communication.

(4) **Dissemination**: The activity that involves the communication and promotion of using the lesson learned in future projects, there are different strategies:

1. Passive: When needed, the user will look for the lessons learned related to the topic they want to solve in the company's repository.
2. Active casting: The lessons are shared to potential users of the specific information
3. Broadcasting: Everyone in the organization receives the added lessons learned.
4. Active dissemination: The employees in the company are notified depending on their role in the company and the type of decisions they made.
5. Proactive: The company has a system that predicts when the lessons learned are needed and shares in a specific interface.
6. Reactive: A form of dissemination that is accessed by the user when needs to find a solution to an ongoing issue.

(5) **Usage**: The final decision of using the knowledge from a lesson learned is made by the person facing the problem to solve; there are identified three different categories:

1. Browse: The recommendation is displayed in a search engine system.
2. Executable: The selection and application of a lesson learned in the system.
3. Outcome: Having a record on what was the result by applying a specific lesson learned, feedback from the use of it.

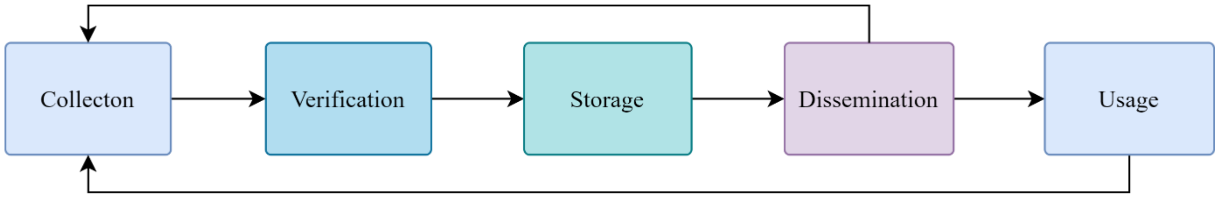


Figure 2-6. Lessons learned general process
Source: own elaboration adapted from [38].

2.7 BIM: Through Quality and Constructability lenses

In this chapter, an explanation of how BIM can be useful for the quality improvement in construction and its relationship with constructability will be explained.

The structure of this section is designed following the PDCA cycle, which refers to four main activities that will lead to continuous quality improvement. The PDCA cycle is intended to identify a specific problem to be solved or an aspect that needs to change in order to improve; includes not only those four steps but identifies a fifth one that corresponds to the accumulated knowledge of the previous cycle, see [**Figure 2-7**] [40]; this cycle will let the company focus on quality improvement by having in mind the process, resource, and management principles [14].

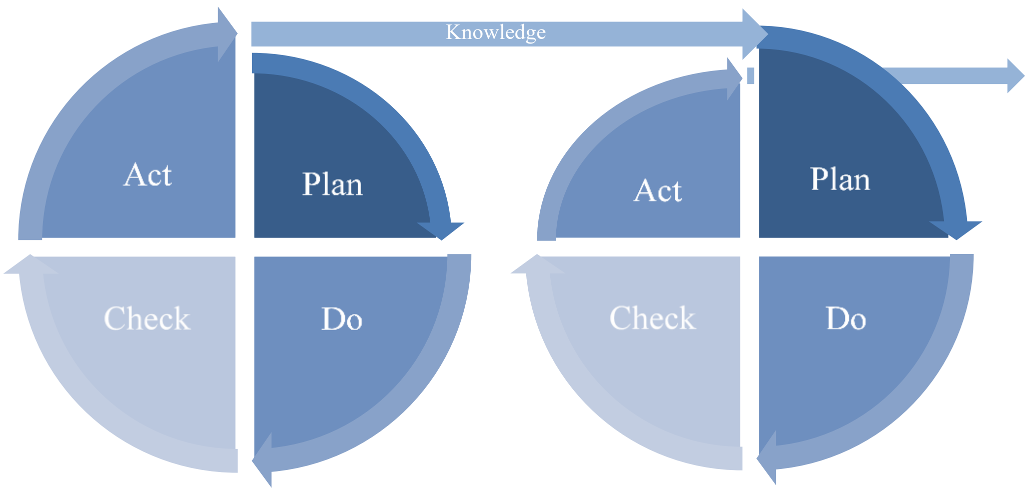


Figure 2-7. Continuous Quality Improvement PDCA Spiral
Source: own elaboration based on [40]

The topics proposed following this schema are shown in [**Figure 2-8**]. The chapter will contain aspects from the pre-construction stage of a project based on the thesis objectives.

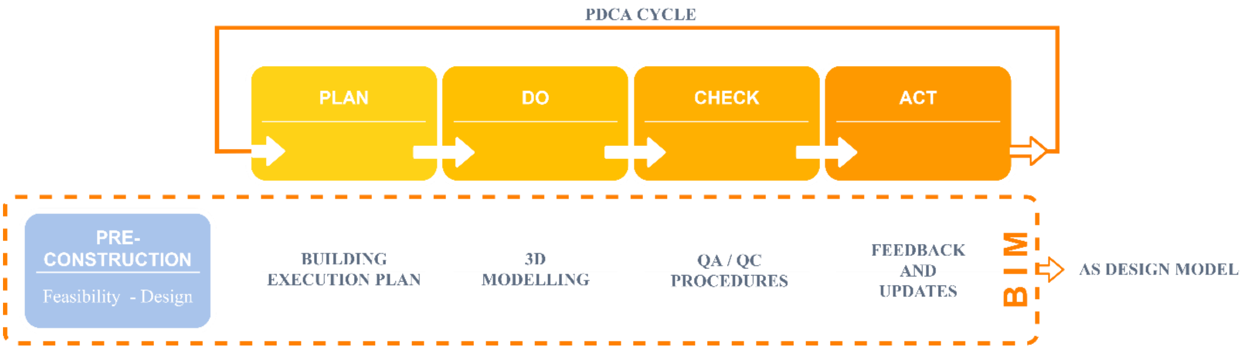


Figure 2-8. Pre-construction phase diagram
Source: own elaboration.

Building Information Modelling

As explained in the general concepts, Building Information Modelling is “one of the most promising improvements related to automation and mechanisation within the AEC industry” [41]; it can be understood in three different categories: As a product, as a methodology to collaborate, and as a facility life-cycle management tool [9].

It is well known that the traditional way of developing a construction project, a separation between the design and the construction team exists [2]; and not only with those two departments involved but also with the supporting team such as the procurement, management, quantity surveyors, cost estimators, pre-construction team, client, among others. The traditional techniques for integrating the team are not as effective; therefore, it is required to research the tools that could facilitate access to Constructability knowledge[19] and a more efficient process to develop the current construction projects.

BIM and Quality

“*If you want to do BIM right, you need to think about the client first*” Holzer [42].

One of the most important factors of a successful BIM Implementation has to do with the integration of not only the geometry and the information of the building elements but of the participants in a project; this form of integration relies on team coordination [42]. The principle of collaboration in the BIM environment with a single source of information in the form of a federated model and a CDE (Common Data Environment) let the quality review of the project in its different phases [11].

There are two specific methods related to quality: Quality assurance (QA) and Quality Control (QC). QA refers to the system “used by construction companies to ensure the delivery of which quality products to their customers and clients” [43] and QC is related to the inspection of the work produced that is according to its specifications. The main benefit of having a focus on QA/QC in the BIM methodology is saving both time and money since it is more comfortable and more convenient to change it digitally rather than physically; this has been explained using the MacLeamy curve in [**Figure 2-9**], which correlates the effort made in a project during the time of developing each of the project's phases with the cost and impact it has while doing in a traditional way versus BIM / IPD effort; by using BIM methodology, the effort is made earlier in the project, the curve shows that the sooner the change, the less impact has on it.

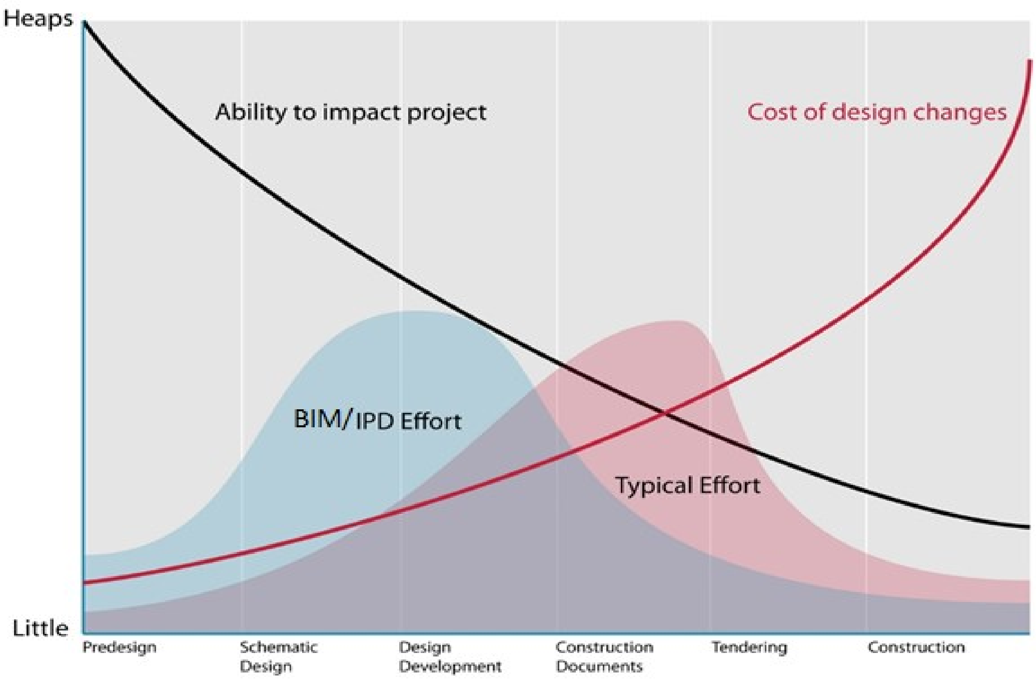


Figure 2-9. MacLeamy curve.
Source: adapted from [44].

The satisfaction of the product received from the producer to the consumer or customer is the basic concept of quality; in the AEC industry this relationship exists among the supply chain of the project in every point of exchange; it is usually managed using a QA and QC systems [45].

The way BIM can address the expected Quality of a model is by clearly define the goals and objectives in a document known as BIM Execution Plan (BEP); the elements related to Quality of this form will be explained in the pre-construction phase section. The definition of BIM requirements to develop standardisation for having an adequate integration with common information and less trouble to synchronize, share, and coordinate the work; this standards become the baseline of what is expected and how quality will be defined for the BIM delivery [43].

In terms of BIM, Quality Assurance refers to the review of the quality of the model "*is a joint effort of the designer and the client, the purpose of which is to improve the quality of the design solutions, their conformance to the client's needs, and the predictability of the construction schedule and cost, to* *facilitate the construction stage, to reduce the amount of modification design required during construction, and to ensure a functional, high-quality building as the end result.*" [46].

According to ISO 9001:2015[12], when planning and establishing quality objectives, it is essential to answer the following questions:

- What needs to be done?
- What are the required resources?
- Who is responsible?
- When needs to be completed?
- How is it going to be evaluated?

It is essential to specify the Quality Control and Assurance plan because it identifies the checkpoints needed in the development and life cycle of a project.

BIM and Constructability

As explained before, one of the main reasons there is a lack of Constructability in the projects have to do with the segregation of the stakeholders of the projects, especially the designers (Architects and Engineers) and the constructors (Contractor); and it shows in traditional delivery methods in [

Figure 2-10]; on the contrary BIM, methodology enhances and promotes the collaboration of all the actors of the project since the beginning its development. It is important, as Holzer [42] highlights, the need to clearly state the collaboration protocols and integrated teams using the BEP, so each key collaborator knows when and how is going to participate in the project.

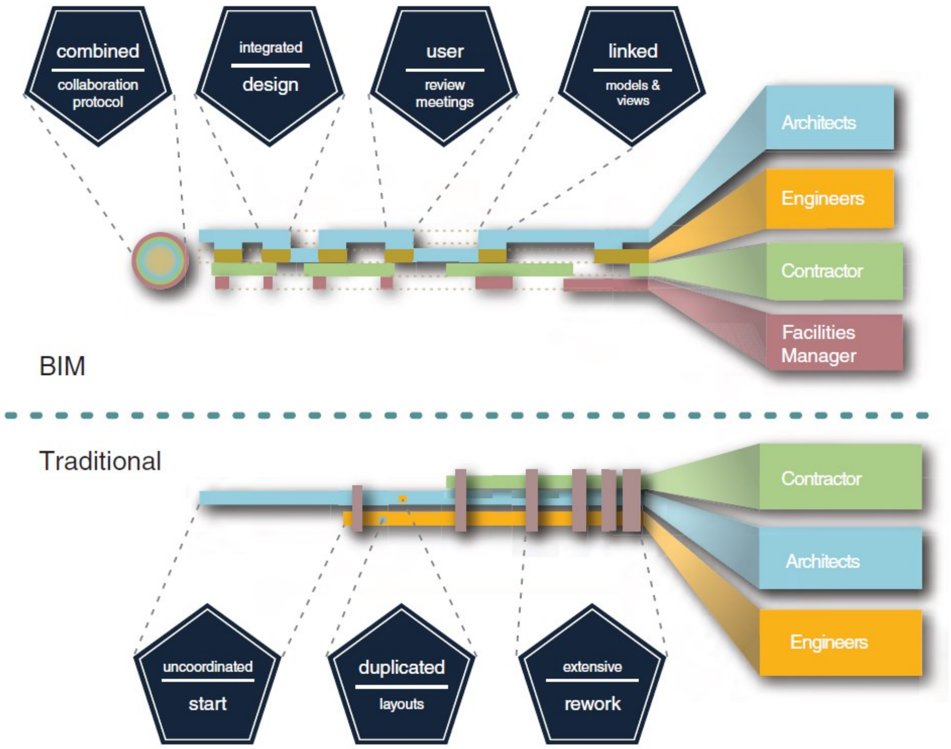


Figure 2-10. Comparison between BIM versus Traditional delivery methods

Source: [42].

A proactive way of producing and achieving successful projects in the Industry comes from applying Constructability [20]. Although Constructability guidelines may be available for the designer, Fischer *et al*. [8] highlighted that a database with the Construction knowledge does not exist, therefore making design decisions based on this input has not been possible; but proposes that with a technology that could integrate the Constructability knowledge in the right time and form, the quality of the projects will increase.

It is suggested that when a high level of uncertainty exists is better to incite construction knowledge, particularly in a formal way; The level of uncertainty comes from the fact that each construction project is unique, and even though a database of lessons learned could exist in the company the use might be limited [26].

For the success of any Constructability program, a robust database of construction knowledge is strongly recommended [29], but it becomes necessary to analyse the Lessons Learned System patterns in order to use Artificial Intelligence technologies [38]. Fisher *et al*. [8] proposed a system that could be able to check the models but specified the requirement of formal documentation of the construction knowledge.

BIM as a tool that integrates the stakeholders in a single source of information creates the possibility to push a formal strategy of sharing and reviewing the construction knowledge during different stages of a project[31]. It is essential to consider how the constructability knowledge is going to flow in the process of the project development, what information is needed, and when it is required [37].

Usually, what happens is that when the design is completed at a detailed level is when the construction experts integrate into the project team [39]; making it less efficient to act accordingly.

Considering the Constructability review to improve the quality of the digital and physical building, to ensure the design is complying with the Constructability objectives of the project [3], this review should consider the Constructability principles and should not be confused by any other type of project review, such as design, coordination, level of detail, comply of standards and regulation or even the completeness of the project.

2.7.1 Pre-construction phase

PLAN - BIM Execution Plan

Quality planning is one of the pillars to have a controlled project; it encourages the assurance of the quality of the model itself. Applying the QMS principles in BIM Execution plan increases the certainty that the project's requirements and expectations are going to be fulfilled and controlled[12].

The BIM Execution Plan or BIM Project Execution Plan (BIM PxP or BIM Plan or BEP) is a document that results from the planning of the BIM project; Kreider and Messner [47] defined it as "*a document* *that lays out how BIM will be implemented on the project as a result of the decision of the group*", it follows a procedure with four main steps:

(1) Definition of the BIM Goals and BIM Uses

(2) Definition of the BIM project workflow

(3) The definition of the Exchange of Information

(4) Identification of the Infrastructure needed for BIM Implementation

As Hayes [11] pointed out, the discussion about the client and customers' expectations are essential, and it needs to be addressed clearly, especially when defining it for BIM because of the marketing behind the concept; it is common to find client's or customer's requirements more related to wishes than to needs; exceeding the effort applied to the development of the project with unnecessary and/or invaluable inputs in BIM.

Goals and Objectives

One of the major steps of planning for BIM is the definition of the Goals and Objectives which are linked to the quality of the construction project; they set what is expected from the BIM model and aligns the stakeholders of the project in a single direction.

Related to the quality, the objectives shall be measurable, applicable, relevant, controlled, shared, and updated if needed.

BIM Uses

In BIM, there are different common language classifications that are meant to communicate in a precise way the intentions of the project; these are part of the standardisation of BIM.

A BIM Use is "a method of applying BIM during a facility's lifecycle to achieve one or more specific objectives"[47]. It is a tool that clarifies the purpose of the use of BIM for the project; Kreider and Messner divided them into five different general BIM purposes based on the general use of BIM rather than the phase of the project since one use can be needed for a different time in the lifecycle of the project: (1) Gather, (2) Generate, (3) Analyse, (4) Communicate, and (5) Realize; each one of them has their individual sub-purposes as well [**Figure 2-11**].

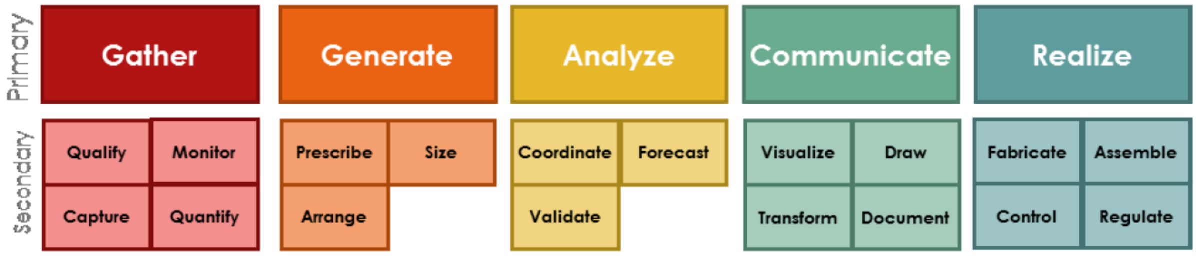


Figure 2-11. BIM Uses.
Source: [47]

The selection of the BIM use is closely linked to the objective(s) of the project; it is applied to an element, phase, discipline with a specific Level of Development within the model. The choice is made by the team during the planning phase setting the baseline of what is the client/project needing and what is going to be delivered, the authors of this classifications pointed out that there are three aspects to consider when choosing them: resources, competency, and experience; if there is a lack of any of them, the quality of the delivery might be at risk [47].

Level of Development

The Level of Development (LOD) is the definition of how much detailed or developed a BIM model is. It is defined as "a reference tool intended to improve the quality of communication among users of BIMs about the characteristics of elements in models"[48]. This tool helps clarify how much effort is going to be done for each element or discipline of the project; the definition can vary from element to element or from discipline to discipline. The LOD definition is linked to the use the BIM model is going to have as well with the phases of the project itself.

Currently, there are different standards that specify how the LOD is communicated, the most used one is from BIM Forum [48]: LOD 100, 200, 300, 350, 400, and 500. The specific definition of the LODs depends on the system and its elements, but a broad concept is that LOD 100 refers to a model element that uses a generic or symbolic representation, the LOD 200 is an approximate representation of the model element, the LOD 300 is a model element in a specific representation, the LOD 350 is as well a specific representation of a model element but coordinated with other elements in the project, the LOD 400 is a specific model element that besides the specification and coordination it also includes the information about its fabrication, and finally, the LOD 500 is a model element where the digital representation has been verified with its physical version.

BIM Dimensions

There are also different dimensions in which BIM address the modelled information in terms of constructability. The dimensions are from 3D, 4D, and 5D. The 3D dimension refers to the representation of the construction project in 3D for means of visualization, documentation, coordination, among other activities, the 4D dimension is the model that includes the necessary information for construction schedule which refers to the time, and the 5D dimension is the model that is intended for cost estimation and budgeting. The definition of the dimensions can vary depending its existence in the market, there are discussions about if the model is able to be dimensioned in such away. In terms of constructability, the model needs to include the needed information for performing the review

QA/QC plan

The quality plan related to the BIM project is established in the BEP; specifying the roles and responsibilities of the stakeholders of the project, the needed infrastructure to obtain the objectives, and goals of the project. The QA/QC plan must include the measurement system that will determine the checking baseline. As part of the QA/QC procedures, the integration of a controlling and reporting systems is recommended [49].

The role that establishes the Quality Assurance Plan is the BIM Manager, and the Quality Control procedure is the BIM Coordinator; the responsibility to do controlled checks of the BIM model is of its own members [50].

There are two main goals for doing a QA plan: (1) Improve the design process and outputs, and (2) Interoperability guidelines between the developers of the project [46].

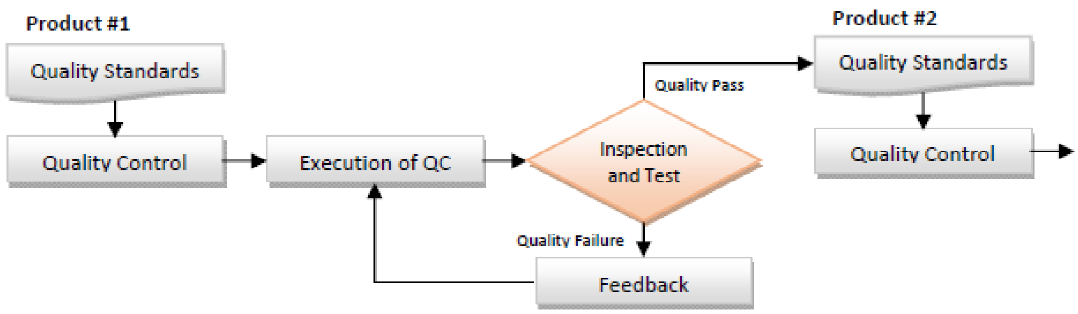


Figure 2-12. Quality applied in the PDCA cycle
Source: [51].

Planning – Constructability – BIM

As stated in the relationship between BIM and Quality, the digital building must be modelled following the goals, uses, and objectives of the project stated in the BEP. Careful attention must be made to not "under or over-model" the project; which means having too less or too much information; it becomes problematic when there is not enough information to perform the coordination and collaboration between departments as well as on the other side has made an extra effort for information or level of detailed not needed in the project; the definition of the BIM uses, and the LODs of the project needs to be clear [42], especially if Constructability is taking into consideration.

The relationship between the dimensions and the constructability - quality of the thesis dissertation has to do with the need to have a clear and common language and definitions to produce and receive a product that matches with what is intended. There is no dimension that specifically addresses Constructability; some relate it to the 4D and 5D because this two are main construction aspects that affect the overall performance.

DO - Modelling

The model has to be prepared for the quantitative and qualitative Constructability review, containing the necessary input for achieving the Constructability objectives of the project [24]. It is essential to understand the information that needs to be modelled based on Constructability knowledge review [31]. As Holzer [42] pointed out, constructability knowledge is required to model not only without clashes among the project's disciplines but to digitally interpret the actual construction process.

Considering the construction information in the initial stages of the project has to be done effectively and efficiently in a process rationally integrated [25].

In order to perform an automated review, it is vital that the BIM models have sufficient and available content, the right information, and an adequate level of detail [22].

According to Fadoul *et al*. [24], the approach of adopting a Constructability program are mainly three: (1) Quantitative Constructability design evaluation, (2) General Constructability review, and (3) Implementing Constructability programmes; the aspects in the model required to facilitate the Constructability review [**Table 2-3**].

Table 2-3. Model requirements of constructability system.

Model Requirements of a constructability evaluation system	
Requirement	Description
Generic	Model to evaluate design solutions.
Scalable	Model valid of different building scopes, it includes individual analysis of design elements.
Flexible	The model can be adapted according to user preferences and capabilities.
Comprehensive	The model includes all constructability principles and characteristics.
Simple	The model is easy to apply and integrate into the design environment.
Accurate	The model shows the design constructability from the program analysis.
Effective	The model facilitates the improvement of design constructability.

Source: Adapted from [24]

CHECK – QA/QC Procedures

The QA/QC procedures of the BIM must be planned since the beginning of the project; the definition should be clearly stated in the BEP of the project, as explained in the planning stage of the pre-construction phase. Quality should be constantly checked. In order to have an organized system, defining the checkpoints in the project lifecycle is needed; these milestones will be settled in the overall schedule [46].

Mirshokraei [52] described QA as the prevention and QC as the correction procedures and elaborated the following schema with the interaction between the two procedures and the BIM methodology [**Figure 2-13**].

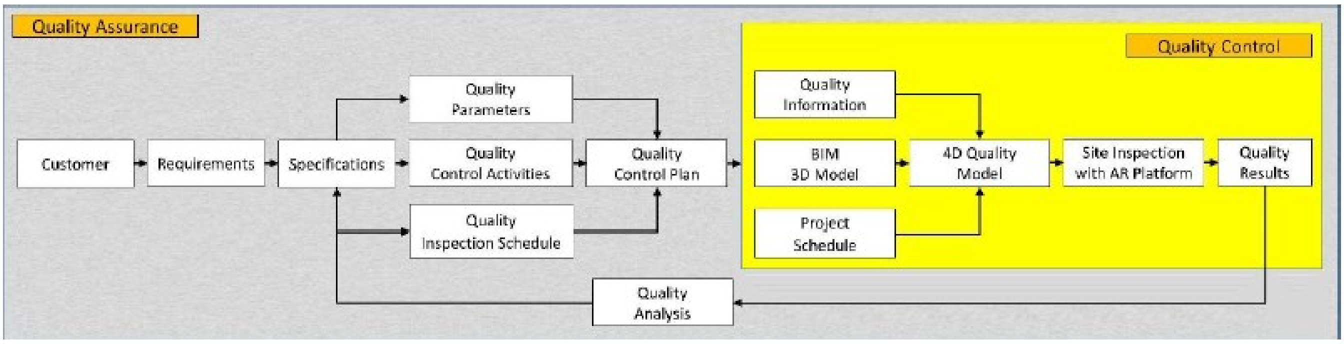


Figure 2-13. Interaction between the QA/QC procedures
Source: [52]

There is a distinguish activities for QA: (1) Checking: which refers to the action of comparing the produced model against the required model, standards, goals, uses, and LODs, among other quality definitions in the BEP. (2) Analysis: which is the action of taking the BIM model and use its information to obtain insights against a specific quality purpose on the project [46].

There are four reviews recommended from the Singapore BIM Guide [50]: (1) Geometry’s LOD, (2) Object location, (3) Object’s system accuracy, (4) Clash coordination with other systems.

Wangara [43] identified five levels in which BIM can be checked:

1. BIM Inventory
2. Spatial BIM
3. Building element BIM
4. System BIM
5. Merged BIM

One filter to check the quality is by defining the level of accuracy; this depends on the discipline it is going to be modelled and checked [43]. One form through rulesets [22]. The introduction of

Constructability measurement can be set to range from "easy to assemble" to "impossible to assemble" [8].

Checking Platforms and Software

In the AEC Industry, there are different QC tools to analyse the status of the project against the set objectives and standards.

Razzak Rumane [1] identified at least ten different ones:

(1) Ishikawa diagram or Cause-effect diagram. (2) Check sheet. (3) Control chart. (4) Data collection. (5) Flowchart. (6) Histogram. (7) Pareto analysis. (8) Pie chart. (9) Run chart (10) Scatter diagram

There are a variety of platforms and software dedicated to model checking; different articles and research have focused their studies in reviewing and comparing them, one example is the following table by [53] where is comparing the language or tool dedicated to the rule checking system with an eleven analysis indicators [**Figure 2-14**].

Language or tool Legend ○ Low ◑ Moderate ● High — Not Applicable ◇ Unknown	1. Formal or standard schema for the rule definition	2. Language expressiveness	3. Ease of defining rules	4. Minimum logic or programming constructs	5. Minimum domain knowledge required	6. Support for complex rules	7. Integrated geometry engine	8. Performance indication	9. Openness	10. Interface to other languages and systems	11. Level of maturity
NLP	—	—	—	○	○	○	—	◇	○	○	○
RASE and IFC Constraint Model	○	◑	◑	◑	○	○	—	◇	●	○	○
LegalDocML and LegalRuleML	●	◑	◑	◑	○	○	—	—	●	○	◑
BPMN	—	◑	◑	○	○	○	—	—	●	—	●
Mvdxml + IfcDoc	●	◑	◑	●	○	○	—	◑	●	○	◑
BIM Assure	—	◑	●	●	●	○	—	●	○	○	◑
QL4BIM	—	◑	◑	◑	○	○	◑	◑	●	○	○
BERA + BOM	—	◑	◑	◑	◑	◑	○	◑	◑	○	○
KBim	—	◑	○	○	○	◑	○	◇	○	○	○
BIMRL	—	●	●	●	●	◑	◑	●	●	◑	◑
DROOLS	—	◑	◑	◑	○	○	—	◑	◑	●	●
Rule Table	—	○	●	●	○	○	—	◇	◑	○	●
Prolog	—	○	○	○	○	◑	—	◇	◇	○	◑
SWRL + IfcOWL	—	◑	○	○	○	○	—	◑	●	◑	●
SPARQL and SPIN + IfcOWL	—	◑	○	○	○	○	—	◑	●	◑	●
Revit Model Review	—	○	◑	●	○	○	—	◑	○	○	◑
Dynamo + Revit	—	○	●	◑	○	◑	◑	◑	◑	○	●
Grasshopper + Rhino	—	○	●	◑	○	◑	◑	◑	○	○	●
Marionette + VectorWorks	—	○	●	◑	○	◑	◑	◑	○	○	●
VCCL	—	○	◑	○	○	○	—	◇	○	○	○
FORNAX Lua scripting	—	○	○	○	◑	●	●	●	○	○	●
*Solibri Model Checker (SMC)	—	—	—	—	◑	◑	●	●	—	—	●

Figure 2-14. Assessment on Rule checking system Language or tool.
Source: [53]

Challenges of the rule-based checking system

Solihin [54] identified key aspects that lead to challenges of the rule checking system:

(1) The way the BIM information is embedded, and if it follows a defined standard.

(2) The understanding of the access lines of the information.

(3) The model query system.

(4) The structure of the rules and the correlation with other rules.

(5) The geometry and space needed for the rule-checking elements.

Constructability QA/QC overview in BIM

Having early check analysis for constructability purposes will help identify and address construction problems sooner, which allows fixing them with less probability to damage the cost and schedule of the project [43].

BIM can automate, visualize, inform, and transform the digital model; it could be considered as a tool that has the capability to analyse the Constructability issues of a project by utilizing the reasoning of a pre-defined Constructability knowledge database [22].

Model-checking plan

An important step when making a plan for constructability purposes is to have the information organized; Pulaski and Horman [37] developed a Matrix Model named Conceptual Product/Process Matrix Model (CPPMM) to improve the method the constructability knowledge is arranged according to the process and the Level of Detail [**Figure 2-15**].

<table>
<tr><th colspan="9">Conceptual Product/Process Matrix Model</th></tr>
<tr><th colspan="3" rowspan="2"></th><th colspan="6">Level of Detail of Constructability Input: Product Model</th></tr>
<tr><th>Project</th><th>Building/Site</th><th>System</th><th>Sub-System</th><th>Components</th><th>Elements</th></tr>
<tr><td rowspan="8">Project Stages: Process Model</td><td rowspan="8">Pre-Construction</td><td>Requirement analysis</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Feasibility</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Concept design</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Schematic design</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Design development</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Detail design</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Construction documents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Submittals/Procurement</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

	Construction	Construction						
	Post- Construction	Operation & Maintenance						
		Demolition						

Note: The shaded cells represent an ideal project, according to Pulaski and Horman.

Figure 2-15. Conceptual Product/Process Matrix Model
Source: Adapted from [37]

The model in [**Figure 2-15**] consist of the correlation between two models: Process and Product models. The process model is related to the stages of project development and its delivery procedure; the product model is related to the structure of a project in a hierarchical way from a whole to a part, which can serve as a guide to plan the constructability reviews accordingly[31].

It becomes necessary to identify the constructability issues that need to be solved in the project to determine the level of detail of constructability knowledge and have a comparison with the content in the BIM model [22].

As explained in the construction knowledge chapter, there are two different types of knowledge: Explicit and Tacit; for making available the explicit knowledge for model checking procedure, the use of a checklist is recommended; on the contrary tacit knowledge is harder be transform into checklist [11].

Constructability ruleset

The relationship between Constructability and Rules is not something new; it has been studied and implemented to transfer the construction knowledge to the rest of the team, especially to the design [55].

The rule-based system is a set of rules that can be applied to the quality check and quality assurance procedures and show the project compliance in terms of Constructability; the rules transform the construction knowledge into project constraints such as availability of elements, transportation, site layout, inventory, and storage spacing, construction techniques, etc. [24].

The relationship between the owner and the builder sets the relevant parameters and variables of the project based on the data collected from the decision levels; which will be the baseline for the Constructability ruleset [26]. A set of Constructability rules based on the experts' construction know-how can be employed in automated checks using BIM [31].

In their article, the Constructability knowledge from the experts was analysed using the tools of concept maps and task modelling; the concept maps identified and constructed the knowledge based on structures and processes from a management context by correlating the elements and its characteristics; the task modelling referred to the reduction of the construction activities into a set of work simpler to execute [19].

To perform an automated Constructability review, a pre-defined rule set of Constructability knowledge is required to enable the extraction of required information from the models [22]. The rules are set by primary and complex concepts, the first one refers to the domain expertise that includes the decision rules to review, and the second one is a combination of at least two primary concepts; the rules use the semantic of Machine Learning [19].

For Fox *et al*. [55] a rule is a fixed statement, it is considered a standard because it can be used in different levels in a project: designs, people, and locations; nevertheless, he implemented a series of guidelines to apply the rules successfully:

(1) Sequence the rules according to its stage to improve the productivity and quality of the construction.

(2) Align the rules to the strategies and databases of the organization to understand the project as a whole and not just parts of a unit.

(3) Follow a specific process and routine for the use of the rules in the project, taking advantage of the technology available.

(4) The best applicable rule is the one that enhances productivity and quality in the project to get the best out of the assessment, consider simplifying the solutions to build more efficiently.

In their process to facilitate the Constructability knowledge to the designers, Fischer *et al*. [8] sort the knowledge based on its application to the design process, identifying five types of knowledge for design decisions:

(1) Applicability Knowledge: Refers to the expertise about the possibility of applying a Construction Method,

(2) Layout Knowledge: Refers to the information about the constraints on the vertical and horizontal layout,

(3) Dimensioning Knowledge: Refers to the awareness about the constraints on the dimensions of the elements,

(4) Detailing Knowledge: Refers to the knowledge about the complementary details supporting the overall construction methods selection, and

(5) Exogenous Knowledge: Refers to the know-how about the required factors outside of the design scope.

The collected knowledge will go through the reasoning to create a knowledge item available to use [8].

A system to have access to knowledge on specific constructability issues was developed with three components:

(1) Knowledge repository in the form of rules often in an IF-THEN statement representation,

(2) The engine that performs the logic of the rules, and

(3) the User to communicate between the end-user and the system [31].

The IF-THEN statement that represents the constructability knowledge for the semantic of the automated process integrated into review methods [22]. The logic behind the rule consists in two main concepts: Definition of Objects, Parameters to Check, and the Value (set or in a range) for the comparison between how it is, and how (according to the constructability knowledge) should be; the scope of the review is defined in the first concept, and the values and question are the conditions of the rule [**Figure 2-16**] [31].

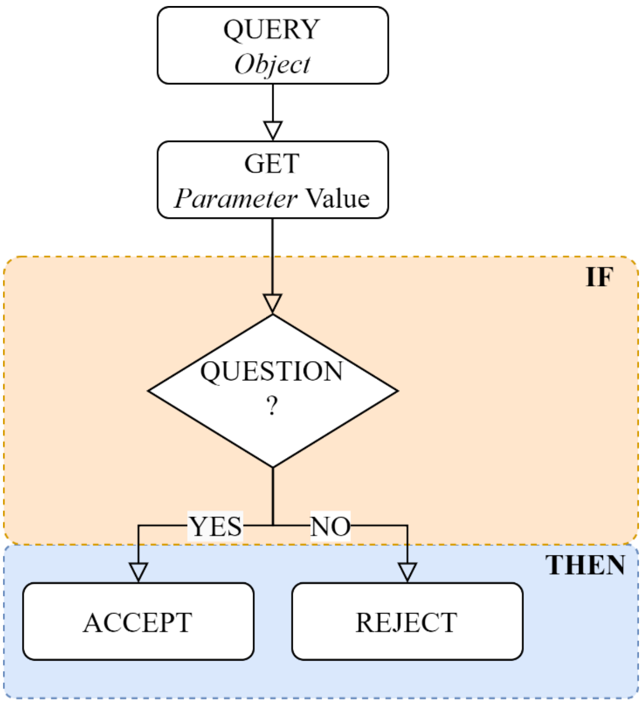


Figure 2-16. Algorithm of selection rule in an IF-THEN statement.
Source: Adapted from [31].

It is required an understanding of the information in the models such as parameters, object elements, spaces, and its relationship; in BIM there are four types of reasoning that will show constructability issues [**Table 2-4**] [22]. The type of reasoning and the relationship with the BIM content has to be correspondent to the process level and LOD the project is at as well as the consideration of any other constraint that may affect the constructability assessment[31].

Table 2-4. Type of Constructability Reasoning for Rule Development

Types of Constructability Reasoning		
Type of Reasoning	**BIM Information Required**	**Examples of Constructability Reasoning Rules**
Parameters of an Object	Location, dimensions (i.e. length, width, and height), area, object type, material, etc.	**IF** there is "bollard;" **THEN** the separation of "retaining wall" needs to be at least 42".
Relationship between parameters of Objects	Parameters of more than one element.	**IF** the thickness of the base plate is NOT thick enough; **THEN** there should be stiffening element at the base of columns.
Spatial reasoning	Parameters of more than one element, mainly regarding the location of the object.	**IF** the access of a CMU wall is NOT enough; **THEN** the material needs to be changed from "CMU" to "Concrete".
Interface design Progress	Naming convention, type of elements, phasing of the model.	**IF** DD phase is TRUE; **THEN** there should be a roof connection design.

Source: Adapted from [22].

Jiang *et al*.[31] found that in previous studies of an automated, rule-based system, the user interface was divided into graphic and non-graphic categories, the difference relied on the database, which was only used for the review; the use of graphic systems helped to have better and more detailed information to come up with a solution of the constructability issues.

For an automated, rule-based constructability assessment, four stages are identified by Jiang *et al*. [31][**Figure 2-17**]:

(1) **Rule interpretation** Refers to the action of transferring the expert's construction knowledge into machine semantics often represented as IF-THEN statements,

(2) **Modelling**: The model is developed according to the needed information of the constructability assessment, the relationship between the rule parameters, objects, spaces, and dependencies are identified as well as the Level of Detail required in the given stage of the project,

(3) **Rule execution**: Refers to the act of putting the model to inspect according to the set of rules. Different information is required at different times of the project; specific algorithms may be required for a more accurate analysis of a constructability issue,

(4) **Constructability feedback**: The results of the rule execution are produced, depending on the timing during the design process, it can either be preventive or corrective feedback.

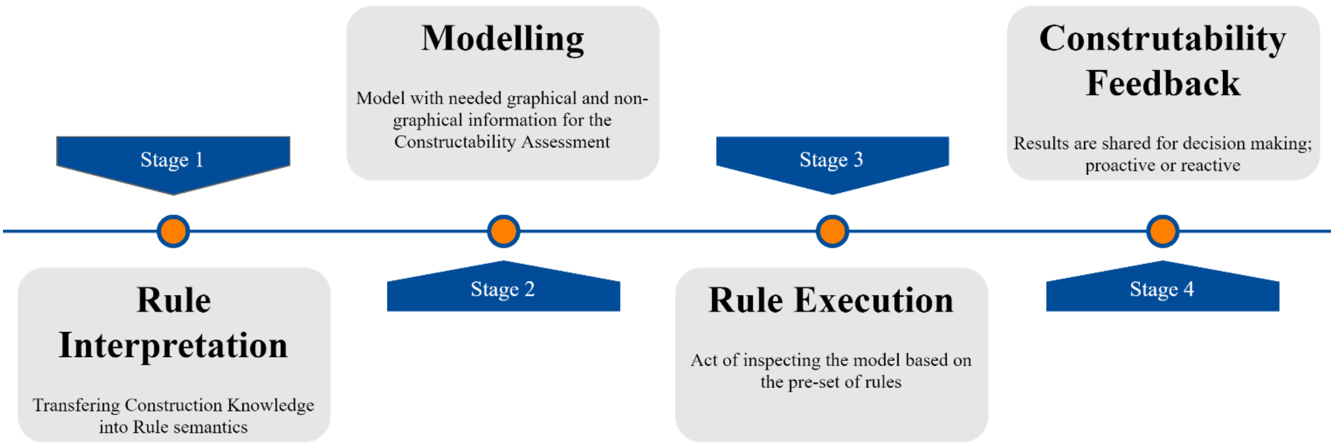


Figure 2-17. Rule-based staged.
Source: own elaboration adapted from [31].

The RASE methodology separates the rules into four categories: Requirement, Applicability, Selection, and Exception but according to Solihin [54], the lack of semantic that could relate it to properly do automated checks made it complex to use.

Constructability knowledge in Lessons learned

It is important to consider that Weber *et al*. [38] distinguished between a lesson learned and a rule in how the user needs to understand and recognize the way the knowledge can be applied in the project, a lesson can be partial while a rule requires its complete application.

In her research Weber *et al*. [38] found that the lessons learned systems hardly contribute to the use of expert knowledge due to the way they are shared and communicated, and it is difficult to understand where and with what conditions they can be applied.

The knowledge needs to be expressed in a specific format using computer semantics; it needs to be described with an action that initiates the experience, the conditions to set the variables that, when they are combined with the contribution (such as a method, a resource, an element, or an action), generate a result; adding a suggestion from the experts to reuse or avoid what was learnt is recommended; and finally, an applicable task, which refers to the employability of the lesson, meaning the specification of where it can be used [38].

The lessons learned need a structure that includes title, description of the issue o situation, description of the solution or method, comment, referenced documentation, source, and its classification system; the more specific, the easier for the user the query [32].

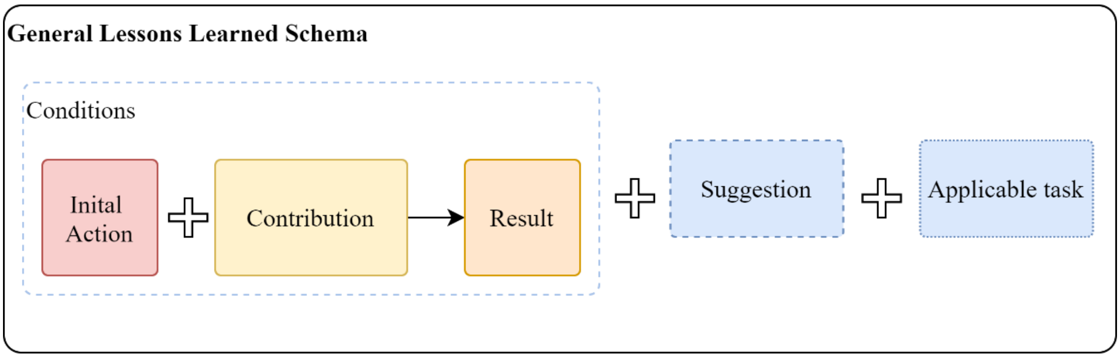


Figure 2-18. General Lessons Learned Schema
Source: own elaboration adapted from [38]

The technical lessons usually are expressed in a causality relationship [38].

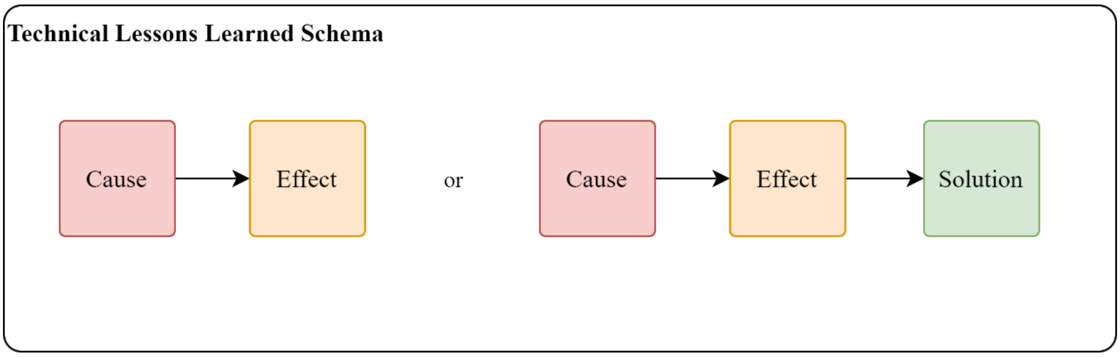


Figure 2-19. Technical Lessons Learned Schema
Source: own elaboration adapted from [38]

Constructability assessment

Companies have to recognize that each project has a variety of goals which need to be prioritized; the model and the assessment have to reflect it [26]. During the process of the majority of the projects, the Constructability input is not included due to the lack of formal databases of the Constructability knowledge and experience accessible to the project developers [29]. For Fox *et al*. [55] even though the Constructability rules have been there and are easy to elaborate, the process has not been successfully implemented. The use of databases that store the Constructability knowledge using an object orientation storage is useful for having a relationship in a lower and higher level of use [56]. A constructability database allows having a structured expert knowledge[32].

For Constructability assessment, there are different tools that have been used as resources of implementation; it includes the Companies' policies and procedures, a formal database of lessons learned, database from a construction technology, and review checklists; the use depends on the availability of such tools and the capabilities the users have towards them [26].

Fisher [56] classified and analysed the available tools for constructability assessment [**Table 2-5**]:

Table 2-5. Constructability Tools.

Constructability Tools			
#	**Category**	**Tool**	**Description**
01	**Policy/Process-based Tools** Refers to tools that assess the Constructability implementation	**Policy and Objective Statements**	A written document that states the Constructability program objectives, the level of commitment, the responsible, and the project for application.
02		**Team/Meeting Agenda**	The Constructability program follows a plan with the definition of the meetings integrating the team and objectives across the execution of the project.
03		**Operation and Maintenance (O&M) Input Checklist**	The input to the project from the O&M team is crucial for complying with the project functionality.
04		**Organization Structure**	It is a tool that organizes the teams with their authorities and responsibilities.
05		**Suggestion Form**	A document that will track the ideas during the project execution.
06		**Pre-Bid Conference List**	A list generated from the Owner-Bidder clarifications meeting to minimize the risks and assumptions of the project.
07		**Pre-Construction Conference List**	A list generated from the Owner-Contractor meeting to set the communication channels.
08		**Contract Incentives**	Is a tool that would set the rules for the execution of the project.

09		**Partner Agreements**	A tool that creates a relationship between the different teams in the project and facilitates the flow of information.
10		**Contractor-determined schedules**	Construction-driven project schedule set by the Contractor responsible for the execution.
11		**Implementation Responsibility Matrix**	It is a document to store in a single source the lessons learned of the project.
12		**Team Building process**	It is a tool to bond and strengthen the project team.
13		**Constructability Engineering Role**	The definition of the role of Constructability experts between technical and managerial tasks.
14	**Modelling tools** Refers to tools that assess the Constructability implementation	**Post-construction Review Checklist**	A document that includes the review on the project execution, including the recollection of the last lessons learned.
15		**Project Constructability Agreement**	A document that sets the responsibility towards Constructability.
16		**Agency Constructability Checklist**	A tool that simplifies the Constructability process.
17		**Formal Implementation Process**	A tool that specifies the process for Constructability program.
18		**Constructability Champion**	The role with the authority and responsibility of applying for the Constructability program.
19		**Value Engineering Process**	The process that relates different alternatives to the design in the hopes of having a more efficient solution, especially in terms of cost.
20		**Idea/Lessons learned log**	A tool that will capture the lessons learned since the stage of an idea.
21		**Critical Path Method**	A tool that understands the execution in terms of sequences and dependencies finding the critical tasks and activities

			that constraint the execution of the project.
22		**Cost/Benefit Analysis form**	Is a tool that analyses the Constructability ideas in terms of cost/benefit of the project.
23		**Constructability Resources**	Refers to the different sources of Constructability knowledge outside the company or the project team, which will support the Constructability implementation.
24	**Technology-based tools** Refers to tools that use instruments and computer tools for Constructability application.	**Graphical Computer-Based tools**	There are different tools: From the Computer-Aided Design (CAD) tool that uses a computer to simulate the construction project to other graphical technologies like multimedia, virtual reality (VR), hypermedia/WWW.
25		**Non-Graphical Computer-Based tools**	Tools divided into databases and analytical tools. The database stores structured Constructability knowledge. Analytical tools include simulations, artificial intelligence, decision support systems.
26	**Tool Integration**	**Tool/Function roadmap**	The matrix that relates the tools with Constructability functions.

Source: own elaboration based on [56]

BIM can be classified as a technology-based tool with both graphical and non-graphical as well as a tool that integrates the project. The following is a procedure adapted from Jiang et al. [31], which includes the activities for a rule-based checking process with an object-oriented schema [**Figure 2-20**].

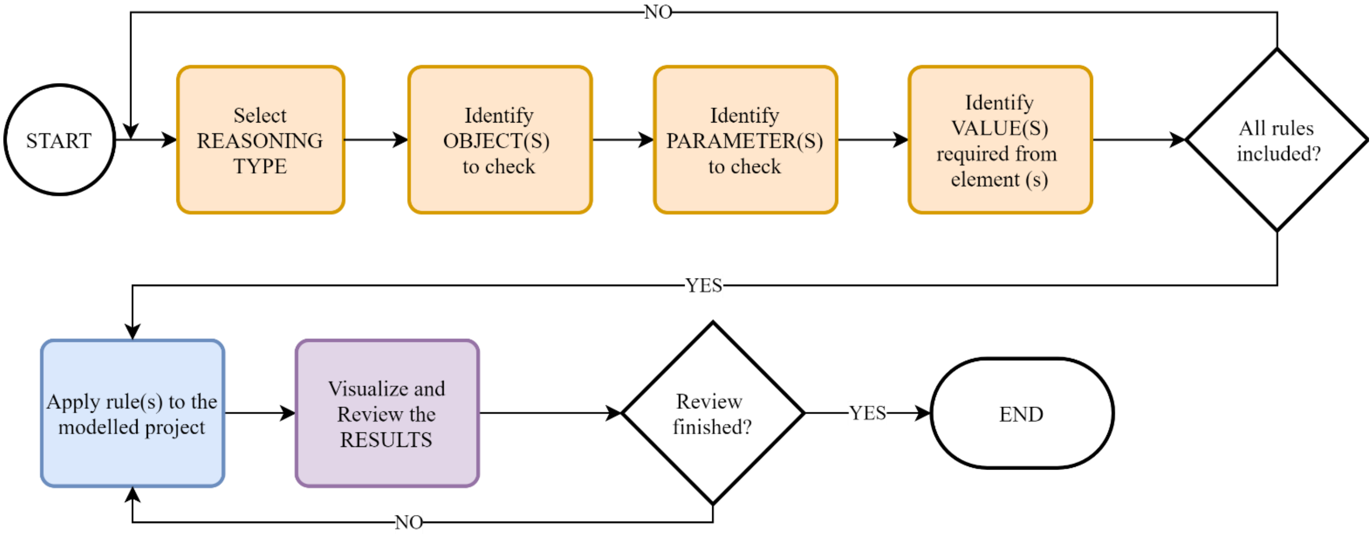


Figure 2-20. Rule-based BIM checking procedure.
Source: Adapted from [31]

ACT - Constructability feedback

Jiang *et al*. [22] highlight the difference between two categories of Constructability feedback: reactive feedback and proactive feedback; the proactive feedback is received by the design team before and during the development of the project which makes it a valuable decision making input; on the contrary, the reactive feedback is handled after the design is finish; when the feedback is communicated in the right time, it will not only help the decision-making process but will also benefit the reduction of the design rework.

Jiang *et al*. [22] differentiate between the two types of constructability feedback depending on the timing the constructability assessment is done during the design phase of the project either proactive feedback and/ or reactive feedback [**Table 2-6**].

Table 2-6. Type of Constructability Feedback by Project Phase

Type of Constructability Feedback by Project Phase						
Pre-Construction Phase	**Design Phase**				**Construction Phase**	**Post-Construction Phase**
Feasibility / Planning	**SD**	**DD**	**15% CD**	**100% CD**	**Procurement**	**Operation / Maintenance**
Proactive	Proactive	Proactive	Reactive/ Proactive	Reactive	Reactive	Reactive

Source: Adapted from [22].

In the final report from Stamatiadis *et al.* [32] identification of the corrective actions from the constructability review were made to correlate how much impact it had in the cost and/or time of the project as well as the effort needed from the personnel involved [**Table 2-7**].

Table 2-7. Qualitative Level of Corrective Actions.

Qualitative Level of Corrective Actions	
Qualitative Level	**Description of Corrective Actions**
Low	The corrective action may require additional project communication or clarification but can be completed without a change order. The effort would be minimal to rectify the situation.
Medium	The corrective action may provoke minor project cost or time increase by change orders, but the overall effects are considered average. The average change order results in a 3.5 per cent increase to the project. The effort must consider additional documentation and time to rectify the situation.
High	The corrective action will result in large additions to the project cost and/or time and would have the potential for leading to project disputes or claims. The effort would incur excessive amounts of added documentation and time to rectify the situation. Additional tension between the contractor and project management staff may result.

Source: Adapted from [32].

Stamatiadis *et al*. [32] identified five different feedback type in their evaluation of applying for constructability review; it is necessary to clarify that this constructability was made to :

(1) Error: wrong information

(2) Notes Clarity: the need to clarify a note in the project

(3) Omission: the absence of an element needed for construction

(4) Drawing clarity: the need to clarify a drawing in the project

When feedback requires clarification, the evaluator classified it as a medium or high level of impact to the project because this type of feedback to the project often leads to rework and disputes that affect the overall performance. Some highlight in the report by Stamatiadis *et al*. [32] is that the reviewer is capable of the act and is influenced by their area of expertise.

To analyse the benefits of applying a constructability review, each feedback can be inspected in a quantitative and qualitative manner. The quantitative will evaluate the cost and/or time-saving by the feedback made; estimating what would have happened if it were not made. The qualitative will evaluate the level of impact on the project.

A basic communication process must be in mind when transmitting the feedback of the project, the senders and its message, the communication path and infrastructure, and how it was understood by the receiver[57].

Construction phase

The as-design model that was generated during the pre-construction phase is then used during the construction phase. Constructability review will also help detect the information required for the different stages of the project, especially construction phase, by comparing the available versus the required content in the BIM models; as the design phases evolve, the different levels of development of the elements in the model will be more detailed.

3 FRAMEWORK

After the review of the literature regarding the subject of this thesis, it has been identified different levels in which the construction knowledge interacts with the project. If the knowledge is understood as gained experience, both the designers and the constructors are acquiring it while the project is progressing. In this sense, Luiten [58] identified three different knowledge achieved for the main activities performed in the construction of a building: Design knowledge, Planning knowledge, and Constructability knowledge; this is coming from both the person executing and the product executed.

With this concept in mind, each activity that is performed in the lifecycle of the building project will generate specific valuable knowledge; the framework intends to:

1. Understand the value of the bi-product of the project: AEC Knowledge.
2. Analyse the outputs of exiting communication between the construction and the design team while the construction phase is in progress to obtain the knowledge.
3. Use lessons learned schema to boost the cross-learning from project to project and from team to team.
4. Use BIM to enrich and integrate Constructability to the process.

The framework is going to be designed in a process approach by analysing the five different elements of single process representation [**Figure 3-1**].

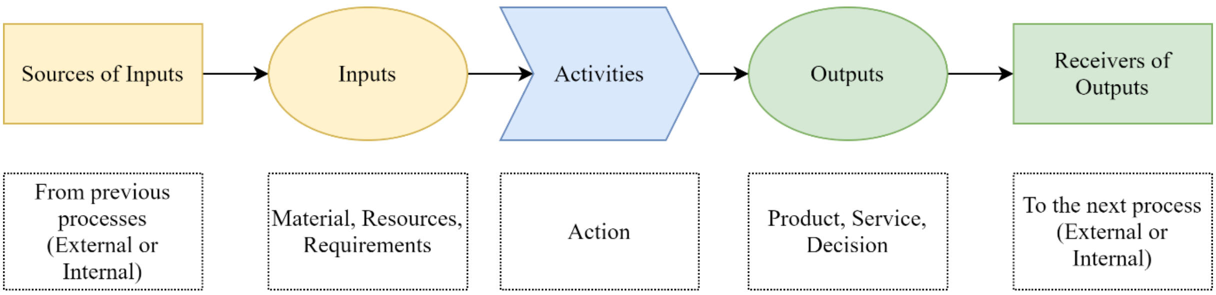


Figure 3-1. Single process schema
Source: Adapted from [14].

3.1 Framework design

The starting point of the framework comes by defining the context of the main process to execute a construction project; this has been simplified in three main stages: Pre-construction, Construction, and Post-Construction. Adapted from Luiten [58], these three major processes will generate its own knowledge [**Figure 3-2**].

The pre-construction phase includes the feasibility analysis of the project and the evolution of the design process, from the schematic to the detailed design. The construction phase includes procurement and construction and management activities. The post-construction phase considers the project handover, and it is integrated into the main process because the operational and maintenance phase is essential to the life of a building.

As a disclaimer, since it is a general schema of the project development process, the diagram is not addressing the different types of contract that exist for building a construction project which can alternate it; it also does not consider the interaction between one or multiple companies involved in the project. The schema is showing a start to finish diagram between the main activities, but for example, in a fast-track project, these activities may overlap as the project demands.

In a traditional process, this knowledge will be isolated from each other, especially because it is enhanced by how the industry is also separated. Even if there is such knowledge, the time and effort required to capture and reuse it usually do not happen.

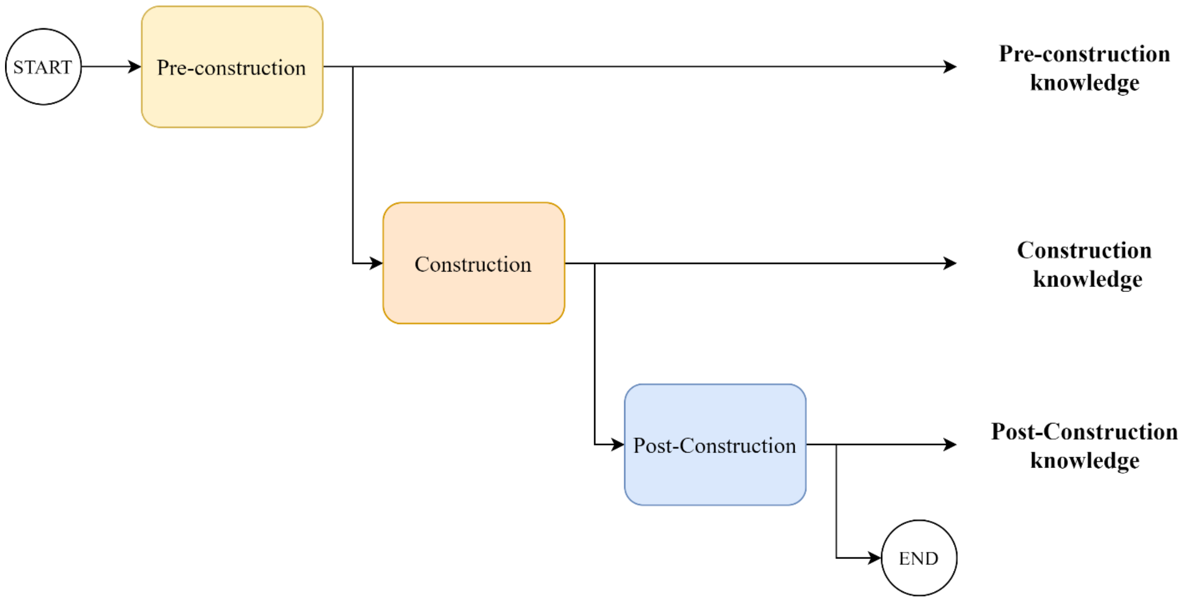


Figure 3-2. Knowlege from the construction project lifecycle.
Source: own elaboration adapted from [58].

In a process-based analysis, one activity is connected to the other in the source of inputs and the materials and resources needed for each of the main phases; the main focus of the [**Figure 3-2**] is to show the bi-product of knowledge that usually is wasted or not even seen. The author proposes to use it to increment the quality of future project execution. When the team is aware and understands the constructability status and the type of constructability issues they have it will lead to prioritizing the effort of the fixing actions according to which ones have a higher contribution to quality improvement of the company [32].

For the integration of BIM into the same context, the BIM model is moving in the process as the project evolves. The principles of collaboration and integration encouraged by following BIM makes the connection of a single source of information [**Figure 3-3**]. It can be inferred that the knowledge is contained in the single source of the project, but as seen before, the knowledge is not only contained in the product (BIM model) but also in who produces it (Designers and Constructors).

"Obviously we must try to comprehend objectively the interaction between measured object and measuring instrument… Maximal knowledge of a total system does not necessarily include total knowledge of all its parts, not even when these are fully separated from each other and at the moment are not influencing each other at"

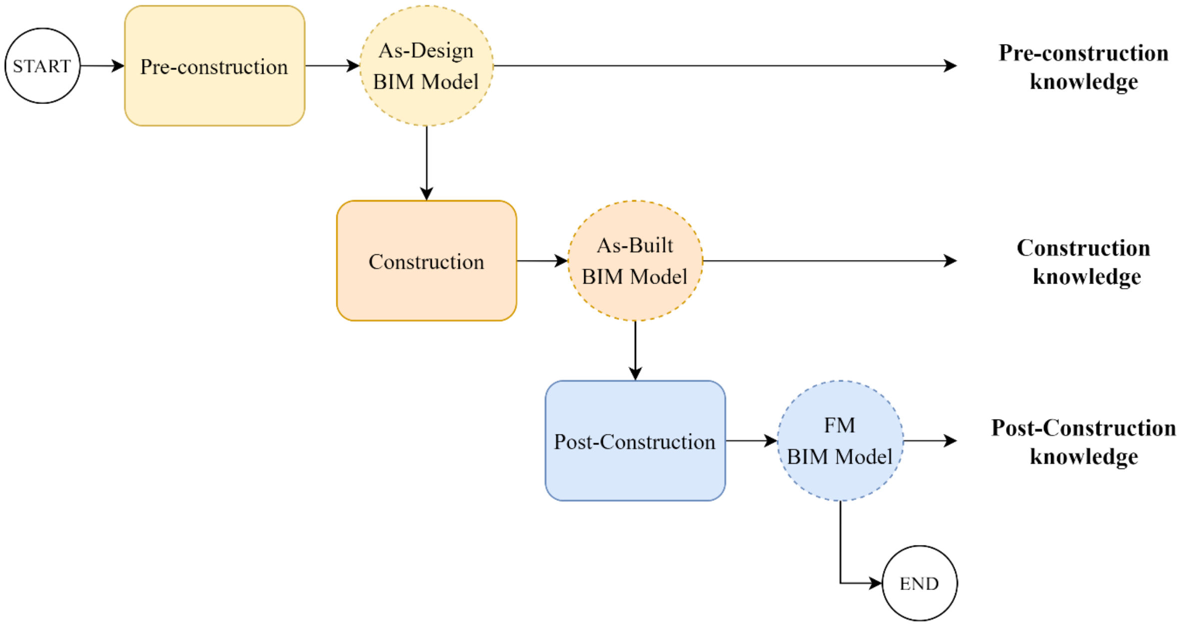


Figure 3-3. BIM Knowlege from the construction project lifecycle.
Source: own elaboration adapted from [59].

The questions the framework intends to answer are:

Can the resulted knowledge be consciously integrated into the project?

Can it be considered on future projects?

How to use BIM to create a powerful tool/dimension of knowledge?

This thesis is proposing BIM related to the Constructability Knowledge; the awareness of the generated knowledge in the projects, and systematically processed it to establish the possibility of using it as a quality improvement technique and a competitive advantage in the market. It is deduced that it will not only help improve one company but the industry in general.

The framework proposed is taken into consideration the lessons learned process [**Figure 3-4**]:

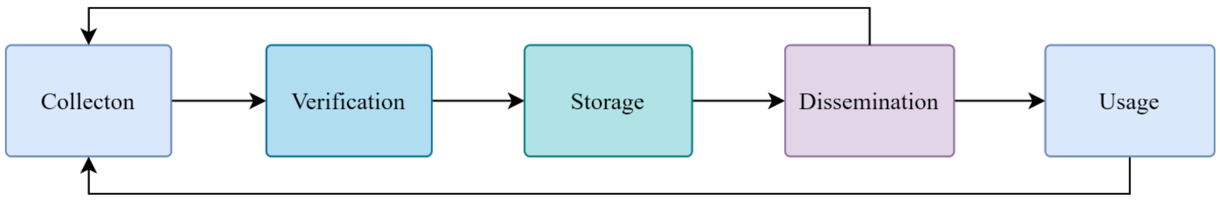


Figure 3-4. Lessons learned general process
Source: own elaboration adapted from [38].

The framework adapts the same steps of lessons learned general process to answer the previously stated questions and to address the use of BIM during the process [**Figure 3-5**]. The initial statement considered for the design of the framework was that BIM as a product includes the Modelled elements (Graphical representation of the physical asset) and Information (Non-graphical representation of the object attributes) which are contained in a single source. Therefore, it is a knowledge container that feeds while the project is developed.

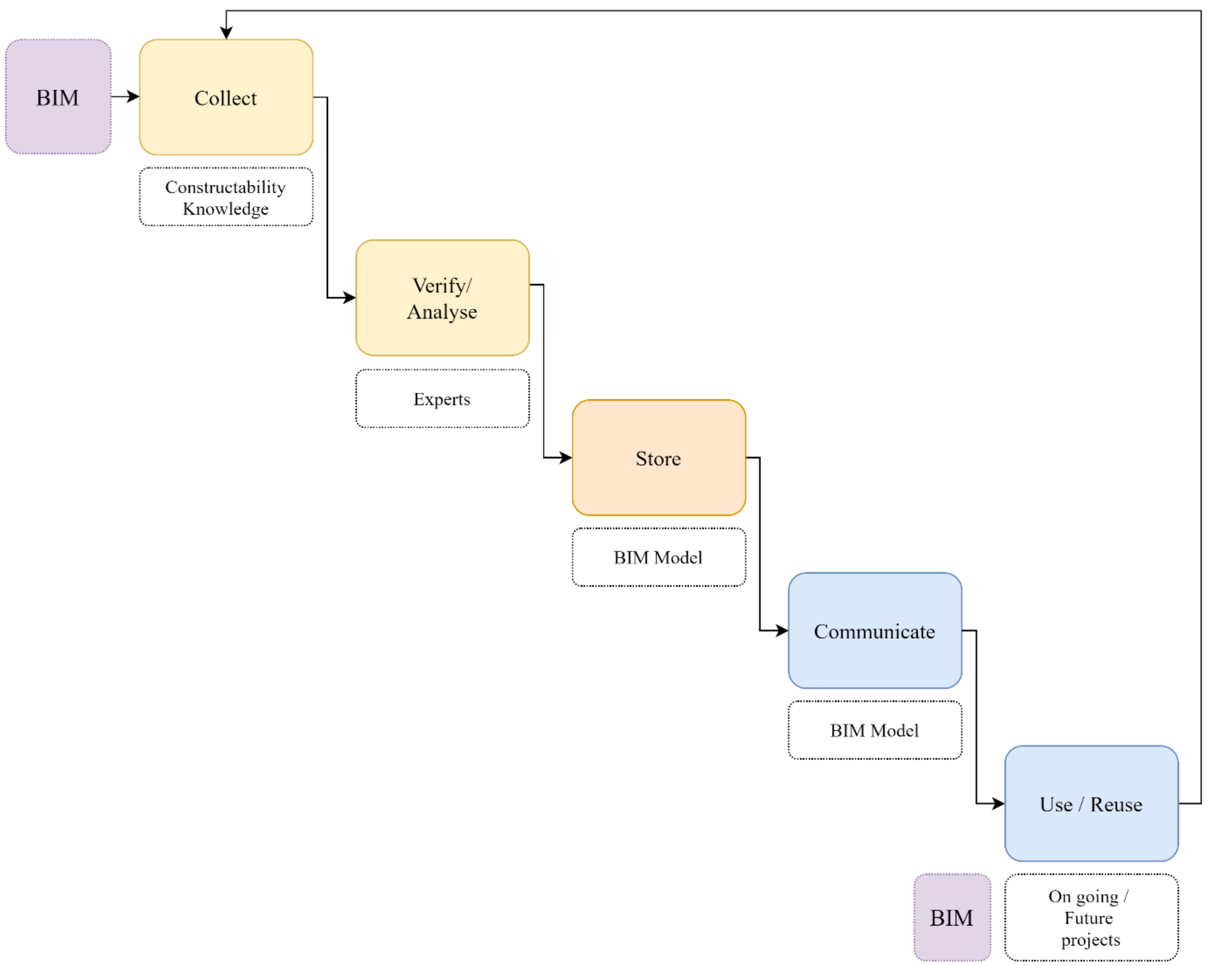


Figure 3-5. BIM procedure based on Lessons Learned.
Source: own elaboration

The framework intends to add value to the BIM Model by integrating the Constructability knowledge and Lessons Learned to reuse it in on-going or future projects.

The objective of the framework is to use it in a loop in the same project and between projects. The steps are explained for the constructability knowledge of the project already in the construction phase or post-construction phase.

(1) In order to do so, the first step will be to collect the knowledge of the project from the Request for Information (RFI) and redlines or mark-ups that happened during the project's construction. Each of this information will be captured in a format to get constructability knowledge, and Lessons learned from it.

(2) The second step considered that the information included would be verified and/or analysed by the expert(s) who will validate the collected knowledge.

(3) The third step is about the storage of this knowledge in the BIM model; this can be integrated into an object-oriented perspective.

(4) The fourth step is about the communication and dissemination of the updates or addition of this information to the selected and identified key roles, and

(5) The fifth step is the use or reuse of this acquired knowledge during the same or the future projects.

(6) The loop of the framework to collect new knowledge will come by analysing the new activities of the construction process of the same project or from a completely new project.

3.2 Detailed Framework

Each of the activities is going to be explained in the following subchapter.

A) Collect

As before, the collect activity is going to be divided into two different sources of input from the existing communication between the construction site and the design office.

Sources

Request for Information (RFI)

To collect the Constructability Knowledge from the Request for Information activity, it is necessary to take the project documentation and collect it in a schedule. All the recorded questions the site team had for the design team while building it are going to be described. The intention is to learn from those questions by categorising them mainly by the type of request and the reason behind the demand.

Each company has its own process; some have a standardised format for this form of communication; some use the regular channels of communication like corporate e-mail, or even phone call to solve their inquiries. Nowadays, with the use of BIM the available online platforms that support real-time RFIs and Mark-ups help digitalise and standardise the process, for example, Dalux, which is going to be used in the case study of the thesis. Nevertheless, to have better access to the information, it is recommended to formally standardised it.

This collection will be expressed in a spreadsheet using the following format, but it can be adapted depending on the available information from the company [**Table 3-1**]:

Table 3-1. Request for Information Format

Request for Information								
#	To	From	Issue date	Requested reply date	Description	Reference	Receiver's reply	Reply date

Source: own elaboration.

Redlines for As-built drawings

To collect the knowledge from the redlines or mark-ups of the project, it is necessary to gather the existing drawings from the site with the annotations that indicate any decision made during the construction that is not properly reflected in the latest version of the drawings. The redline system is done to communicate the updates in the project and to generate the as-built drawings, which are usually part of the handover of the project to the client. The reason for identifying the element involved in this information is because later on, the intention is to store it in an object-oriented schema for BIM use.

To compile this information, it is proposed in this framework to use a spreadsheet with the following format [**Table 3-2**]:

Table 3-2. Redlines Information Format

Redlines Information		
#	Element involved	Description

Source: own elaboration.

B) Verify / Analyse

Obtain Constructability Knowledge

After the collection of the existing procedures (RFIs and Redlines), it is necessary to transform it into Constructability Knowledge. An analysis is needed to go through the obtained information and define it. It is encouraged that this activity is done with a team of experts and balance it with a non-fully expert to not waste any valuable insight. Filtering and checking the information that is going to be stored is the essence of this step. For any clarification about the content of the collected information, the source of knowledge available is encouraged.

Request for Information (RFI) and Redlines

To analyse the obtained information, the following schema is proposed _FIG_. It clearly combines the previous recollection of data into one that will make the user analyse the activities happening between the construction and the design team. The column about reason and classification behind the demand or the change from the original design help with the definition of the constructability knowledge and the lesson learned obtained. The analysis will be shown in a single table with the insights obtained based on the previous collection, the following format is presented [**Table 3-3**]:

Table 3-3. Knowledge from RFIs and Redlines

Knowledge from RFIs and Redlines						
#	Element	Description	Type	Discipline	Reason/ Classification	Constructability Knowledge/ Lesson learned

Source: own elaboration

C) Store

The third step in the framework has to do with the storage of processed knowledge. The intention is to use BIM to integrate the Constructability context.

There are different questions regarding the storage of knowledge, such as:

How to store it?

Where to storage?

Who will do the storage?

When will the storage be done?

The activity of storage is explained in two main processes:

1. The workflow of interaction between the construction and the design team in terms of how the knowledge is transferred into the model.
2. The workflow on how this knowledge will be stored in a database for the designers to query and use it.
3. A third way to store the knowledge will be by creating a checklist that will be integrated into the QA/QC process of the project based on previous projects.

In the framework, the interaction between the two departments starts with the sharing of the issue for construction model; this includes the drawings and specifications needed for the construction phase of the building project. One form of interaction, as expressed before, will be the RFIs which will have the raw content of the knowledge. The issue will be answered as normal by the designer either by just answering the question, updating the model or generating a design instruction with clearer and precise information. This will loop until there is no other question or request or the construction is finish, which will lead the redlines process with the indication of all the updates of the original design. As explained, the information will be added in the as-built model for the handover. Finally, the connection with cross-learning by transferring the knowledge from one project to another [**Figure 3-6**].

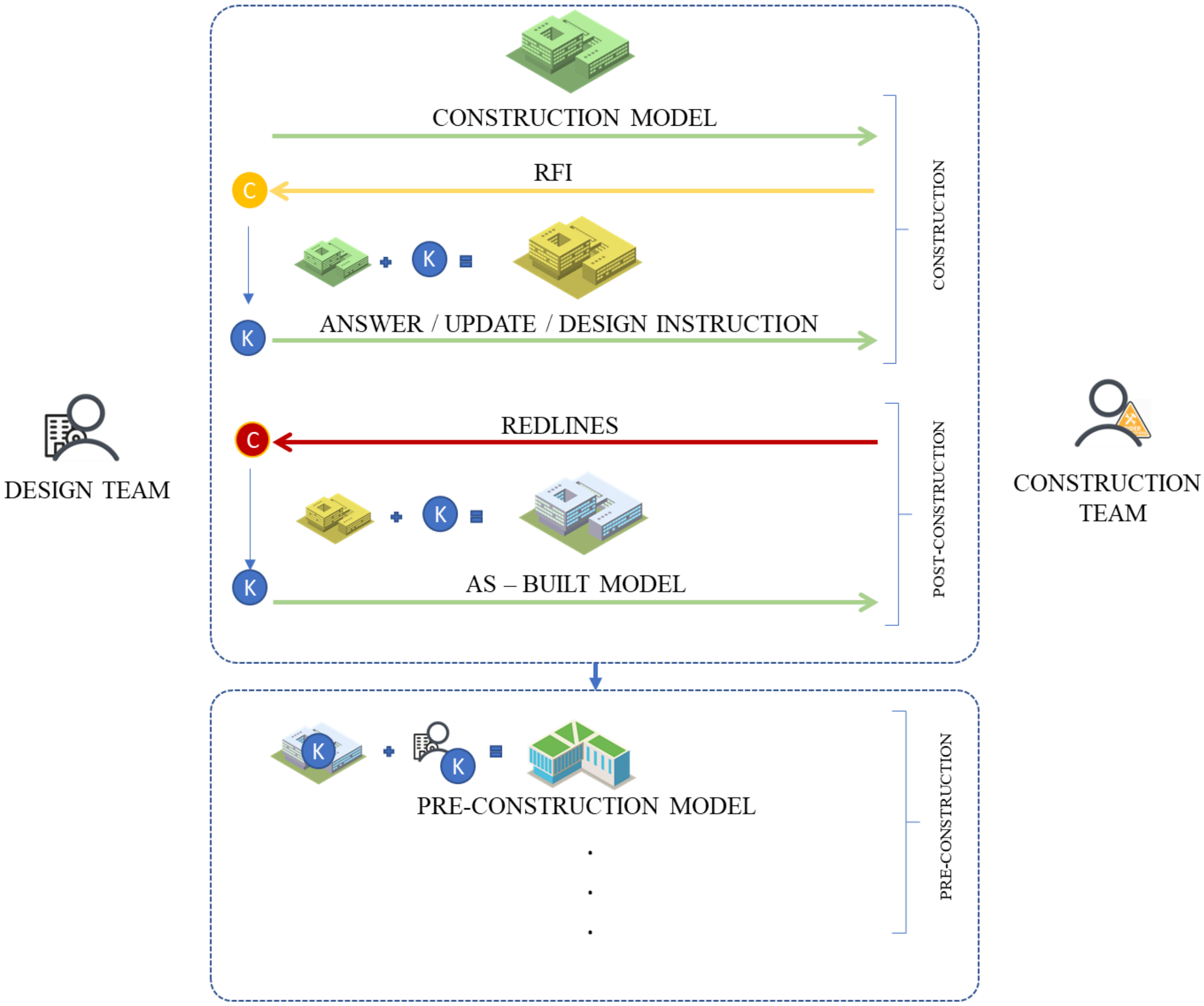


Figure 3-6. Interaction between Construction and Design Team
Source: own elaboration

This interaction will lead to the roles involved in recollecting, verifying, and now storing the knowledge. The construction site experts will open the issues and discussion between the teams, but their main interest will be to solve the problems as soon as possible. The framework proposes to assign the responsibility this context information to the knowledge manager of the project, which will do this as part of its responsibilities either in the middle of the end of the project.

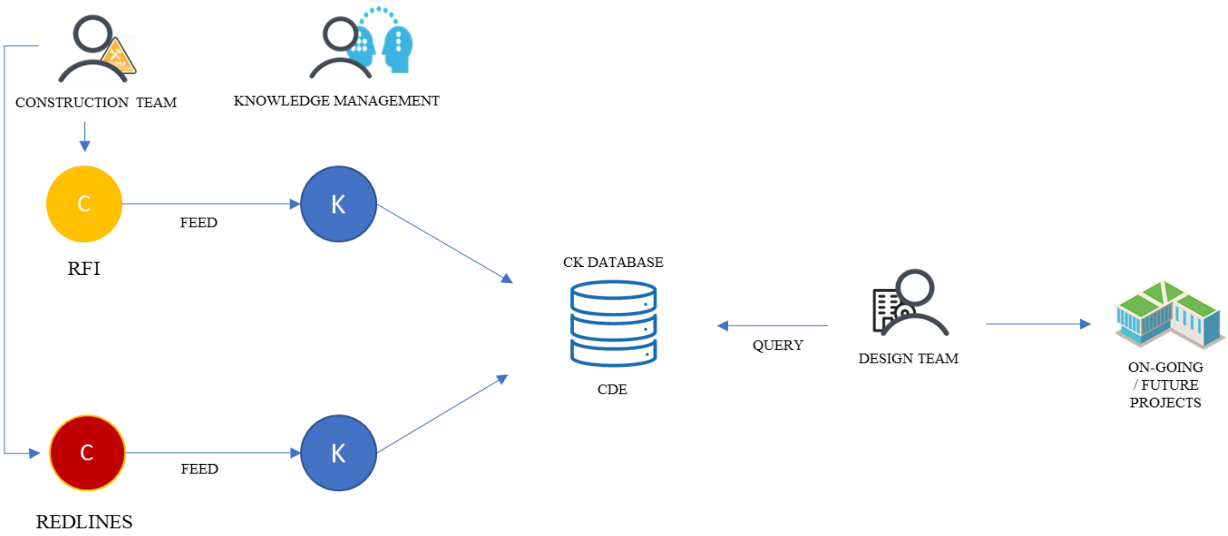


Figure 3-7. Relationship with the Construction Knowledge Database
Source: own elaboration.

The second part of the storage has to do with the creation of a Construction Knowledge Database, relation the projects, the building elements (BIM), the issues that happened during the construction, the reason behind those issues to get the related knowledge. An E-R diagram was developed to give a conceptual model [**Figure 3-8**].

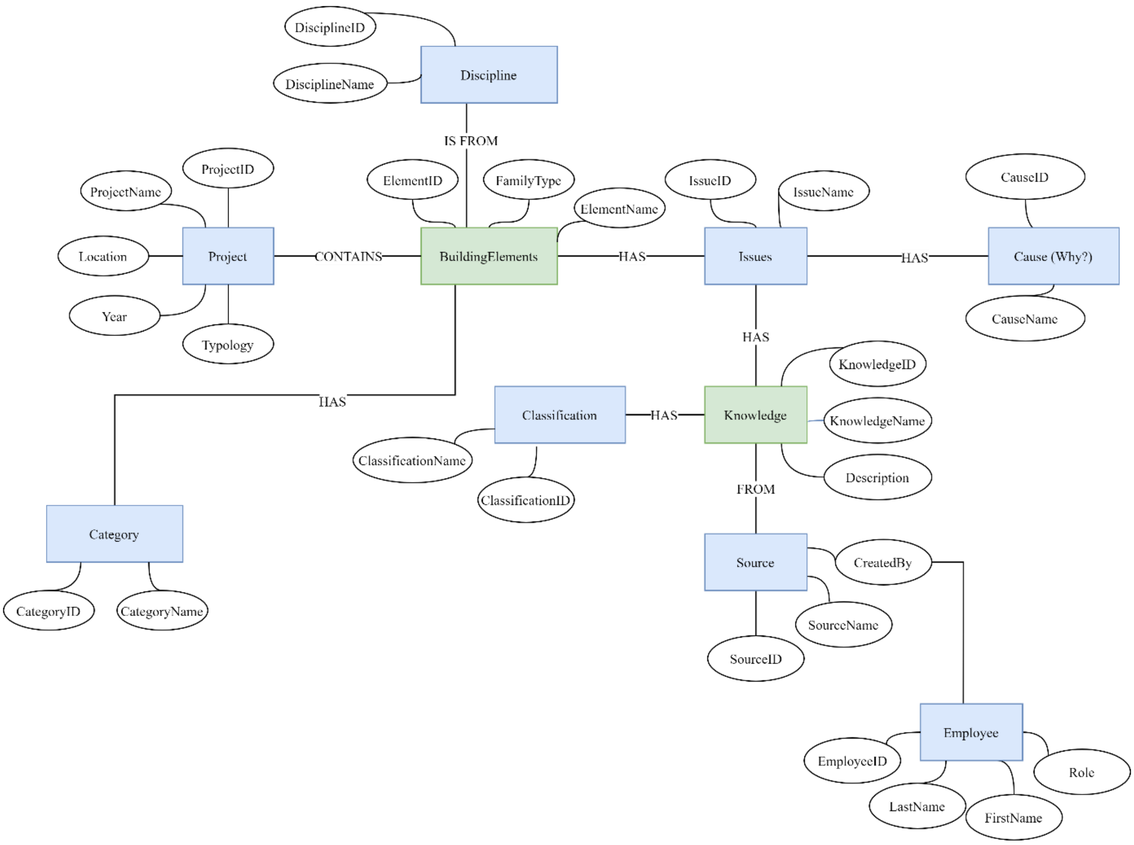


Figure 3-8. E-R diagram.
Source: own elaboration

Which later was transformed into an E-R relational model, selecting the corresponding Primary and Foreign keys involved, as well as the type of data needed to work [**Figure 3-9**].

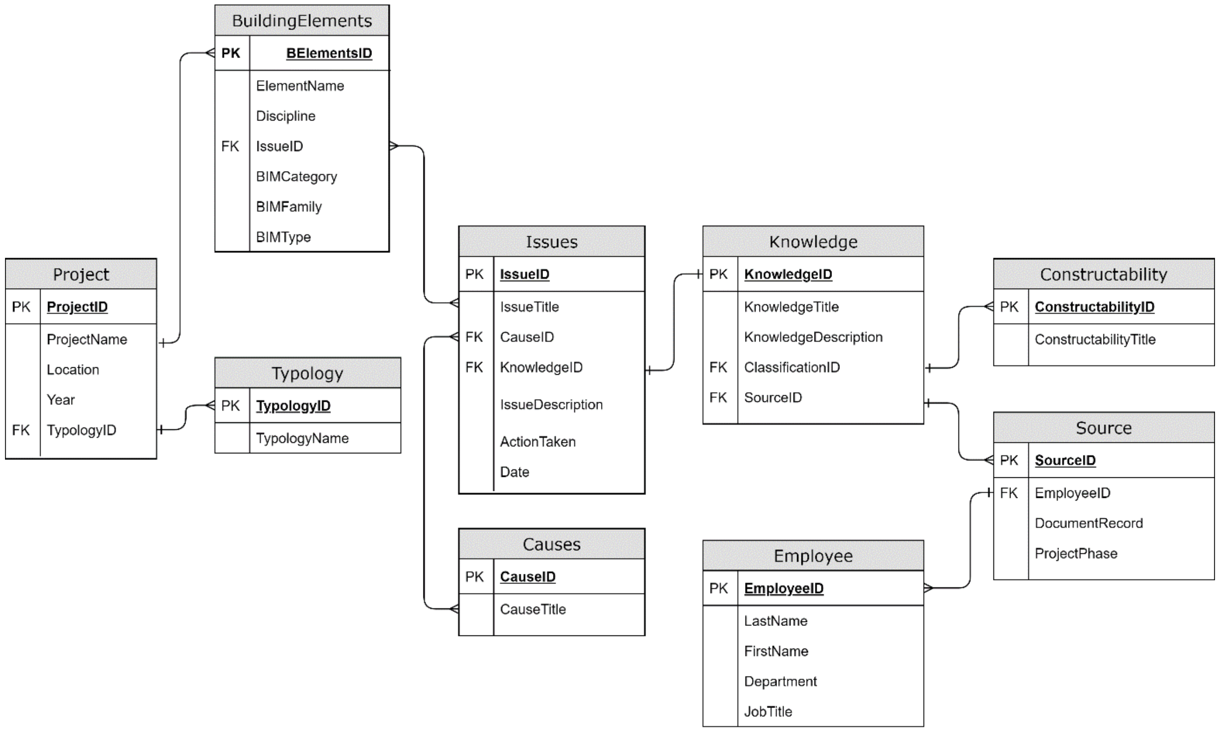


Figure 3-9. E-R Relational model
Source: own elaboration

The last storage option has to do with the availability and transfer of knowledge by using a checklist based on previous experiences in the AEC industry. This will need to be elaborated based on the experience and specifically related to the objective of learning from previous projects.

D) Communicate

All the changes and new knowledge of the company needs to be shared and communicated, all the different knowledge containers analysed in the previous steps will follow the same communication procedure, the difference may rely on who in the company will receive the notification about the updated information and the shared knowledge.

Based on the literature review, ofter if there is no reward system for sharing knowledge it depends on the importance or impact of the acquired knowledge to be shared, this framework, since it is hand-to-hand working while the project is developed and is encouraged to feed the required information adding these procedures to the tasks of the designer and the constructor the shared culture is going to be requested during all the lifecycle of the project.

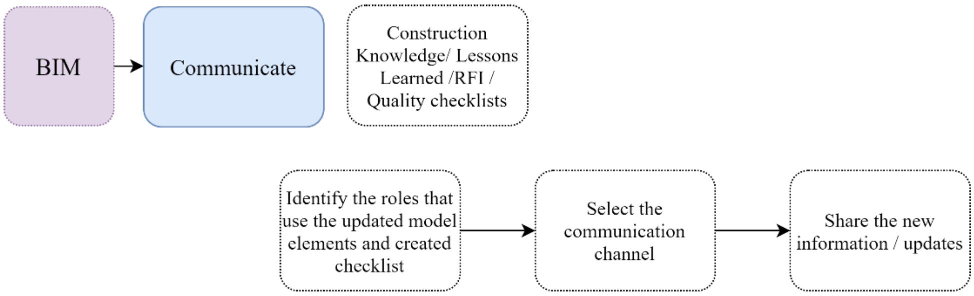


Figure 3-10. Framework: Communicate steps.
Source: own elaboration

1. **Identify the roles involved in the updates**: Identify the roles that will use the updated modelled elements saved in the Constructability Knowledge Database and the QA/QC checklist created in the last project (designers and constructors).
2. **Select communication channel**: This step needs to follow the standard procedures for communicating with the team in each of the departments; it would be different for each company.
3. **Share** the new knowledge and updates using the selected communication channel, share the links to get the access to the Constructability Knowledge Database based on role permissions and the QA/QC checklists on time to apply for the future development of a project.

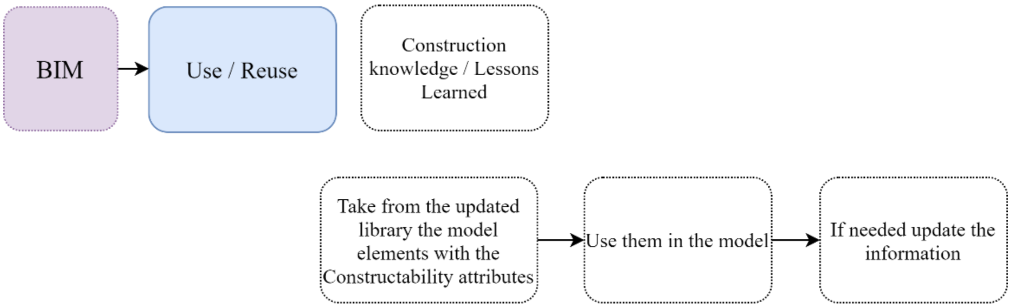
The communication channel has to consider the hierarchy in the company. It will decide the granularity and availability of the information based on the roles and responsibilities of the involved people as well as the security of the gathered information using controlled access based on permissions.

E) Use / Reuse

The last step of the framework has to do with the most powerful step which is related to using and reusing the knowledge acquired from the lessons learned to improve the quality of the company, especially the construction company. This is as well divided into two different workflows, one dedicated to the Construction knowledge and Lessons learned and the second one is the use of the RFI lessons and the Quality checklists that were communicated in the previous steps.

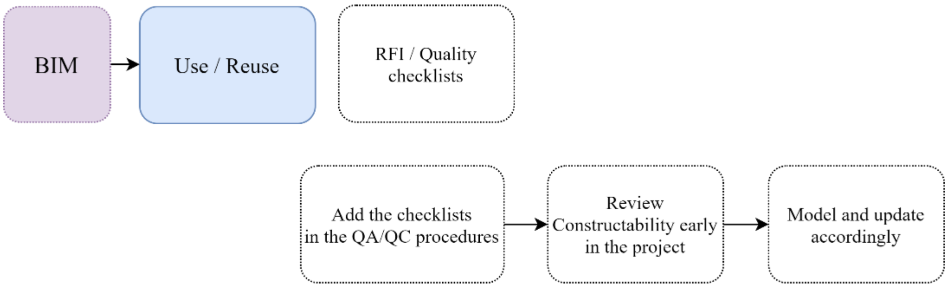
When the knowledge, documented as lessons learned, is utilized in present and future projects, the construction company obtains the efficiency in their work [26].

Use Construction Knowledge and Lessons Learned



1. When there is a new project development, include in the process the review of past projects using the query system of the Constructability Knowledge Database.
2. Train the design team to query in the Database.
3. Use the acquired knowledge in the model.
4. If needed, update the information.

Use RFIs lessons and Quality checklist



1. Add the checklists in the QA/QC procedures
2. Review Constructability early in the project.
3. Model and update accordingly.

F) Framework Loop

The system of the framework creates a loop of experience. It is encouraged to continue the insight of the collected information from one team to the other; even including other knowledge from different departments in the AEC Industry.

3.3 Framework implementation

A plan of implementation is needed for the designed framework in order to incorporate in a design-built company. The following are defined taking into consideration the strategic, tactical, and operational strategies.

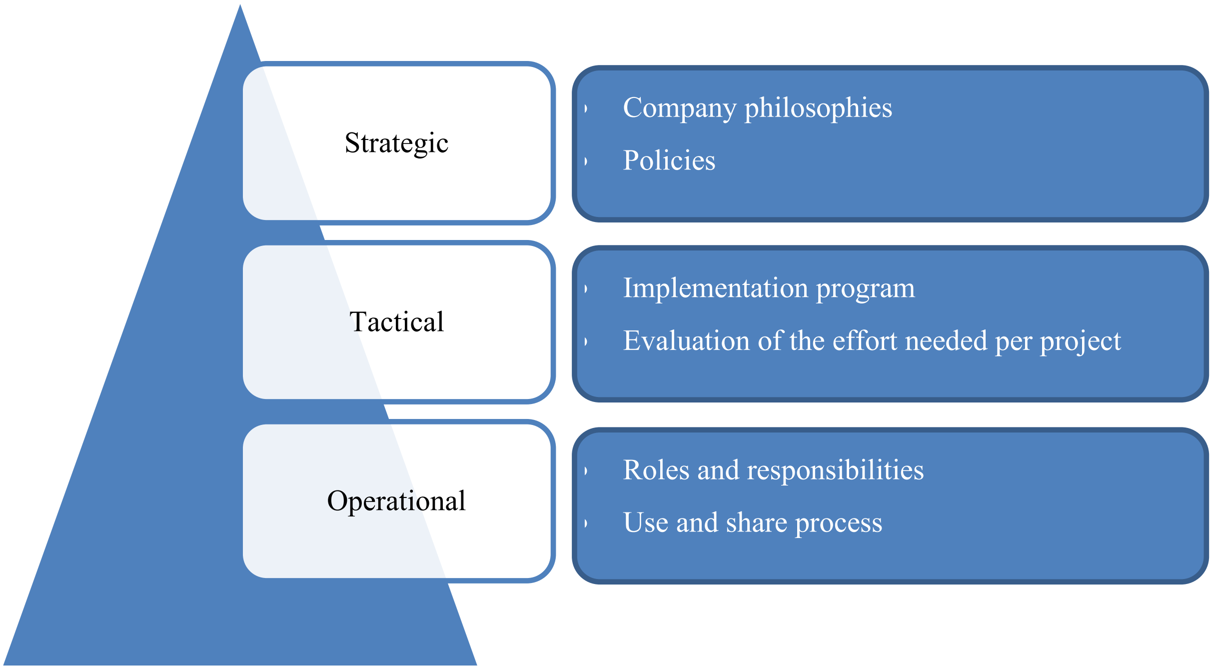


Figure 3-11. Implementation strategies
Source: own elaboration.

A description of the short, medium, and long-term goals according to the strategy:

1. Short-term plan:
    a. Select the pilot project to implement the framework in the company.
    b. Define the roles and responsibilities related to the KM of the company.
        i. Identify the knowledge manager is essential not to overload the existing roles and focus its participation and orchestrate of the framework.
        ii. Identify the key participants of the pilot project from the design and the construction team.
        iii. Define the team of implementation.
    c. Communicate and train according to the activities and tasks related to the framework according to their role and participation in the development of the pilot project.
    d. Promote and reward the use and share procedures based on the implementation program in the pilot project.

2. Medium-term plan:
    a. Define the Implementation program.
    b. Define the reviewing process, including the frequency, key performance indicators based on the finding of the pilot project.
    c. Evaluate the effort according to the project and team participation.
    d. Define the system to identify for other projects its implementation.
    e. Adjust, if needed, the framework with the findings of the pilot project.
    f. Communicate and train the rest of the company (not just those involved in the pilot project).
    g. Promote and reward the use and sharing of knowledge procedures based on the implementation of the framework in their daily activities.
    h. Communicate the improvements the company had based on the use of the framework.

3. Long-term plan:
    a. Define the needed policies related to those involved in the framework, such as constructability, knowledge management, and quality improvement.
    b. Align the strategy based on the company's philosophies and plan of quality improvement.
    c. Evaluate the benefits of the framework implementation, and adjust, if needed.

Three key aspects need to be taken into account for the implementation:

1. Involvement and understanding
2. Integration and collaboration
3. Commitment and engagement

The applicability of the framework is related to the considerations taken by Kivrak *et al*. [60] when defining those related to Knowledge Management (KM):

1. Cost: That the application of the framework does not imply additional cost.
2. Workload: That the implementation does not increase the workload of the participants.
3. Legal: That its application considers the contract clauses and conditions as well as ownership of the project.
4. Standardisation: When the application must follow the same format for representing the knowledge in order to use it systematically.

4 CASE STUDY

The purpose of the thesis and the application of the framework is to not only increase the quality of its outcomes but to take advantage and value from the knowledge the company has acquired over all these years in the industry by intentionally integrating the knowledge in their process.

The first part of the case study explains the company involved, the project selected to apply the designed framework, and the software selected. The second section of the case study is the application of the framework in each of its steps and activities, as explained in the previous chapter.

4.1 Company

"*Experience Matters"* [61].

Hermosillo is a design-build company from Mexico. It is a company that is in the construction industry for more than 55 years delivering world-class construction and making many lasting relationships along the way. Hermosillo is an industry leader trusted for those seeking quality, innovation and reliability when building in Mexico. The organization has locations throughout Mexico, represented with regional offices located in Mexicali (open 1963), Tijuana (1991), Monterrey (2001), Mexico City (2005), and Guanajuato (2016).

"A general contractor that reliably delivers on time and on budget. That takes experience, and we bring Industry, category, and process knowledge to the table like no other firm in Mexico (…) We know the unique intricacies of building in Mexico and the international ways our clients like to do business. Our experience has taught us that every aspect of our business must be exceptional – our communications, our project management, our safety, our adoption of technology and most importantly, our respect for others. It all comes down to experience." [61] Hermosillo has invested in technology and innovative methodology of work for years, they follow a VDC program with successful practices that achieve high-quality standards in complex projects.

4.2 Case study

The project

For the selection of the case study, a model registry in the company was created [

Figure 4-1].

General Project Information								Model by Time			Model by Technology		Model by development				Model metrics	
ID	ProjectID	ProjectStage	ProjectType	ProjectTypology	Area (m2)	Year	BIM Use	StartDate	EndDate	Duration	Software used	Software Version	Model Authorship	ProjectLOD	Disciplines Modelled	NumberOf Models (linked)	OriginalModel file size (KB)	Modelled Elements
1	016DE	Construction	New Construction	Heavy Automovile plant	35,667.00	2015	ModelOnSite, 2D documentation	5/1/2015	10/01/2017	2 y	Revit, Navisworks	2015	Single Team (HMO)	300	A, S, C, M, E, F, H	26	195,216.00	625
2	014DF	Tendering	Expansion	Automovile plant	9,033.61	2016	2D documentation	3/5/2016	21/5/2016	18 d	Revit	2015	Single Team (HMO)	200	A, S, X	3	45,100.00	621
3	020DF	Tendering	New Construction	Plastic plant	6,397.02	2016	2D documentation	5/7/2016	25/8/2016	1 m 20 d	Revit	2016	Single Team (HMO)	200	A, S, B	1	87,380.00	2893
4	021DF	Tendering	Renovation	Residency	28.50	2016	2D documentation, Render	21/8/2016	25/8/2016	4 d	Revit	2016	Single Team (HMO)	300	A, S	1	23,728.00	235
5	022DF	Tendering	Expansion	Sanitary Industry Plant	31,421.20	2016	2D documentation, Render, Video, Presentation, Structural foundation QTO	12/9/2016	22/11/2016	2 m 10 d	Revit	2016	Single Team (HMO)	200	A, S, C	2	177,100.00	8390
6	023DF	Tendering + Construction	Renovation	Sanitary Industry Plant	5,172.86	2016	2D documentation, 3D design reviews, specification schedules	3/10/2016	8/5/2018	1 y 7 m	Revit	2016	Multiple Teams (HMO + Subs)	300	A, S, M, E, F, H, C			
7	031DF	Tendering	Expansion	Industrial Construction	798.12	2016	2D documentation, specification schedules	23/11/2016	19/12/2016	1 m	Revit	2016	Single Team (HMO)	200	A, C, H, S	1	28,608.00	615
8	032DF	Tendering	New Construction	Hospitality	11,730.00	2016	2D documentation, QTO, Specifications	19/12/2016	20/1/2017	1 m	Revit	2016	Single Team (HMO)	200	A, S	8	842,140.00	1373
9	002DG	Tendering	Expansion	Pigments industry	36,350.00	2017	3D view - PDF presentation	09/04/2017	22/04/2017	13 d	Revit	2016	Single Team (HMO)	200	A, S	5	393,280.00	1425
10	004DG	Tendering	New Construction	Metal components plant	4,095.00	2017	2D documentation, design options,	28/06/2017	14/09/2017	2 m	Revit	2016	Single Team (HMO)		A, S, C	3	145,136.00	
11	007DG	Tendering	New Construction	Retail Warehouse	9,998.70	2017	2D documentation	27/01/2017	07/02/2017	10 d	Revit	2016	Single Team (HMO)	200	A	1	25,636.00	862

Figure 4-1. Model Registry
Source: own elaboration.

General Project Information								Model by Time			Model by Technology		Model by development				Model metrics	
ID	ProjectID	ProjectStage	ProjectType	ProjectTypology	Area (m2)	Year	BIM Use	StartDate	EndDate	Duration	Software used	Software Version	Model Authorship	ProjectLOD	Disciplines Modelled	NumberOf Models (linked)	OriginalModel file size (KB)	Modelled Elements
1	016DE	Construction	New Construction	Heavy Automovile plant	35,667.00	2015	ModelOnSite, 2D documentation	5/1/2015	10/01/2017	2 y	Revit, Navisworks	2015	Single Team (HMO)	300	A, S, C, M, E, F, H	26	195,216.00	625
2	014DF	Tendering	Expansion	Automovile plant	9,033.61	2016	2D documentation	3/5/2016	21/5/2016	18 d	Revit	2015	Single Team (HMO)	200	A, S, X	3	45,100.00	621
3	020DF	Tendering	New Construction	Plastic plant	6,397.02	2016	2D documentation	5/7/2016	25/8/2016	1 m 20 d	Revit	2016	Single Team (HMO)	200	A, S, B	1	87,380.00	2893
4	021DF	Tendering	Renovation	Residency	28.50	2016	2D documentation, Render	21/8/2016	25/8/2016	4 d	Revit	2016	Single Team (HMO)	300	A, S	1	23,728.00	235
5	022DF	Tendering	Expansion	Sanitary Industry Plant	31,421.20	2016	2D documentation, Render, Video, Presentation, Structural foundation QTO	12/9/2016	22/11/2016	2 m 10 d	Revit	2016	Single Team (HMO)	200	A, S, C	2	177,100.00	8390
6	023DF	Tendering + Construction	Renovation	Sanitary Industry Plant	5,172.86	2016	2D documentation, 3D design reviews, specification schedules	3/10/2016	8/5/2018	1 y 7 m	Revit	2016	Multiple Teams (HMO + Subs)	300	A, S, M, E, F, H, C			
7	031DF	Tendering	Expansion	Industrial Construction	798.12	2016	2D documentation, specification schedules	23/11/2016	19/12/2016	1 m	Revit	2016	Single Team (HMO)	200	A, C, H, S	1	28,608.00	615
8	032DF	Tendering	New Construction	Hospitality	11,730.00	2016	2D documentation, QTO, Specifications	19/12/2016	20/1/2017	1 m	Revit	2016	Single Team (HMO)	200	A, S	8	842,140.00	1373
9	002DG	Tendering	Expansion	Pigments industry	36,350.00	2017	3D view - PDF presentation	09/04/2017	22/04/2017	13 d	Revit	2016	Single Team (HMO)	200	A, S	5	393,280.00	1425
10	004DG	Tendering	New Construction	Metal components plant	4,095.00	2017	2D documentation, design options,	28/06/2017	14/09/2017	2 m	Revit	2016	Single Team (HMO)		A, S, C	3	145,136.00	
11	007DG	Tendering	New Construction	Retail Warehouse	9,998.70	2017	2D documentation	27/01/2017	07/02/2017	10 d	Revit	2016	Single Team (HMO)	200	A	1	25,636.00	862

Figure 4-2. Model Registry Selected project.
Source: own elaboration

From the list, it was selected a project from 2016, named 023DF [**Figure 4-3**]:

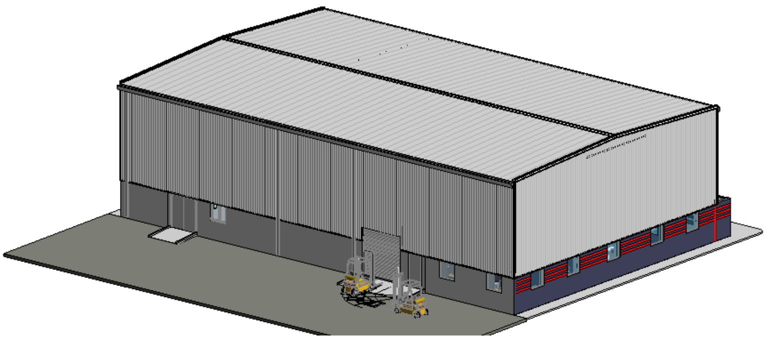


Figure 4-3. 3D Model of the selected project.
Source: own elaboration from company

The building was part of a facilities improvement project of a sanitary industry plant located at the north of Mexico. The building covers a total area of 871.35 sq. m with a built area of 620.00 sq. m with a clear height of 7.16 m to accommodate a switchyard, access ramp, warehouse office, spare parts warehouse, maintenance workspace, administrative offices, and two mezzanines for engines warehouse.

The construction project includes:

- Earthwork and civil work for the building and the switchyard pavement area.
- Foundations for the steel structure and load-bearing walls.
- Steel structure and load-bearing walls with steel deck mezzanines and their access steel stairs.
- Metal sheet walls and roof system with exterior gutters and downspouts.
- Interior and exterior finishes for the warehouse.
- Equipped with the installations:
    - Underground Compressed air system
    - Recycled Water and Wastewater system
    - Electrical system
    - Voice and data preparation
    - HVAC system
    - Fire protection system

In terms of BIM, the project was developed using Revit 2016 for 2D documentation, 3D design reviews, specification schedules, it was modelled elements from the disciplines of architecture, structural, mechanical, HVAC, and civil, in general, the LOD of the federated model is 300.

Even though the documentation and design reviews were made using BIM methodology, at the moment of the development of the design, construction, and post-construction the communication between the design and the construction team of the design-build company has made using an internal sharing platform, uploading AutoCad and PDF drawings; therefore every communication was not using the benefits of BIM on-site.

The applied framework

The framework follows the same schema as the one explained in the previous chapter. This chapter is structured following the proposed process [**Figure 4-4**].

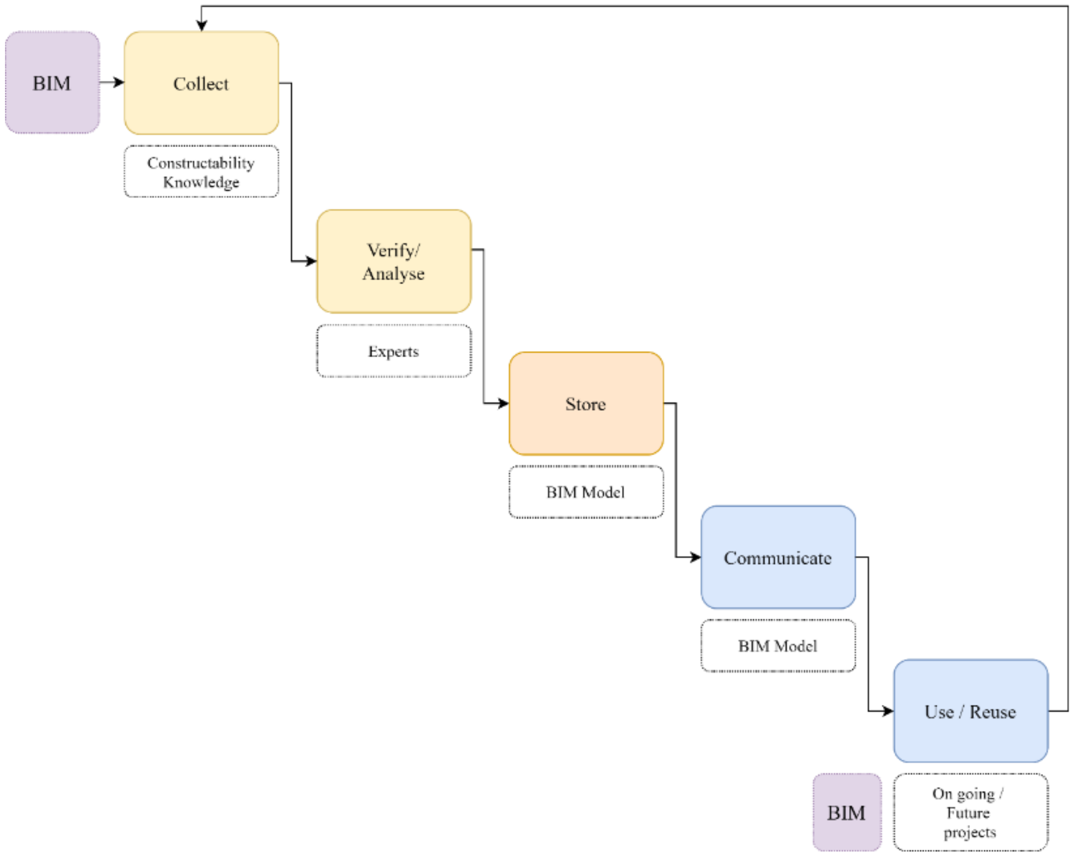


Figure 4-4. BIM procedure based on Lessons Learned.
Source: own elaboration

The software - platform

For doing the case study, mainly two different platforms are used for the purpose of applying the proposed framework. It is intended to analyse if the software selected will help in pursuing the expected results, and analysis in regards to it will happen in the chapter of findings and discussions.

For the authoring software, Revit from Autodesk version 2021 in a student version was selected, following the same authoring software of the selected project. It will need to take into account the update of the version of the model.

For the CDE platform, Dalux is the selected environment to test the intended cross-learning experience from the site to the office teams in the framework.

Dalux is a user-friendly platform created in 2005 in Copenhagen with projects in more than 115 countries [62]. The platform has four different modules which include: Dalux BIM Viewer, Dalux Box, Dalux Field, and DaluxFM working both in desktop and mobile devices to make it accessible for their clients to access and connect in a single source of information.

4.3 Framework

A) Collect

The first step of the framework has to do with the collection of the knowledge, following the schema, there are two sources of knowledge to extract the data, the first one is from the Request for Information (RFI) procedures and the second one if from the Redlines process.

The record of these two processes is available in the selected project to do the case study.

Request for Information (RFI)

Hermosillo follows a formal communication system between the construction site and the design office, as explain, both teams belong to the same design-built company.

The development process in the Hermosillo is as follows:

1. Once the project is awarded, the design team starts with the development of the project taking the basic engineering design (BED) model and drawings (developed during the tendering stage) with the requirements and specifications of the client.
2. According to the project schedule, the design team releases drawings for approval to the client, and once they are approved, they issue them for construction.
3. Once the construction project starts any request from the construction team will come either by e-mail format or by using an RFI format to communicate with the design team.

The case study has a number of RFI that happened during the execution of the project back in 2017. As mentioned before, this request between departments is made either with an RFI format or by e-mail; for the purpose of the case, only the formal RFI through the use of the standardised format is collected.

The RFIs are stored in the internal servers of the company in a folder that contains the individual formats of the RFI, but it does not follow a list of them. The creation of the list of RFI with the information containing in the formal during this step is required.

Following the framework, it was created a list with the different information from the RFI format in order to analyse it in the next step [**Figure 4-5**].

General Project Information								
#	To	From	Issue date	Requested reply date	Description	Reference	Receiver's reply	Reply date
1	Design	Project Manager	19/09/17	21/09/17	The drawing MH-101 indicate the evaporators are installed over the windows, please confirm.	NH-101	The evaporators are installed over the windows as requested from the client	21/09/17
2	Design	Site Supervisor	26/09/17	27/09/17	The drawing A-106 the bollards does not indicate the deep of its foundation. Please do a section detail	A-106	Send detail of embelled bollard and an anchored alternative, the construction decision will be shown in the redlines and as built drawings	27/09/17
3	Design	Site Supervisor	26/07/17	28/09/17	The drawing A-104 wall types plan the wall B' goes from 1 to 4' and indicate is a apparent finish wall block with vynil paint and metal sheet with fiber insulation wall. Please give details of the purlins, connections, and metal sheet location, the fiber will be exposed?	A-104	The detail is in the structural drawing S-19. Wall B' elevation.	27/09/17
4	Design	Document Controller	27/09/17	29/09/17	According to the last published document list in the server 29 drawings are pending of approval and 19 drawing approved for construction that have not sent or available to construction site. We need a commitment date of submission and/or status of each of the 48 drawings.	KFI-GNR-LM-07	Annexed you will find the updated status of the document list. Two different status: Deliver to site, and pending of approval by client	27/09/17
5	Design	Project Manager	04/10/17	05/10/17	The south window of the warehouse office diverge between the drawing A-101 and A-105 one indicates the window is type W-04 and the other is W-01. Please review and fix drawings.	A-101 / A-105	The mentioned window is W-01. The drawing will be fixed accordingly.	05/10/17
6	Design	Site Supervisor	05/10/17	09/10/17	Please specify what is the height of the cyclonic fence as well as the technical specifications for the procurement request.	A-301	Annexed the drawing ID-09 interior chain link fence.	5/10/17
7	Design	Project Manager	10/10/17	11/10/17	The drawing S20 indicates a schema of the concrete curb without measurements and location. It is needed a well defined plan with the location of the curb as well as a detail of the element. Keep in mind the concrete specification and that it is available on site.	S-20	Annex the drawing ID with the location and detail of the concrete curb.	11/10/17
8	Design	General Project Manager	11/10/17	12/10/17	The contract clarifications indicate a note that the system is according to the drawings in folder 3.	Construction Agreement	Annexed the linked to the folder.	12/10/17
9	Design	General Project Manager	11/10/12	12/10/17	The contract clarifications indicate that the supply of the pump in the drawing MWB-DP200 EGC is out of scope. Please send the drawing.	Construction Agreement	Annexed the drawing in the previous sent folder.	12/10/17
10	Design	General Project Manager	11/10/17	12/10/17	A list of 21 drawing as exhibit C in the contract and another drawing list of 74 drawings, which one is the one based for the contract?	Construction Agreement	Exhibit C list is the project manual and the Exhibit F is the preliminary project site drawings for the project.	12/10/17
11	Design	General Project Manager	12/10/17	13/10/17	The drawing A-102 roof plan indicates 4 downspouts but are not located symetrically therefore they capture different volumes of rain water. Confirm design. does the gutters considered overflows?	A-102, A-506, C-110	The are considered for each downspout is 150.30 sq. m. ID-011 is annexed.	13/10/17
12	Design	Project Manager	16/10/17	17/10/17	Please indicate the swing direction of the window type W-04. The floor plan does not indicate it	A-101	The windows open to the inside.	18/10/17
13	Design	Project Manager	16/10/17	17/10/17	Please define the measurements of the ramps and the swiftyard. The drawing C-105 has one measurement but the drawing S-20 has another one, one considers that the ramp includes the personnel door entry and the other one does not.	C-105, S-20	A revision and update of the drawing S-20 is being made.	18/10/17
14	Design	General Project Manager	18/10/17	18/10/17	The drawing MH-101 specify mini-splits without heating but the sub-contractor has the following specifications that includes them.	MH-101	Both equipment are cooling and heating, the difference in the nomenclature is the availability in the market. The equipment sent are less noisy, capacity is really similar, energetic efficiency and performance vary slightly. In conclusion, there is no inconvenient to installed the suggested equipment.	20/10/17

Figure 4-5. RFI form case study sample
Source: own elaboration

Redlines for As-built drawings

For the collection of the redlines in the project, the company used a printed version of the project's drawings and marked with a red pen the changes the project suffer during the construction; with this information, the design office receives a scanned copy of the drawings and makes the necessary changes to the model and to the drawings [**Figure 4-6**].

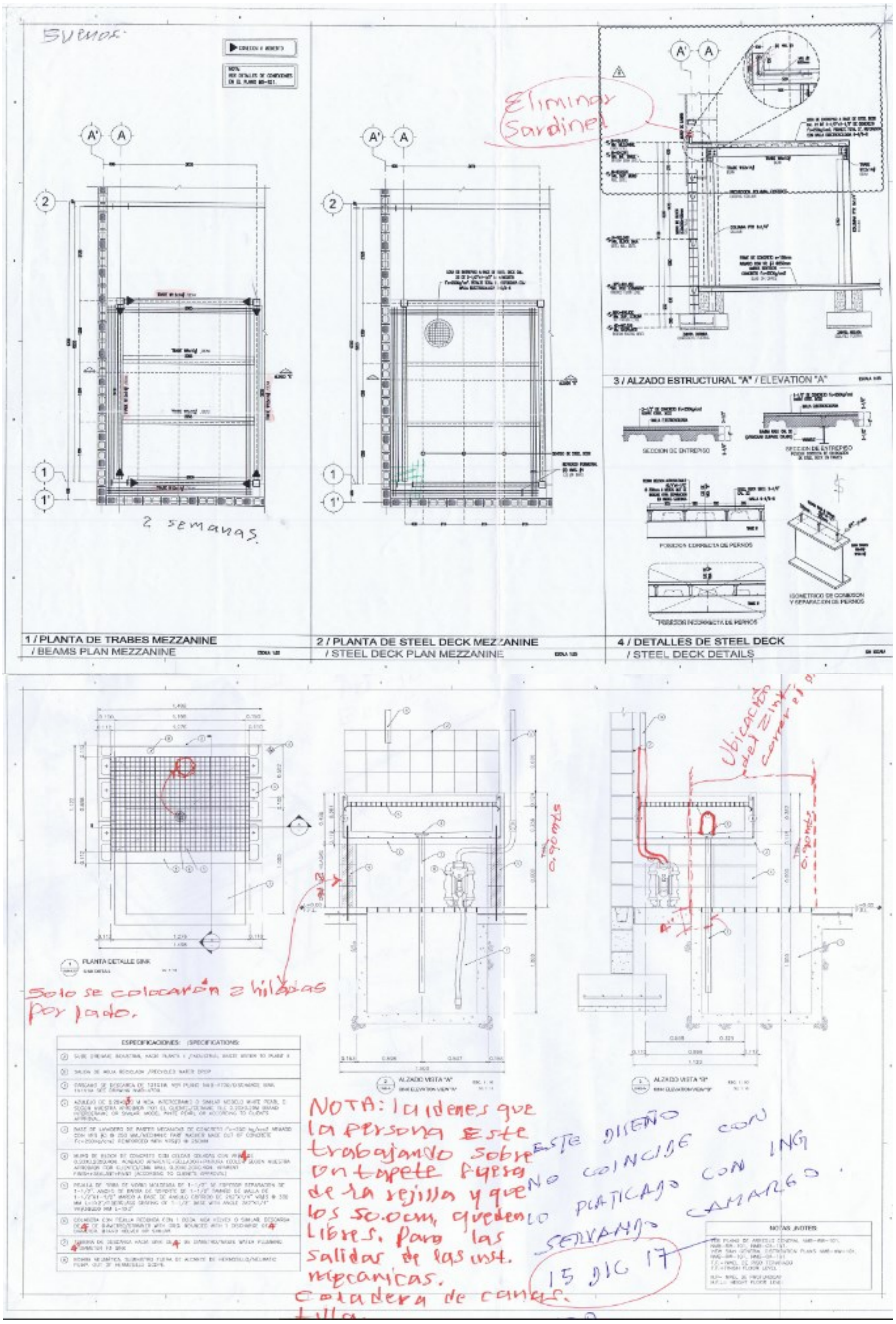


Figure 4-6. Scanned Redlines of Case Study
Source: own elaboration from Hermosillo documents

In the case study records, it did not exist any other form where the red lines were expressed in a table; therefore, after reviewing the drawings, a schedule was created with the information needed in regards of Constructability [**Figure 4-7**].

Redlines Knowledge							
#	**Element**	**Description**	**Why**	**LL**	**Drawing Reference**	**Discipline**	**Action**
1	Handrail	The mesh fence in the second mezzanine changed to removible handrail.	Client?	Understand client needs	A-101	Architecture	Change
2	Drywall / Windows	The position of the drywall agaist the window frame changed according to drawing details.	Constructability ?	The drywall goes below the window frame level. It was like this in the top connection but in the bottom one did not followed the same procedure.	A-507	Architecture	Move
3	Grounding system	The position of the grounding line system changed position according to drawing plan.	Less material?	-The grounding system instead of being far from the building it was installed close to the block wall. -The grounding can be in the sidewalk, the drawing reflected the position after the sidewalk.	E-200	Electrical	Move
4	Metal stud	The spec of the metal stud changed	Availability? or wrong description?	-The metal stud changed from 6" to 3-5/8"	A-105	Architecture	Change
5	Concrete curb	The concrete curb in the second mezzanine was eliminated	Extra design	- It is not clear why the elimination, maybe it was not needed like the other mezzanine did not have the detailed.	S-21	Structure	Eliminate
6	Stair plate	Addition of two kwik bolt 3/4" diam. L=5 1/2" on each exterior side of the plate instead of the slab extension detail.	Costructability ? Time /Cost	- When the slab is already done, the extension of the slab it needs more time and effort, therefore the kwik bolts solution is better.	S-23	Structure	Add
7	Stair foundation	The slab extension of the stair foundation was eliminated.	Costructability ? Time /Cost	- The stair was added later in the construction, demolishing the are for doing the stair foundation was more time and cost, the system changed to a kwik anchor.	S-23	Structure	Eliminate
8	Wall	The position of the wall moved.	Constructability ? Simplify	The position of the wall moved to simplify the detail of the wall and hide the structure using the same level and not creating a step in the wall.	A-203	Architecture	Move
9	Window	The height of the window changed to 1.20 m instead of 1.14 m	Drawing mistake?	The windows had the same height but the drawing reflected a different height?	A-203	Architecture	Change
10	Wall	The nomenclature for the wall changed from M6 to M3	Double info	It was created a different wall type M6 but it already existed as M3.	A-203	Architecture	Change
11	Wall	The nomenclature for the wall changed from M6 to M3	Double info	It was created a different wall type M6 but it already existed as M3.	A-108	Architecture	Change
12	Wall	The position of the wall moved.	Constructability ? Simplify	The position of the wall moved to simplify the detail of the wall and hide the structure using the same level and not creating a step in the wall.	A-108	Architecture	Move
13	Column	Detail to hide the column added	Missing design?	To hide the steel columns in the office a detailed was added	A-108	Architecture	Add
14	Molding	A plate was added of 3"x3"x1/4" h=1.22 m	?	?	A-108	Architecture	Add
15	Metal stud	Change in the spec of the metal stud from 1-5/8" to 2-1/2"	Availability? or wrong description?	?	A-108	Architecture	Change

Figure 4-7. Redlines registry
Source: own elaboration from Hermosillo recorded documents.

Collecting with Dalux

After the collection using a schedule, from the digital pdf or scanned image of both the RFI and the Redlines recorded documents it is proposed to use a digital platform to transform this in an active data, as well as the purpose of connecting it to the 3D model and BIM using the selected platform of Dalux.

Project Set up

Once the project is created in Dalux, it is necessary to set the information that will be contained in the project. In this case, from the Revit model, it was created the IFC model. For this project, there were two different models that will be federated using the platform. In this case, the breakdown of the project was by discipline: One model contains the architecture, and the second model contains the structure. The first model contained some elements from MEP discipline in a schematic form.

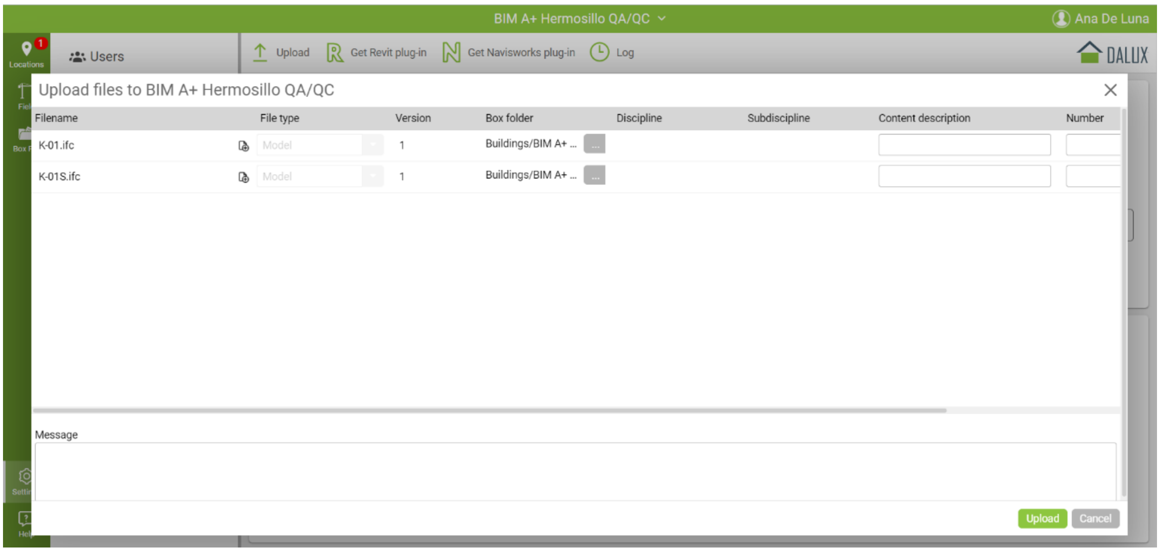


Figure 4-8. Dalux upload process.
Source: own elaboration using Dalux

Figure 4-9. Dalux location view
Source: own elaboration using Dalux

Work packages

The second step in Dalux is to create the work packages that will contain the workflow related to the discipline; it will generate the interaction in the platform between the stakeholders included in this CDE. For the case study, it was created five different work packages: Civil works, Architecture, Structure, MEP, and Management. It was also created different accounts that represented the Design team and the Construction team [**Figure 4-10**].

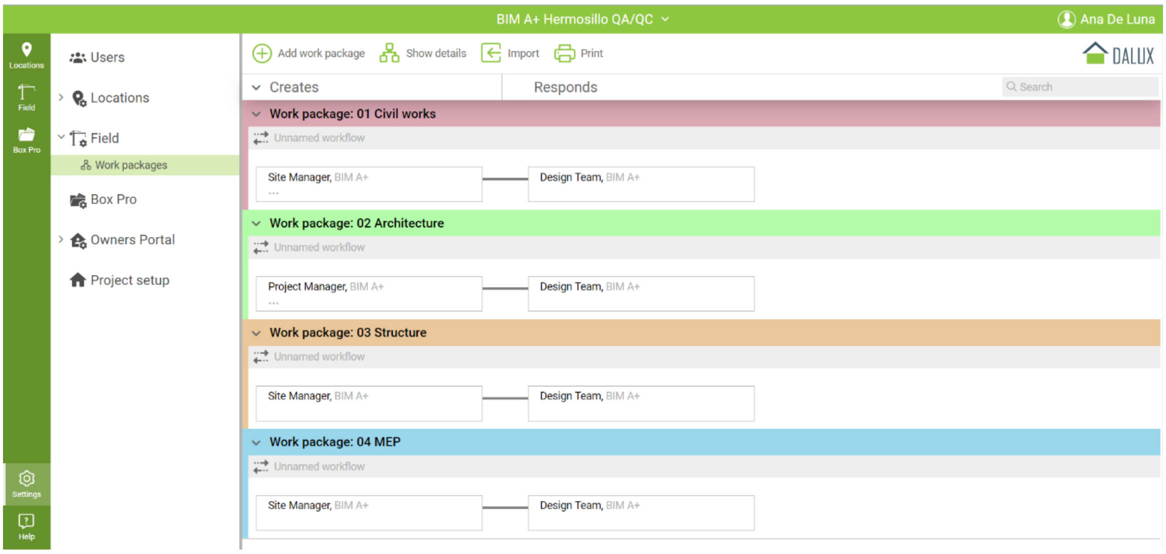


Figure 4-10. Dalux work package process.
Source: own elaboration using Dalux

RFI - Task

The third step regarding the use of Dalux for performing the RFIs of the project is creating Tasks. This is a tool in the platform where the user is able to customize an activity, for this case, the RFI [**Figure 4-11**].

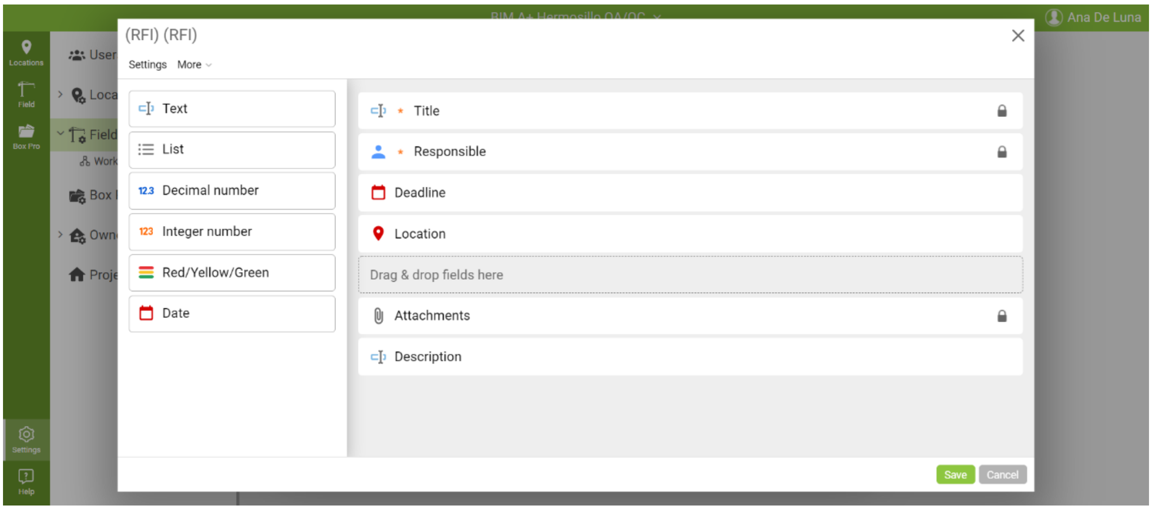


Figure 4-11. RFI Task in Dalux
Source: own elaboration using Dalux

RFI - Assign to object

As explained, the RFI system used for the project was more paper-based in a digital form-based, the use of a CDE or BIM on-site software was not used, therefore to do this step for the post-construction analysis is needed. After creating the task of RFI, the need to upload the drawings to the system was required and based on the drawings, a series of RFI was linked in the project [**Figure 4-12**].

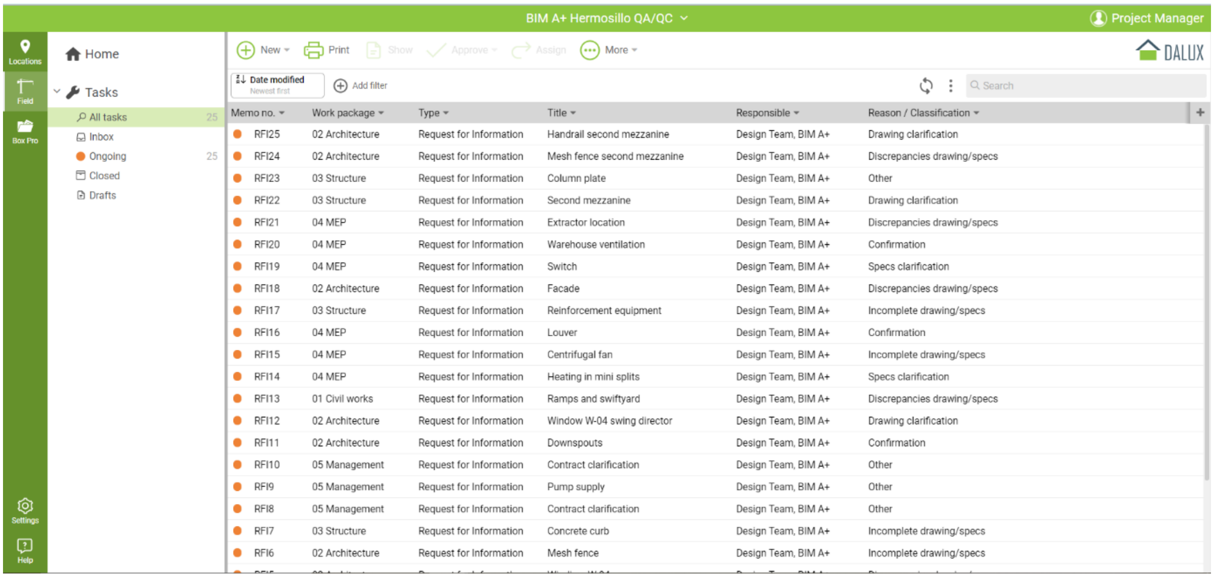


Figure 4-12. RFI Tasks of the project
Source: own elaboration using Dalux

Each of the tasks can be linked either to the drawing or the 3D view of the IFC model [**Figure 4-13**].

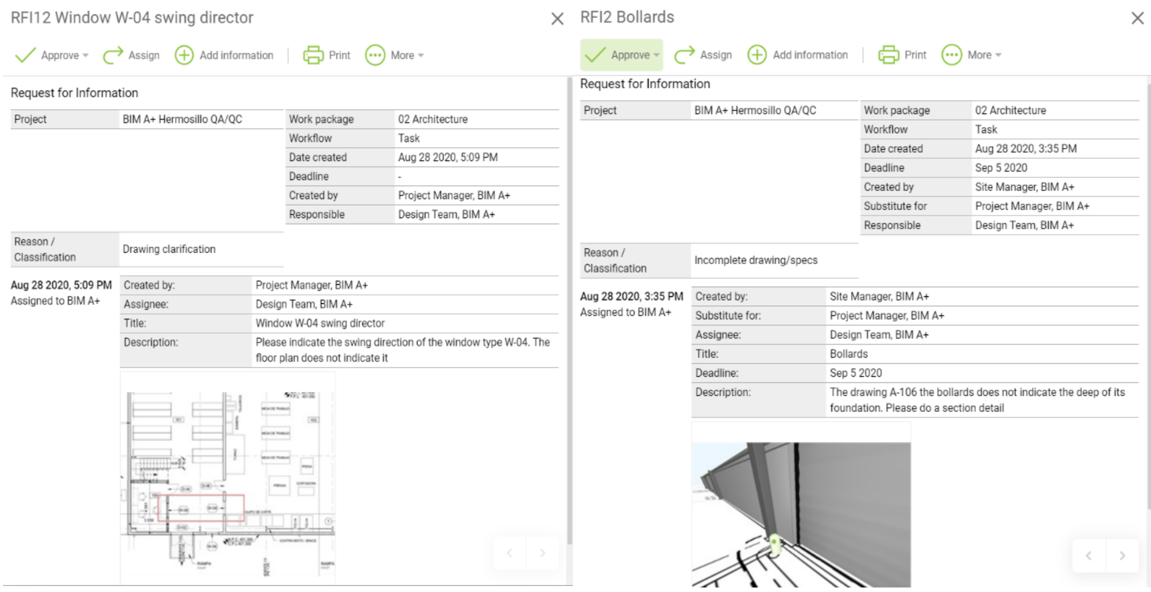


Figure 4-13. RFI window using Dalux.
Source: own elaboration using Dalux

RFI - Export collection

The collection of the RFI will stay in the platform, but it can also be export to a different format, for example, in Excel. The information that is going to be to export can be customizable [**Table 4-1**].

Table 4-1. RFI collection from Dalux

Memo no.	Work package	Type	Title	Responsible
RFI25	02 Architecture	RFI	Handrail second mezzanine	Design Team, BIM A+
RFI24	02 Architecture	RFI	Mesh fence second mezzanine	Design Team, BIM A+
RFI23	03 Structure	RFI	Column plate	Design Team, BIM A+
RFI22	03 Structure	RFI	Second mezzanine	Design Team, BIM A+
RFI21	04 MEP	RFI	Extractor location	Design Team, BIM A+
RFI20	04 MEP	RFI	Warehouse ventilation	Design Team, BIM A+
RFI19	04 MEP	RFI	Switch	Design Team, BIM A+
RFI18	02 Architecture	RFI	Facade	Design Team, BIM A+
RFI17	03 Structure	RFI	Reinforcement equipment	Design Team, BIM A+
RFI16	04 MEP	RFI	Louver	Design Team, BIM A+
RFI15	04 MEP	RFI	Centrifugal fan	Design Team, BIM A+
RFI14	04 MEP	RFI	Heating in mini splits	Design Team, BIM A+
RFI13	01 Civil works	RFI	Ramps and swiftyard	Design Team, BIM A+
RFI12	02 Architecture	RFI	Window W-04 swing director	Design Team, BIM A+
RFI11	02 Architecture	RFI	Downspouts	Design Team, BIM A+
RFI10	05 Management	RFI	Contract clarification	Design Team, BIM A+
RFI9	05 Management	RFI	Pump supply	Design Team, BIM A+
RFI8	05 Management	RFI	Contract clarification	Design Team, BIM A+
RFI7	03 Structure	RFI	Concrete curb	Design Team, BIM A+
RFI6	02 Architecture	RFI	Mesh fence	Design Team, BIM A+
RFI5	02 Architecture	RFI	Window W-04	Design Team, BIM A+
RFI4	05 Management	RFI	Drawing approval	Design Team, BIM A+
RFI3	02 Architecture	RFI	Wall Axis B'	Design Team, BIM A+
RFI2	02 Architecture	RFI	Bollards	Design Team, BIM A+
RFI1	04 MEP	RFI	Evaporators	Design Team, BIM A+

Source: own elaboration from Dalux platform

Redlines - Task

For the connection of the redlines using Dalux, a different task is created named RD (Redlines). Since the task is the same as the RFI task, it only needs to assign it to either the elements or the drawings the same way as the other record instrument.

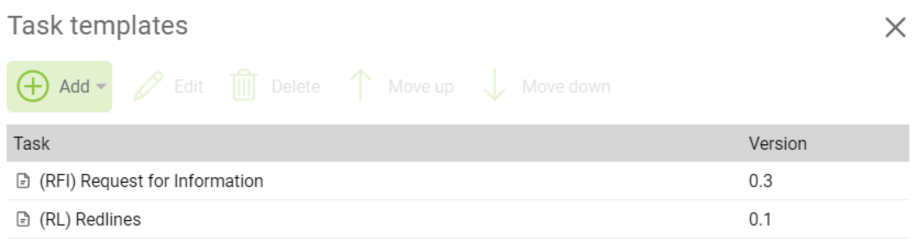
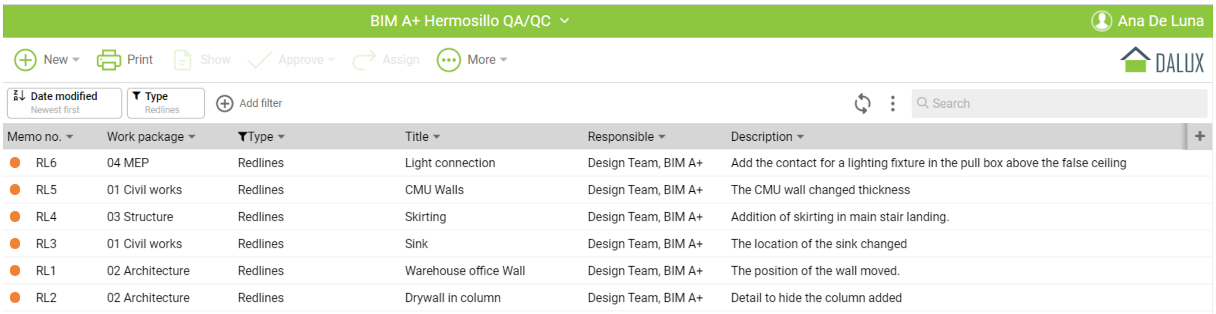


Figure 4-14. Task templates for the case study.
Source: own elaboration from the use of Dalux.

Similar to the RFI, the task of the redline will contain the responsible, the description, the work package involved, and the title of the redline.

Redlines – Assign to object

After the creation of the Redline template, a series of redlines based on the previous schedule were set up in the platform.



Memo no.	Work package	Type	Title	Responsible	Description
RL6	04 MEP	Redlines	Light connection	Design Team, BIM A+	Add the contact for a lighting fixture in the pull box above the false ceiling
RL5	01 Civil works	Redlines	CMU Walls	Design Team, BIM A+	The CMU wall changed thickness
RL4	03 Structure	Redlines	Skirting	Design Team, BIM A+	Addition of skirting in main stair landing.
RL3	01 Civil works	Redlines	Sink	Design Team, BIM A+	The location of the sink changed
RL1	02 Architecture	Redlines	Warehouse office Wall	Design Team, BIM A+	The position of the wall moved.
RL2	02 Architecture	Redlines	Drywall in column	Design Team, BIM A+	Detail to hide the column added

Redlines – Export collection

The same way it was able to export the data from the RFI collection to another type of format is possible as well with the task of redlines.

B) Verify / Analyse

After the collection of the information, especially by using a platform such as Dalux, the following analysis was possible to do.

Analysis of RFIs

The RFIs submitted in the project are going to be analysed by its causes to create lessons from it. They are going to be classified in the following list:

- Confirmation
- Incomplete drawings/specs
- Drawing clarification
- Discrepancies drawings/specs
- Specs clarification
- Other

Table 4-2. RFI analysis

Memo no.	Work package	Type	Title	Responsible	Reason / Classification
RFI25	02 Architecture	RFI	Handrail second mezzanine	Design Team, BIM A+	Drawing clarification
RFI24	02 Architecture	RFI	Mesh fence second mezzanine	Design Team, BIM A+	Discrepancies drawing/specs
RFI23	03 Structure	RFI	Column plate	Design Team, BIM A+	Other

RFI22	03 Structure	RFI	Second mezzanine	Design Team, BIM A+	Drawing clarification
RFI21	04 MEP	RFI	Extractor location	Design Team, BIM A+	Discrepancies drawing/specs
RFI20	04 MEP	RFI	Warehouse ventilation	Design Team, BIM A+	Confirmation
RFI19	04 MEP	RFI	Switch	Design Team, BIM A+	Specs clarification
RFI18	02 Architecture	RFI	Facade	Design Team, BIM A+	Discrepancies drawing/specs
RFI17	03 Structure	RFI	Reinforcement equipment	Design Team, BIM A+	Incomplete drawing/specs
RFI16	04 MEP	RFI	Louver	Design Team, BIM A+	Confirmation
RFI15	04 MEP	RFI	Centrifugal fan	Design Team, BIM A+	Incomplete drawing/specs
RFI14	04 MEP	RFI	Heating in mini splits	Design Team, BIM A+	Specs clarification
RFI13	01 Civil works	RFI	Ramps and swift yard	Design Team, BIM A+	Discrepancies drawing/specs
RFI12	02 Architecture	RFI	Window W-04 swing director	Design Team, BIM A+	Drawing clarification
RFI11	02 Architecture	RFI	Downspouts	Design Team, BIM A+	Confirmation
RFI10	05 Management	RFI	Contract clarification	Design Team, BIM A+	Other
RFI9	05 Management	RFI	Pump supply	Design Team, BIM A+	Other
RFI8	05 Management	RFI	Contract clarification	Design Team, BIM A+	Other
RFI7	03 Structure	RFI	Concrete curb	Design Team, BIM A+	Incomplete drawing/specs
RFI6	02 Architecture	RFI	Mesh fence	Design Team, BIM A+	Incomplete drawing/specs
RFI5	02 Architecture	RFI	Window W-04	Design Team, BIM A+	Discrepancies drawing/specs
RFI4	05 Management	RFI	Drawing approval	Design Team, BIM A+	Other
RFI3	02 Architecture	RFI	Wall Axis B'	Design Team, BIM A+	Incomplete drawing/specs
RFI2	02 Architecture	RFI	Bollards	Design Team, BIM A+	Incomplete drawing/specs
RFI1	04 MEP	RFI	Evaporators	Design Team, BIM A+	Confirmation

Source: own elaboration

After the category, the platform can make a series of filters and way of seeing the information that will let the user see the data in a different way and learn from it, for example, the following [**Figure 4-15**] shows the analysis of the RFIs by the discipline involved, the way it is presented it can be understood that the most questioned discipline in the project was Architecture, by having nine RFIs, after that the MEP discipline with seven doubts from the construction site to the design team.

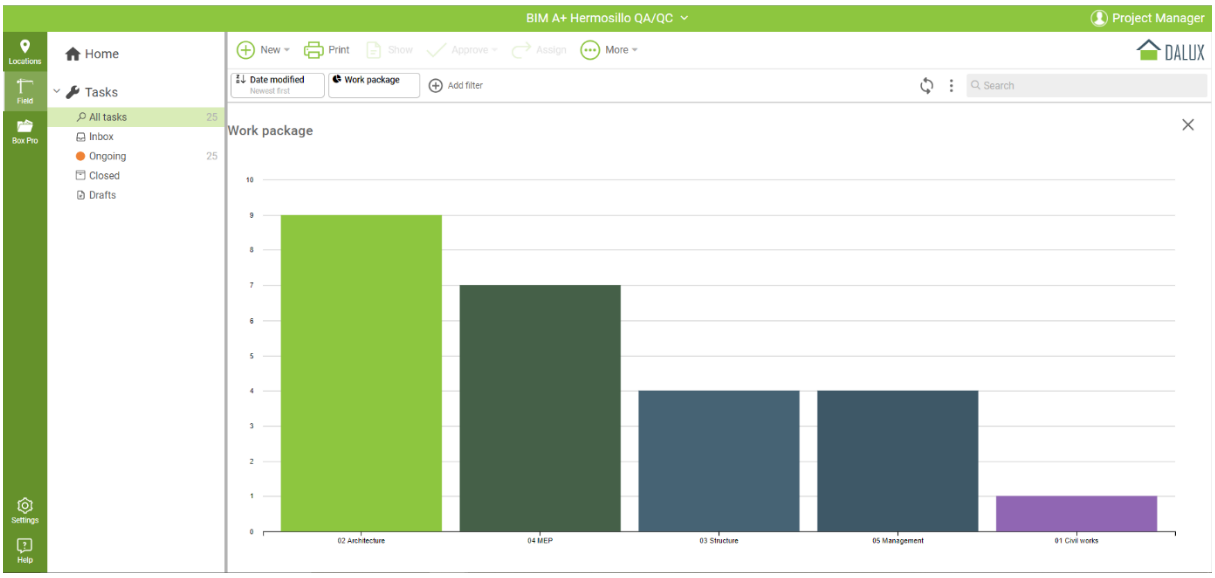


Figure 4-15. RFI filtered by discipline in a bar graph from Dalux.
Source: own elaboration from Dalux

Dalux also let the user to use a pie chart to understand and see in a format of percentages the same information extracted by following the Tasks tool in the platform [**Figure 4-16**].

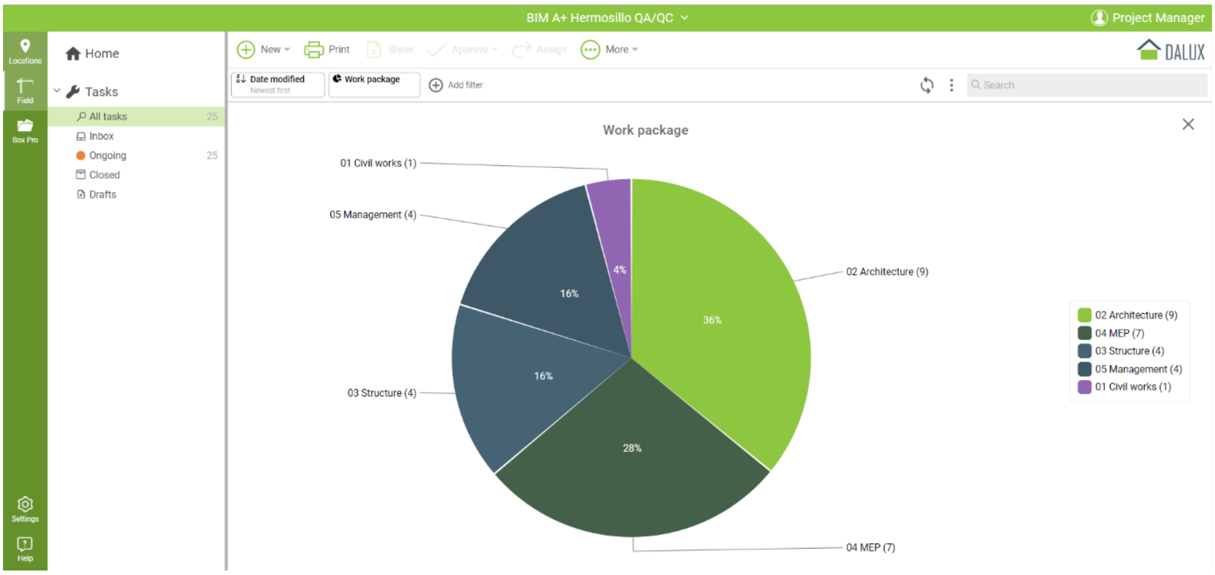


Figure 4-16. RFI filtered by discipline in a pie graph from Dalux
Source: own elaboration from Dalux

An updated version was created to relate the tool to the capacity of the knowledge learning experience, to do so a list was included in the Tasks tool for the RFI tasks with the different options the construction team can use to classify the reasons behind the RFI and leave a context in the record that will help to transform into knowledge. The graphs now are made based on this additional information put in the Tasks tool.

The first graph shows the amount of RFIs with the reason in a bar representation; it is shown that based on the inputs six RFI were related to incomplete drawings and/or specs and then, with the same amount of five; the discrepancies and other reasons [**Figure 4-17**].

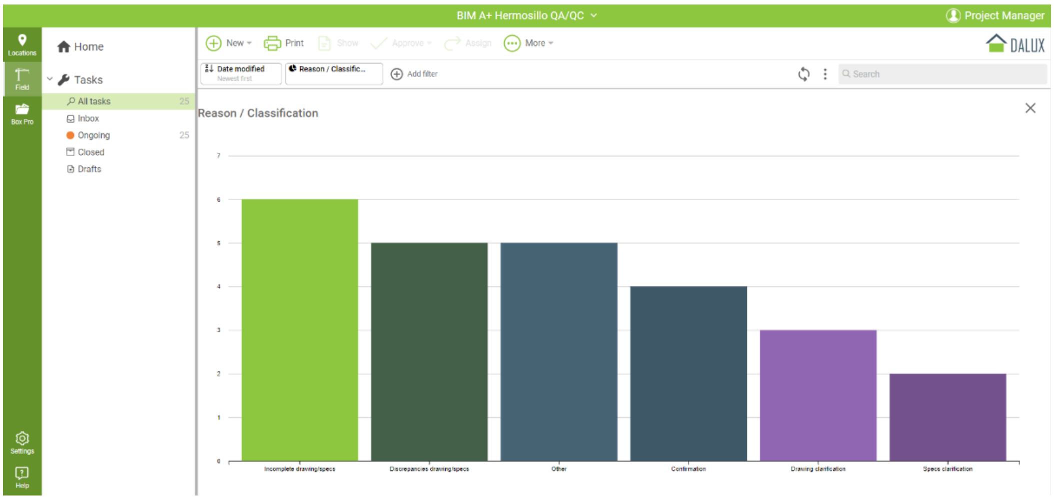


Figure 4-17. Reasons RFI Bar graph
Source: own elaboration using Dalux

Similar to the previous example, the reasons can be seen in a percentage form showed using a pie chart; based on the inputs the most common reason of RFI in this project is related to incomplete drawings and/or specs, the second most common is discrepancies between the drawings and the specs and the third one refers to other reasons [**Figure 4-18**].

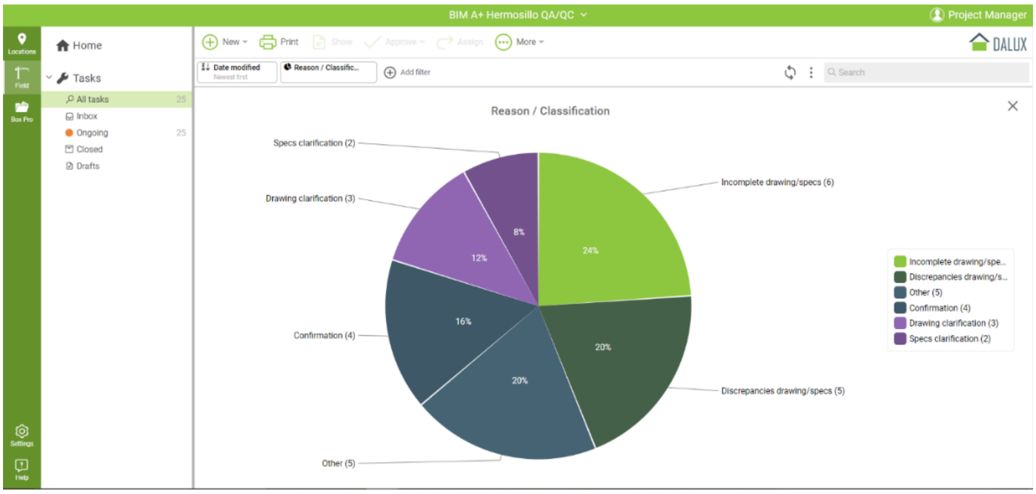


Figure 4-18. Reasons RFIs Pie graph
Source: own elaboration using Dalux

Analysis of Redlines

Similar to the RFI integration of attributes to the records of the communication between the design and the construction team, for the redlines, it was added:

Constructability reason: This attribute will display a list of selected Constructability principles that will relate the decisions in the site regarding the issues in that changed in the redlines.

The list includes [**Table 4-3**]:

Table 4-3. Constructability attributes set

#	Attribute	To fill the Questions with Constructability Knowledge
01	**Operation & Maintenance / Functionality**	• When the redline was motivated by the consideration of the Operation and Maintenance of the building. • If it complies with the functions related to its design intention.
02	**Simplicity**	• When there is a simpler way to build / assembly the element.
03	**Standardisation**	• When there is a change to standardised, such as repetition. • When the change between the original and the updated version was related with the objective to standardisation.
04	**Modularisation**	• When the project needed to comply with preassembly methods.
05	**Specifications**	• When there is the need to update the specifications of the modelled element taking in mind construction and procurement phases.
06	**Availability**	• When the specifications need to update according to the available materials and resources.
07	**Site / Location**	• When the location affected the project, once is the site reviewed. • When there is an update due to its geographical experience.
08	**Weather**	• When the cause of update is related to the weather such as the selection of materials and construction techniques.
09	**Building Methods**	• When the model does not represent the main construction method of the project.
10	**Logistics**	• When it is related to the fabrication, transportation, and installation aspects.
11	**Skills**	• When it is related to the construction skills and in alignment with the competencies.
12	**Sequencing**	• When it is related to reflect the construction sequence.
13	**Safety**	• When it is related to any safety consideration of the project.
14	**External factors**	• When an external factor affected the constructability of the project.
15	**Aesthetics**	• To comply with the requested aesthetics

Source: own elaboration

Action Taken: It refers to a list of the direct activity derivative from the decision taken in the construction site. It was identified five different cases in the project:

- Move: When the decision make an element in the project move its original position and location.
- Change: When the decision makes the element change any aspect of it.
- Eliminate: When the original building element was no longer needed in the project.
- Add: When it was needed to include a building element not considered in the original design.
- Confirm: When the need for confirmation was needed from the original design, it is related as well with the RFIs workflow.

Lessons Learned: It refers to a text box where the user creating the redline will be able to summarize the lesson learned derivate of the change, this can also be filled by the designer after the understanding of the redline. It will complete the knowledge process.

Impact: A colour coded description scale from green to red, which will show the magnitude of the impact of the learned situation.

- Green being the lowest impact
- Red being the highest impact

Description: It is a text box where the user will explain the situation.

Similar to the RFI, the visualization of the input data is possible to explore a different way of filtering the information to understand and learn from this analysis.

The first graph shows the percentages of the constructability reasons that make the original project change; the majority has to do with standardisation [**Figure 4-19**].

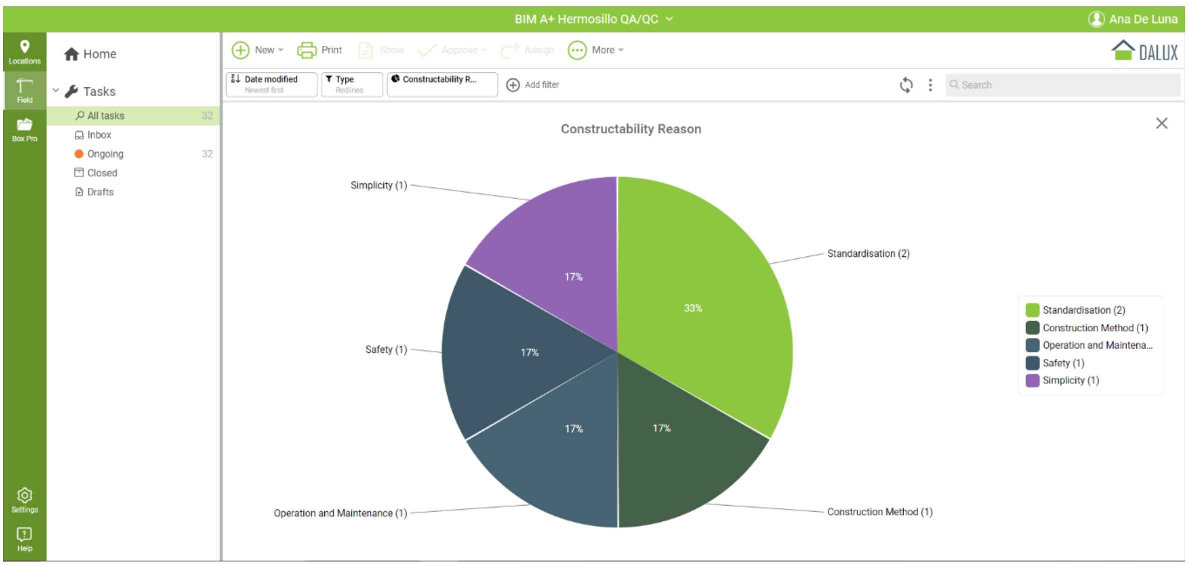


Figure 4-19. Redline Constructability reason pie chart
Source: own elaboration using Dalux

The second chart has to do with the relationship of the redlines and the action taken on-site, as we can observe, 50% of the updated project derivate in additional building elements [**Figure 4-20**].

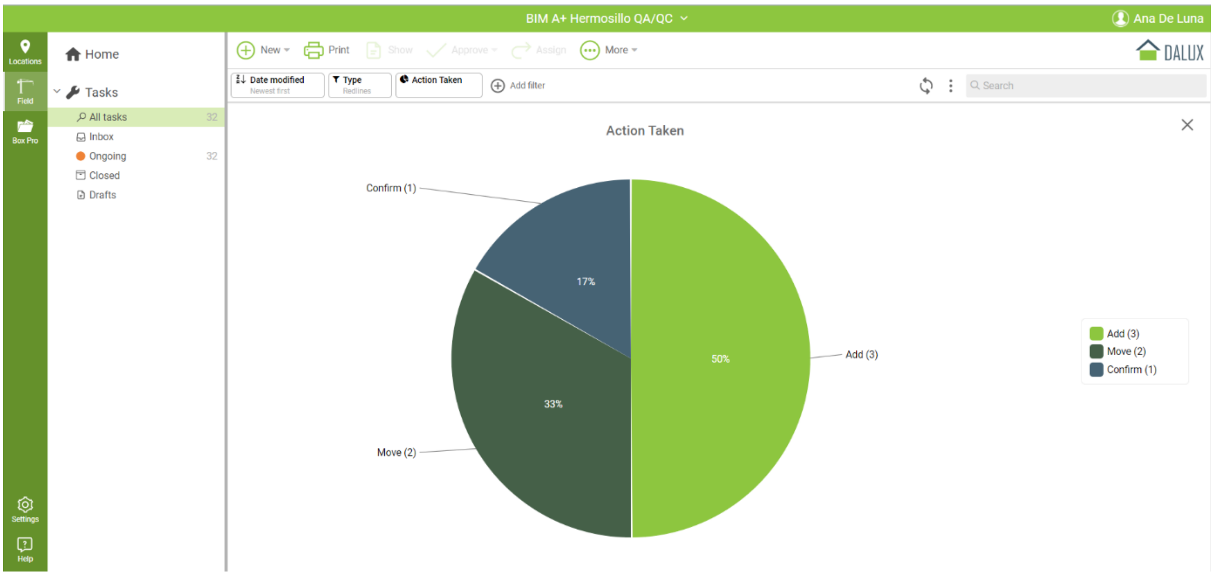


Figure 4-20. Redline Action taken pie chart.
Source: own elaboration using Dalux

The third chart is showing the amount of cases where the impact is red, yellow, or green according to the user creating the redline. The majority in the case study was considered a red impact [**Figure 4-21**].

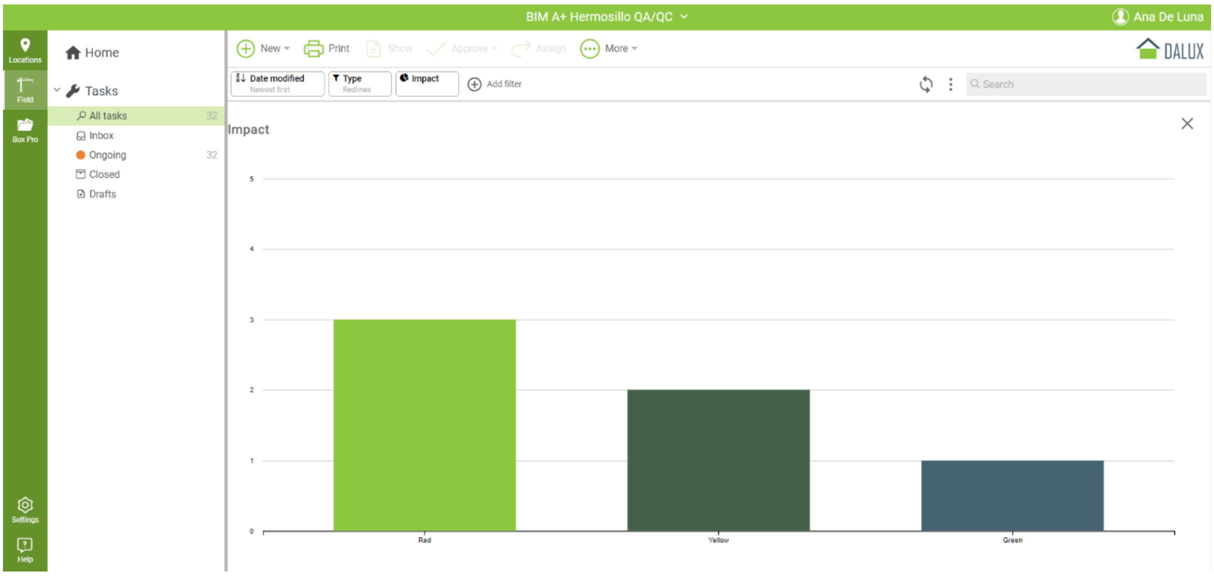


Figure 4-21. Redline Impact bar chart.
Source: own elaboration using Dalux

Constructability Knowledge Checklists

The knowledge can be analysed by transforming it through the use of checklist related to constructability. This must be created based on the lessons learned of projects will be initiating standard of checklist for each of the projects.

For the case study, it was selected five constructability knowledge collected in the previous steps and transform it into a Yes or No question that will integrate into the review of the project, and this can be included in a checklist database to reuse as a standard from project to project [**Table 4-4**].

Table 4-4. Constructability Knowledge checklist sample

#	Constructability Knowledge	YES/NO Checklist questions
01	When the downspouts release in a closed pavement area it is necessary to create storm drains to avoid water puddles in the transit area	- Is there any obstruction/obstacle for the water to drain from the roof to the designated area?
02	Add dimension from the edge of the building to the centre of the downspout.	- Are all the building elements dimensioned to a referenced point the drawing?
03	The height of the wall changed for the real height of the block and the mortar that build the wall.	- Are all the building elements with the real procured dimension? - Is it considered the dimension of the connecting elements in the overall element dimension?
04	The "U" shape concrete beam for the openings is less constructible than the "I" shape.	- Are the building elements simplified for the construction phase?
05	The concrete pouring for the mezzanine slab changed from control joint to a construction joint at 12 m of pouring. It could not be made for 19 m all together	- Is the location of the construction and control joints considering the construction sequence and pouring logistics?

Source: own elaboration

After the analysis of the lessons learned and constructability knowledge, and the set of questions are created, Dalux can be used to create QA/QC checklist with a tool in their platform in the Forms templates [**Figure 4-22**. Checklist template creation**Figure 4-22**].

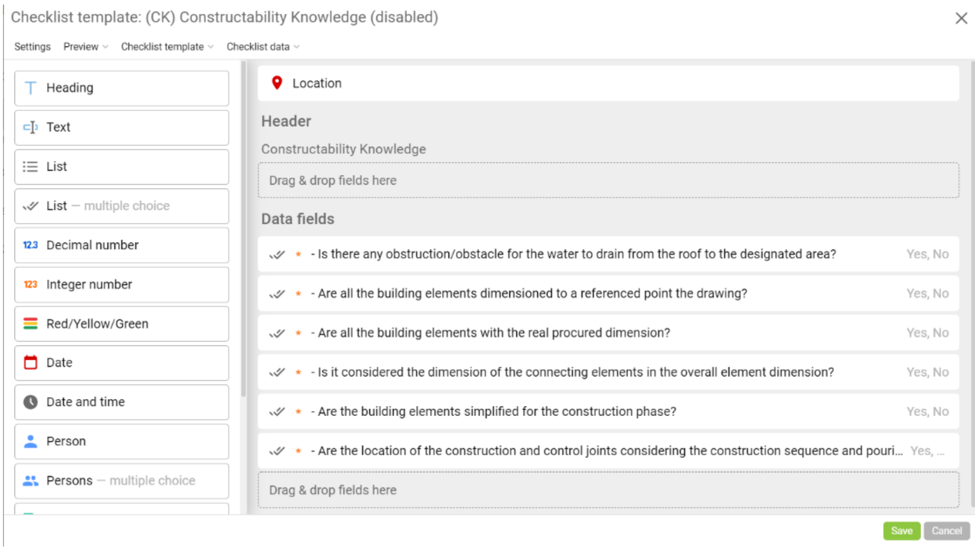


Figure 4-22. Checklist template creation
Source: own elaboration using Dalux

C) Store

Storing the reviewed outputs from the activities and documented records of RFIs and Redlines can be done in different ways, as the framework states it.

Common Data Environment (CDE)

The first way is to use the platform Dalux as the CDE of the project and save the lessons learned in the previous format by adding a Lessons learned to attribute to the Tasks tool, but the availability of this knowledge should not stay within the people involved only on that project, but it has to be disseminated to the rest of the company, therefore, after the completion of the project this information can be extracted from the platform and retrieve it in a different way for the rest of the team in the company.

It is proposed to use a platform with the features and tools that Dalux has been able to provide, to make it possible to customize the formal documentation of the RFI and redlines of the project with additional quick and easy to use properties related to the knowledge and lessons learned.

While the project is on-going the chance to perform the formal collection and analysis becomes the responsibility of an independent role, proposed in the process as a knowledge manager. In a post-construction phase, they will be responsible for taking, from the CDE the collected knowledge

Constructability Knowledge Database

This leads to the second possibility of storage, which is using the schema in the framework with the Constructability Knowledge Database, adding the information collected in the previous steps of the scheme.

For the case study, the E-R diagram was transformed into a Database using the DB Browser for SQLite. The database was populated with the data it was collected in previous steps using the same DB Browser

[**Figure 4-23**]. The intention of the database is to make it accessible for the rest of the team to query the required information and use it for the projects' design.

Table: Causes

	CauseID	CauseTitle
	Filter	Filter
1	1	Drawing clarification
2	2	Discrepancies drawing/...
3	4	Confirmation
4	5	Incomplete drawing/specs
5	6	Other

Table: Employee

	EmployeeID	LastName	FirstName	Department	JobTitle
	Filter	Filter	Filter	Filter	Filter
1	1	Camargo	F.	Construction	Constructi...
2	2	Rivera	J.	Construction	Supervisor
3	3	Hernandez	A.	Construction	Project ...
4	4	Garcia	M.	Construction	MEP ...

Table: Issues

	ssueID	IssueTitle	ElementIC	onstructabilityII	KnowledgeID	ssueDescriptio	ActionTakenID	Date
	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	1	Handrail	1	3...	1	Change in th...	2	13/12/2017
2	2	Sink	2	13	2	Client ...	1	14/12/2017
3	3	Extractor	3	6...	3	Change in th...	1	19/10/2017
4	4	Evaporator	4	14...	4	Confirmation...	5	21/09/2017
5	5	Skirting	7	11	5	Addition of ...	4	03/01/2018
6	6	Bracing	8	14	6	Eliminate ...	3	25/08/2017

Table: BuildingElements

	BElementsID	ElementName	Discipline	IssueID	BIMCategory	BIMFamiliy	BIMType
	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	1	Handrail	Architecture		Barandillas	Barandilla	900mm Pipe 3
2	2	Sink	Architecture	NULL	Mobiliario	Table-Rectangular	4'x3'
3	3	Extractor	HVAC		NA	NA	NA
4	4	Evaporator	HVAC	NULL	NA	NA	NA
5	5	Mesh Fence	Architecture	NULL	Modelos ...	Chainlink_Fence_-...	8'h-6' max spacing
6	6	Stair	Structure		Escaleras	Escalera ...	Office Warehouse 3

Figure 4-23. Constructability Knowledge Database population.
Source: own elaboration

For the case study, the database consists of ten tables, including Action taken, Building Elements, Causes, Constructability, Employees, Issues, Knowledge, and project.

D) Communicate

The purpose of the case study to Hermosillo is to communicate the new information using a formal communication existing system, such as company e-mail with the necessary link to access to this information as well as training for each part of the framework steps to the users that query and that feed the platforms. Encouraging the use of the stored knowledge to produce greater quality products and grow as a company.

Following the steps of the framework in the case study:

1. **Identify the roles involved in the updates**

   There are different roles that can feed and can benefit from the collective knowledge and lessons learned; the identification is related to different levels:

   a. Project Level: The employees that participated in the development and lifecycle of the project in the company.

i. Construction Site:
   1. Project Manager of 023DF
   2. Site Manager of 023DF
   3. MEP Manager of 023DF

ii. Office:
   1. Design manager of 023DF
   2. Design Leader and coordinator of 023DF
   3. Supporting designers and modellers of 023DF

b. Department Level: The employees that will use the information, specifically from the design department for a future project.
   1. Design manager
   2. Design leaders and coordinators
   3. Designers and modellers

c. Company Level: The employees that the knowledge will benefit the relationship between their roles and their responsibilities
   i. Construction department
   ii. Procurement department
   iii. Design department
   iv. Estimators department

2. **Select communication channel**: The company communicates to its team in an e-mail form with links to the internal server.
3. **Share and Communicate**.

E) Use / Reuse

Post-construction

The use and reuse of the collected, analysed, stored, and communicated knowledge from previous steps in the framework will happen when it is available and accessible for the next projects preferably in the pre-construction phase of the project life-cycle.

Still, in the post-construction activities, a process that connects the acquired knowledge with the BIM objects in the executed project is needed.

The following workflow is proposed in the case study [**Figure 4-24**]:

Figure 4-24. Workflow to connect the knowledge into BIM Object
Source: own elaboration

Constructability Knowledge parameter

After the storage and communication of the available information, it is necessary to identify the connection between the knowledge and the BIM model. Even though the CDE will collect valuable information it still is not connecting directly to the BIM elements, therefore it becomes necessary to create a constructability knowledge parameter in the authoring software, in this case, Revit, and create a link to the CK Database where the information is contained [**Figure 4-25**].

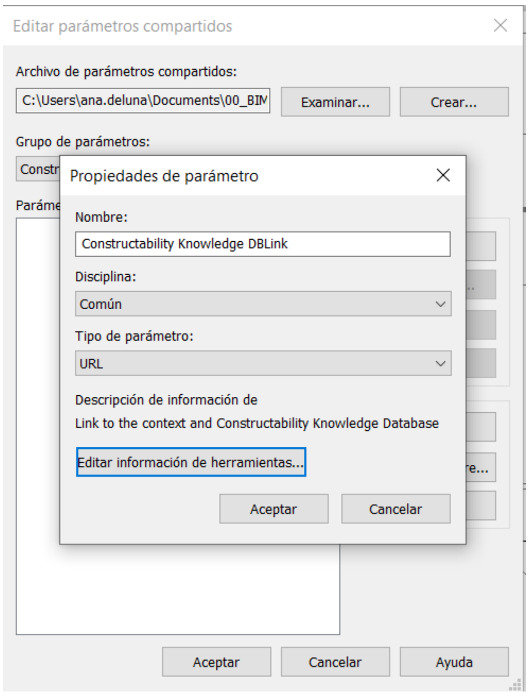


Figure 4-25. Shared parameter creation – URL Type
Source: own elaboration

The BIM objects that had a context related to the acquired knowledge while the project was built is going to have in its parameters a link to the database. After it, the BIM library of the company will be updated with the elements that suffer a modification for future use [**Figure 4-26**].

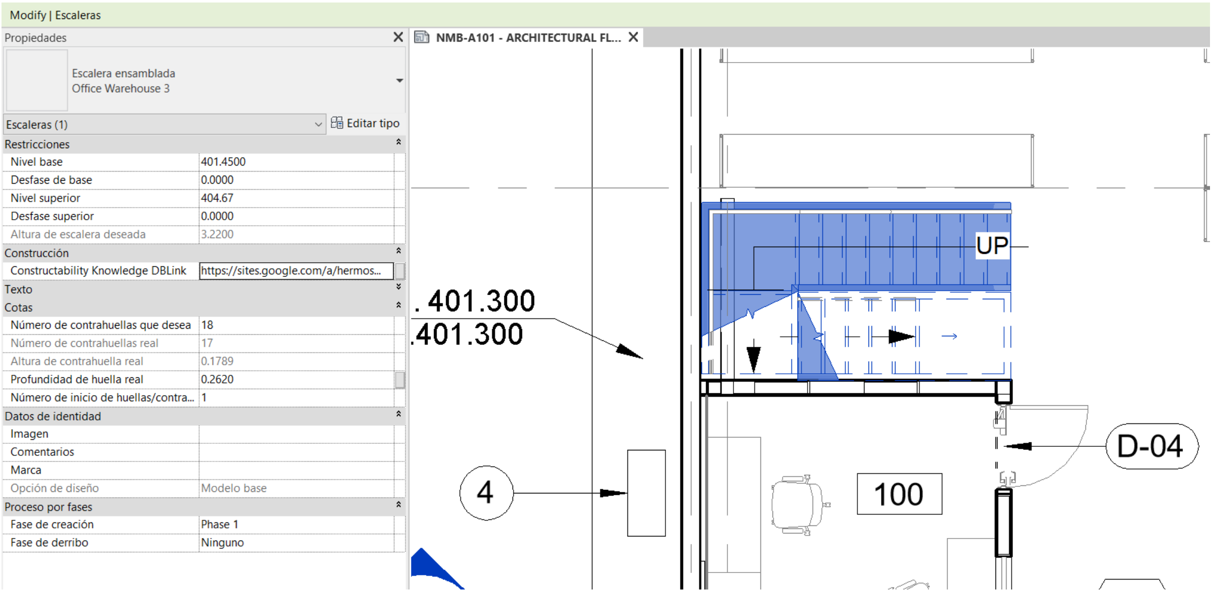


Figure 4-26. Constructability Knowledge Database Link example
Source: own elaboration.

Pre-construction

The use and re-use of the knowledge had to do with access to the database. This will be communicated to the team in the previous step, including a quick lesson on how to query it.

Use of Constructability Knowledge Database

The use of the database is related to the collected knowledge before and use it as a company repository to retrieve at the beginning of the projects, especially while making design decisions.

Query Database

Three examples of queries that can be done using the designed database:

Query #1

Which projects contain elements with Constructability issues, what is their description and the action related to it?

This type of query will help the designer identify the project in which a certain constructability issue happened, what action was required, and which was the knowledge acquired. This way, the designer will be able to go to the certain project to see the final as-built drawings and model and use it accordingly in the on-going project; by understanding the issue description of what happened, not only the knowledge description would help but it will create a bigger context and learning experience [**Figure 4-27**].

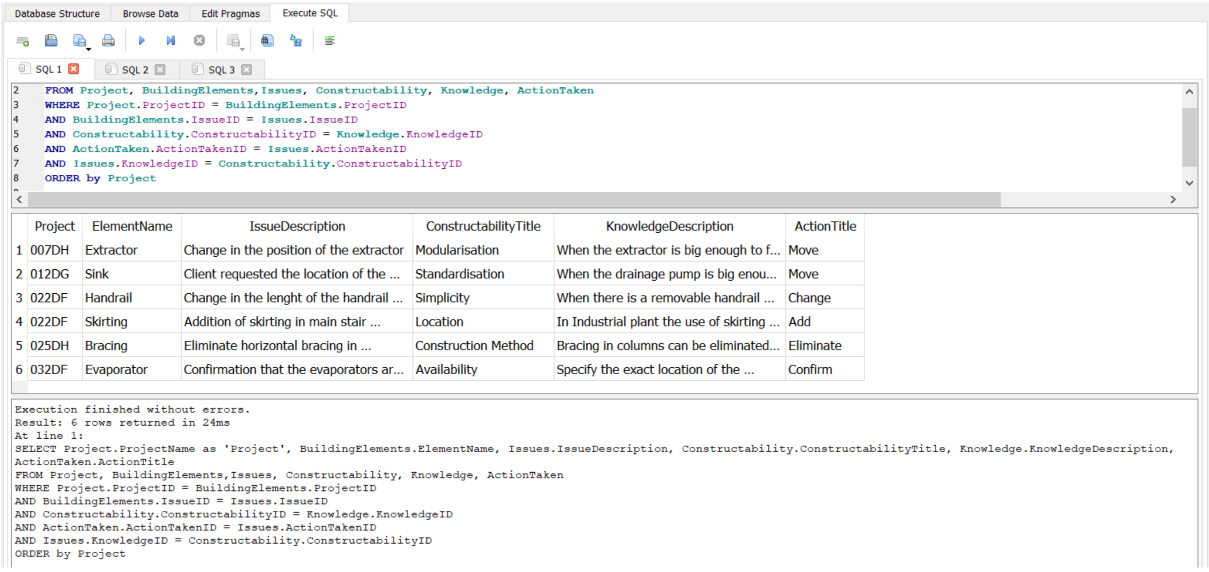


Figure 4-27 Query #1 from SQLite
Source: own elaboration

Query #2

Which disciplines on which projects contain constructability issues?

This query can help the project manager understand the sub-contractors involved with the highest amount of constructability issues and make decisions accordingly. For the designer, it will help not only to identify on which project the issue happened but in which of the breakdown structure of the model (by discipline) the specific object element can be found [**Figure 4-28**].

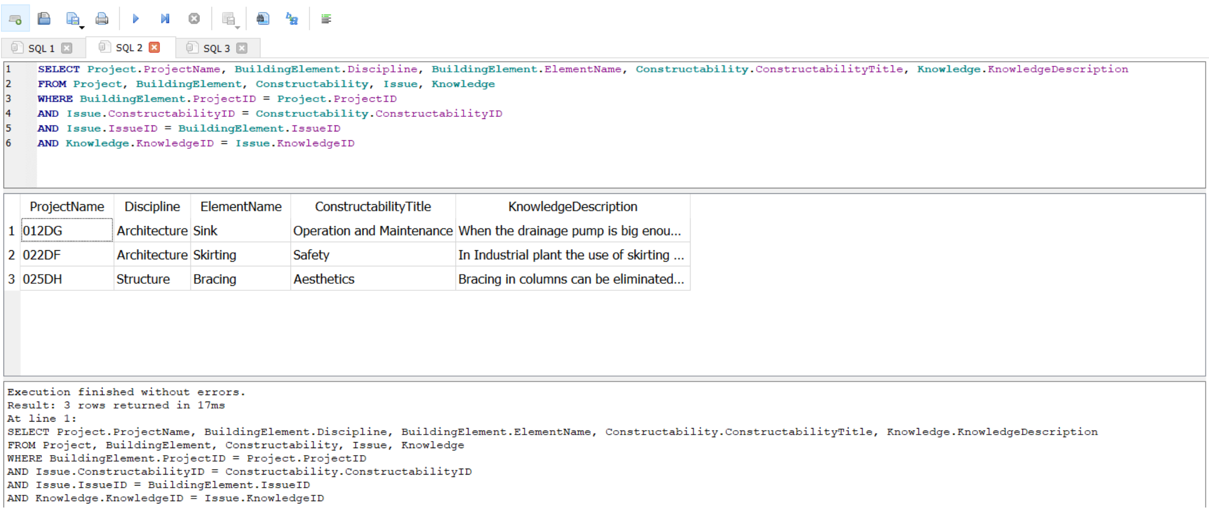


Figure 4-28. Query #2 from SQLite
Source: own elaboration

Query #3

Which project of what typology in which location contains an issue and who is responsible for the lesson learned integration?

This query addresses from a management perspective, in which the relationship with the source of knowledge will help the designer go deeper in his or her investigation about the constructability issue. It will also give the designer an idea of the location and how it affects the constructability of certain elements [**Figure 4-29**].

SQL 1 SQL 2 SQL 3

```
SELECT Project.ProjectName as 'Project', Typology.TypologyName as 'Typology', Project.Location, Employee.JobTitle AS 'Responsible', Issue.Date as 'Issue date', Buildi
FROM Project, BuildingElement, Constructability, Issue, Employee, Typology
WHERE BuildingElement.IssueID = Issue.IssueID
AND Issue.EmployeeID = Employee.EmployeeID
AND Constructability.ConstructabilityID = Issue.ConstructabilityID
AND Project.ProjectID =  BuildingElement.ProjectID
AND Project.TypologyID = Typology.TypologyID
AND Constructability.ConstructabilityID = Issue.ConstructabilityID
```

	Project	Typology	Location	Responsible	Issue date	Discipline	Element	Reason
1	012DG	Metal Industry Plant	MICHOACAN	Supervisor	14/12/2017	Architecture	Sink	Operation and Maintenance
2	022DF	Sanitary Industry Plant	NUEVO LEON	Construction Manager	03/01/2018	Architecture	Skirting	Safety
3	025DH	Automovile Industry Plant	NUEVO LEON	Supervisor	25/08/2017	Structure	Bracing	Aesthetics

```
Execution finished without errors.
Result: 3 rows returned in 21ms
At line 1:
SELECT Project.ProjectName as 'Project', Typology.TypologyName as 'Typology', Project.Location, Employee.JobTitle AS 'Responsible', Issue.Date as 'Issue date',
BuildingElement.Discipline, BuildingElement.ElementName as 'Element', Constructability.ConstructabilityTitle as 'Reason'
FROM Project, BuildingElement, Constructability, Issue, Employee, Typology
WHERE BuildingElement.IssueID = Issue.IssueID
AND Issue.EmployeeID = Employee.EmployeeID
AND Constructability.ConstructabilityID = Issue.ConstructabilityID
AND Project.ProjectID =  BuildingElement.ProjectID
AND Project.TypologyID = Typology.TypologyID
AND Constructability.ConstructabilityID = Issue.ConstructabilityID
```

Figure 4-29. Query #3 from SQLite
Source: own elaboration

This was only three examples of the type of queries the user can make; the database will be related to the models to reuse the objects that have the constructability context.

Identification and Use

After the query is being performed, it can be identified which BIM object in the BIM Library of the company is involved in the knowledge. The BIM object is an as-built model that has to suffer changes due to its constructability in previous projects; therefore it can be used and reused in different projects, and it can be enriched with new challenges and knowledge once is built again.

If the type of knowledge and constructability issue contained in the object is related to a specific and unique situation of the previous project, it can also make the designer consider this variables and factors in its design and adequate accordingly; for example, if the object changed due to availability in the location. The designer can verify or note to review this characteristic in the new developing project. The designer will be proactively checking constructability aspects of the project before it is built thanks to the context in the constructability knowledge database.

5 FINDINGS AND DISCUSSIONS

In this chapter will be the analysis after the application of the framework in the case study. A review of the different aspects and steps followed in the previous chapter is going to be developed.

5.1 Overview of the framework

After performing the case study, it has been identified that the proposed framework interacts with the lifecycle of the project differently depending on the team and the activities they develop in the project.

The [**Figure 5-1**] illustrates a summary of the lifecycle of the project (Pre-construction, construction, and post-construction) with the identified key roles and departments in the Constructability knowledge cross-sharing framework (Design team, Construction team, and Knowledge manager).

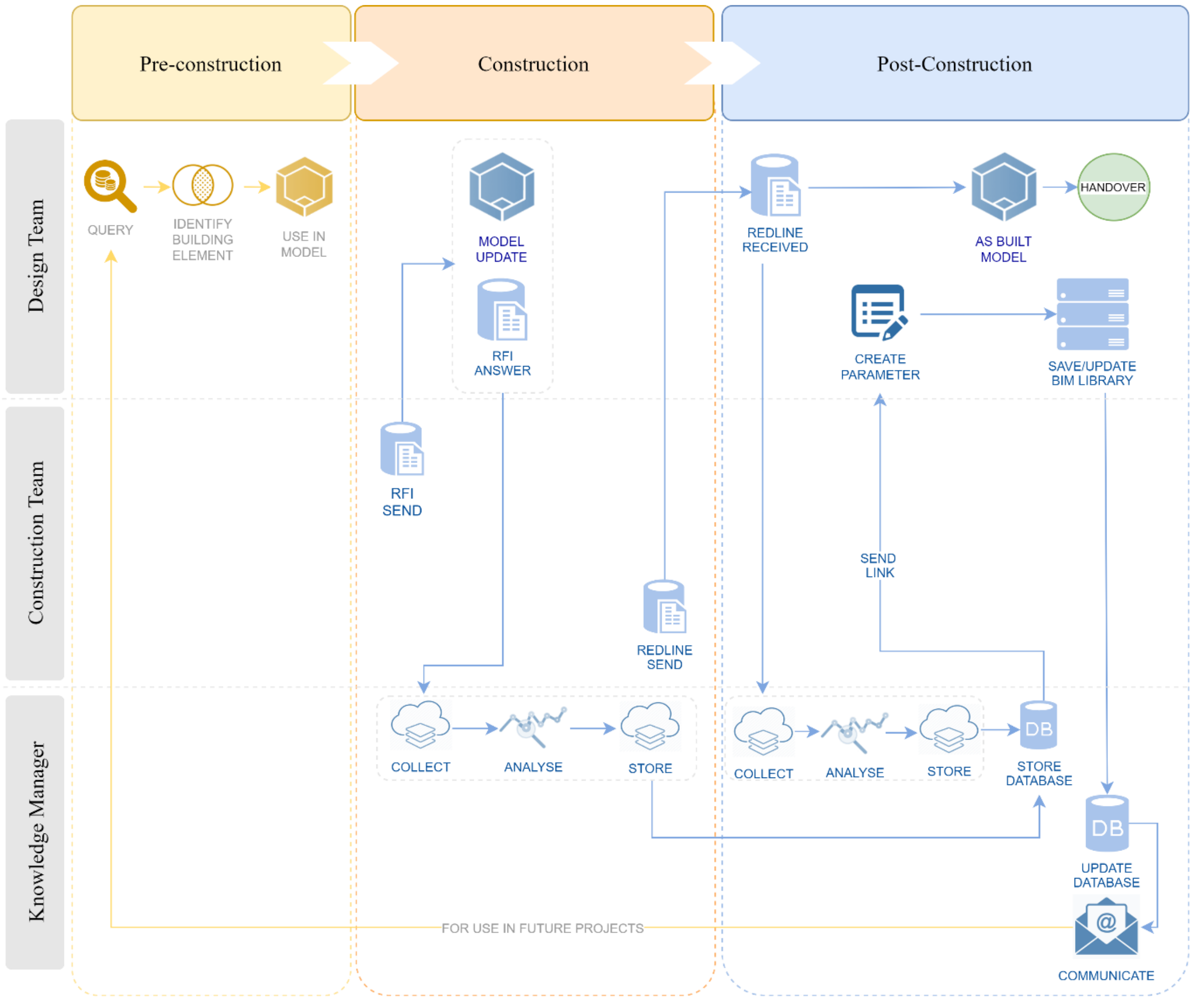


Figure 5-1. Framework across the lifecycle of the project
Source: own elaboration

A knowledge manager role has been proposed to perform activities out of the scope of the other departments to not distract them from other existing activities; but nevertheless, both teams have to schedule meetings, to review and analyse the collected information that will be integrated and properly stored in the Constructability Knowledge Database (CKDB).

5.2 Software – Platform review

The platform of Dalux was used in the case study. A list of highlights and lessons learned from it are listed as a review for the purpose of the thesis topic:

- **Easy-to-use**: Dalux, as its web page advertises is a friendly and easy-to-use platform for the general user. Although it is recommended to have a general overview of the platform, which the author had, to understand the best practices of it.
- **Adaptable**: As with other CDE-like platforms, the use of the thesis is not built-in, but with the tools available in Dalux it was possible to adapt it and customize the information required to apply the framework.
- **Customizable**: Dalux has customizable templates either for Tasks or Checklists which are easy-to-use without any knowledge about programming.
- **Visual-aid**: The field section of Dalux displays all the collected data of the project, for the purpose of the thesis topic it was possible to filter the information and view it in different ways, as shown in the case study which enhances the analysis and decision making during and after the construction finishes.
- **Focused**: Although Dalux has different modules, it is mostly focused in the construction phase of the project, for a design-build company is better to have integrated as well the procurement and design department in the CDE.
- **Time consumption**: It has been found that it is still considered the amount of time spent in uploading the ifc file to the platform, especially when the project is just 620.00 sq. m.
- **Connection**: Even though the model of the project can be uploaded in Dalux it does not read the drawings, this has to be uploaded from a different file format such as pdf and align it to the model. It has been found that this way is useful to locate the constructability issues in a lower-level dimension; it is still not connected to the actual object and feeding it in the platform.

5.3 Framework review

Collecting review

The intention of analysing the RFIs of the project is to learn from the moments the delivered information from the design team was not clear, complete, correct, or any other issue during the construction of the project.

This will make the team learn from it and apply it in future projects in order to increment the quality of the model, drawings, and specifications.

The Constructability knowledge can be extracted either from the requested information described from the site manager or by the reply from the design team. This format contains a link of communication between both parties.

The measurement and analysis of the RFIs in the project is a measure and a tool for the quality of the project; identifying the nature of the RFI such as confirmation of the design, coordination or missing information, and the regulations and clauses to the contract confirmation [11].

The intention behind analysing the redlines of the project is to understand the decisions made during the construction that implied in an adapted solution from the original design; it can either be a change in the specifications, the construction method, move, eliminate, or any other adaptation to the original design.

When the redlines come without explanation, it does not help in the process of understanding and learning, especially for colleagues that were not involved in the project.

The recorded information from the Hermosillo was not gathered in a single source list, only by creating the list and view all the contained information together gives the user a greater understanding of what happened in the project.

It is easier to understand the causes of an RFI format because there is a description in the way of communicating the requested information to the other team member, but it is still not straight forward. In the case of the redlines, it only expresses the changes, and without including a format of communicating them other than the markups in the drawing, it does not give the designer room to learn about what was the reason and intention behind the change.

The project itself, expressed in a model form without its context and its history recorded somewhere it does not say anything; therefore, only the people involved will understand what happened and what can be learned. A system that does not depend on these specific people is more powerful for the company, which is the intention of the framework.

Using a digital format as the channel of communication between the design and the construction team, such as the use of Dalux, will generate active data that can easily be viewed and filter to learn from it. From the visualization and the analysis of the filtered information, decisions can be supported by real-time experiences.

Analyzing review

During the execution of the case study, it was decided to integrate classification systems that will help the analysis of the information. Putting this classification system as a list to select from is to standardize the inputs and to make it easier for the user to integrate the constructability knowledge in an explicit form. The chosen classification corresponds to the analysis of the repeated situations of the project selected. It would be beneficial to analyse this classification system after performing the framework in other projects and updating the list when needed.

Even though in the case study there is a separation in the analysis of the RFI and the Redlines, having a different kind of inputs, it is proposed to also integrate the constructability reason, action taken, lessons learned, and impact into the RFI to have more details about the context of the requests.

The fact that Dalux can export in Excel format makes it easier to connect the data using other tools, for the purpose of the case study it was not explored, but it has been detected the potential to link this information in a different way.

It has been found that the filtering and visualization that Dalux has for the information was enough to further perform the constructability knowledge framework.

Transforming the knowledge into a checklist tool is an effort that can be done once and be useful to pass from project to project. The creation of yes or no questions must be clever enough to properly address the constructability issues. The fact that Dalux also has a template to facilitate the transfer of this checklist is an important quality check, and assurance tool, the only downfall for it is that the platform is mostly thought for the construction process and does not integrate the designers in the same way as other CDEs in the market.

The responsible for analysing the level of impact and the type of constructability review feedback is recommended to be done by a construction expert that can understand the type of issues and the possible effect in a construction project. Having a team to do the constructability review will lead to more diverse feedback since reviewers tend to deepen their comments based on their area of expertise [32].

Storage review

The case study explored three different storage containers throughout the project. This creates the need to extract the information at various points of the project, shown in the _FIG_. It would be interesting in the future that once an input is put in a source like CDE, it can connect to the BIM model and to the developed CKDB. The CKDB is showing a basic structure of the possibilities it can create; it needs further development about the user experience and the interface to make it accessible for the company.

Communication review

One important aspect of the communication activity of constructability knowledge is training. People need to understand how easily they can access to the database and take from the BIM library the updated objects to use. It has to be an activity that integrates well with the current processes and be careful to not overload the team with extra work that is not beneficial for the time constraint when a project is being developed.

Use review

It is important that the knowledge, as expressed before, not only comes from the constructability topics, but there are about design, management, planning, and different scenarios will give different output, as well as when seen the variables of the presented information, the user will get a different level of knowledge based on their own background. The lessons are not fixed since they can evolve continuously.

6 CONCLUSIONS

There have been efforts made in previous research from the reviewed literature towards the relationship between the main topics of this thesis, Quality and BIM. It was clear since the beginning the need to narrow down this connection among the two concepts.

Defining the term of quality is precisely related to having clear expectations about the results the client and the company want from it. It was then identified as a technique to address the improvement of quality in the AEC industry. The selection of constructability as the approach towards the main objective of the dissertation is strongly related to how much the developed design of a construction project quality affects the overall performance of a design-build company.

The implementation of constructability is directly related to the product the industry produces; it focuses on reviewing and developing the projects with the lenses of complying with its principles. When the design and engineering of a project do not consider how it is going to be built then time, cost, and overall experience is totally affected. The core of constructability is knowledge; the construction knowledge is a valuable intangible of every entity that belongs to the industry.

The knowledge is generated every time something is produced, even on each of the activities involved in the process of building a facility. Knowledge management is a strategy every company should invest in to not repeat mistakes and errors that cost limited resources and to improve the level of quality by cross-learning from its own history.

The question is raised about how BIM, being the current technology and methodology the AEC industry is using for digitalizing the building projects, can be a powerful mean to contain and facilitate the assessment of constructability knowledge. Knowledge can be collected from each activity performed during the life cycle of a project, construction knowledge specifically is extracted from the construction phase, but it has to be integrated into the pre-construction phase to be useful.

A framework following the lessons learned system schema is designed and tested in the third and fourth chapter of the thesis, finding that it is possible to use BIM-related platforms, software, and models to collect, analyse, store, communicate, and use the construction knowledge available in each project by slightly modifying the inputs when the communication between the design and the construction team happens.

7 REFERENCES

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8 ANNEXES

Table 8-1. CIIA Constructability principles.

Constructability principles CII of Australia		
#	Principle	**Description**
01	**Integration**	Constructability knowledge must be carried out in a built-in way.
02	**Construction knowledge**	Include construction expertise since the beginning of the development of the project.
03	**Team skills**	Coordinate the abilities, skills, and experience of the stakeholders to achieve the project objectives.
04	**Common objectives**	Define, clarify, and state the constructability goals of the project.
05	**Available resources**	Correlate the technologies used for the project with the capacities and resource of the team involved.
06	**External factors**	Considered for budget and schedule planning of the project.
07	**Schedule**	Detailed timeframe considering the constructability goals and general objectives of the project.
08	**Construction methodology**	Since the planning and design – engineering phase, the construction process should be taken into account.
09	**Availability**	Needed to enhance and facilitate the procurement stage of the construction.
10	**Specifications**	The coordination of the design and engineering specification of the project taking in the mine construction phase.
11	**Technology**	Innovation improves the implementation of Constructability.
12	**Feedback**	Creating a loop of knowledge by having a lesson learned the system from the evaluation of the experts in the team.

Source: Adapted from [6].

Table 8-2. CII Constructability principles.

Constructability measures principles CII		
#	Principle	**Description**
01	**Engagement of construction personnel**	Integrate into the execution plan the formal implementation of the constructability program.
		The planning of the project involves construction knowledge and experience.
		Engagement of construction personnel in the project strategy.
		Identification of Constructability responsible in the project.
02	**Construction-sensitive schedules**	Construction requirements are considered in the project schedule.
		Design, Engineering, and procurement are according to construction requirement in the project schedule.
03	**Modularization and preassembly**	The design solution considers modular and prefabrication construction methods.
		The solutions consider fabrication, transportation, and installation aspects.
04	**Standardization**	The design is standardized, as well as the supply chain.
05	**The design facilitates construction efficiency**	The design considers simplicity, flexibility, installation sequence, workforce skill, and availability.
		The specification of the project considers construction efficiency.
		Site layout considering construction accessibility.
		Weather conditions are considered in the construction plan.
		The revenue is simplified by the construction sequence.
06	**Innovative construction methods**	One factor for construction efficiency is for the site layout.
		The methods, equipment and construction system are innovative.
07	**Advanced computer technology**	The use of Building Information Modelling is applied.

Source: Adapted from [29].

Table 8-3 Constructability prerequisites.

Constructability prerequisites	
Factor	Prerequisite description
Environmental	Design and construction standards.
	Environmental factors (economic, social, technology, certification, etc.).
Technical	Known, new and creative methods of construction.
	Experienced and professional experts in design.
	Experience and knowledge of all members.
	Analyse project site before construction.
	Review drawings and give feedback to the design team.
	Integrate contractors in the early stage of the project to share knowledge and construction experience.
	Use of models for project understanding.
	Use of checklists.
Managerial	Importance of communication, coordination, and respect among stakeholders.
	Use a database to share and exchange information.
	Create and develop a support program.
	Plan according to project goals.
	Use of adequate tools and equipment.
	Awareness of Constructability from the stakeholders.
	Team building skills.
	Integration of all stakeholders.
	Innovation in the tools, methods, and technology used for information and communication.
	Traditional vs new contractual responsibilities.
	Cost of implementation and training for Constructability.
	Commitment and participation of all members.

Source: Adapted from [6].

Table 8-4. Construction Principles

Constructability Principles		
#	Principle	**Description**
01	**Site**	A research of the construction site
02	**Planning**	Development of project plan
03	**Methods**	Selection of main construction methods
04	**Involvement**	Construction personnel involved early in the project
05	**Objectives**	The understanding project, client and companies' objectives
06	**Schedule**	Having a construction driven schedule
07	**Simplicity**	Design simple assembly
08	**Standardisation**	Standardisation and/or repetition of design
09	**Modularisation**	Preassembly and/or modularisation design
10	**Visualization**	Use a model for visualization and clash detection in the project
11	**Sequencing**	Feasible construction sequence
12	**Storage**	The project recognizes the space required for inventory storage on site
13	**Safety**	The project contemplates the construction site health and safety
14	**Skills**	Project is designed for the construction competencies
15	**Materials**	The specifications of the project using available materials
16	**Efficiency**	The design has an efficient layout
17	**Detail**	The construction drawings give detailed and clear information
18	**Tolerances**	The project has set the construction tolerances
19	**Weather**	The selection of materials and construction techniques consider the weather of the site location

Source: Adapted from [15].

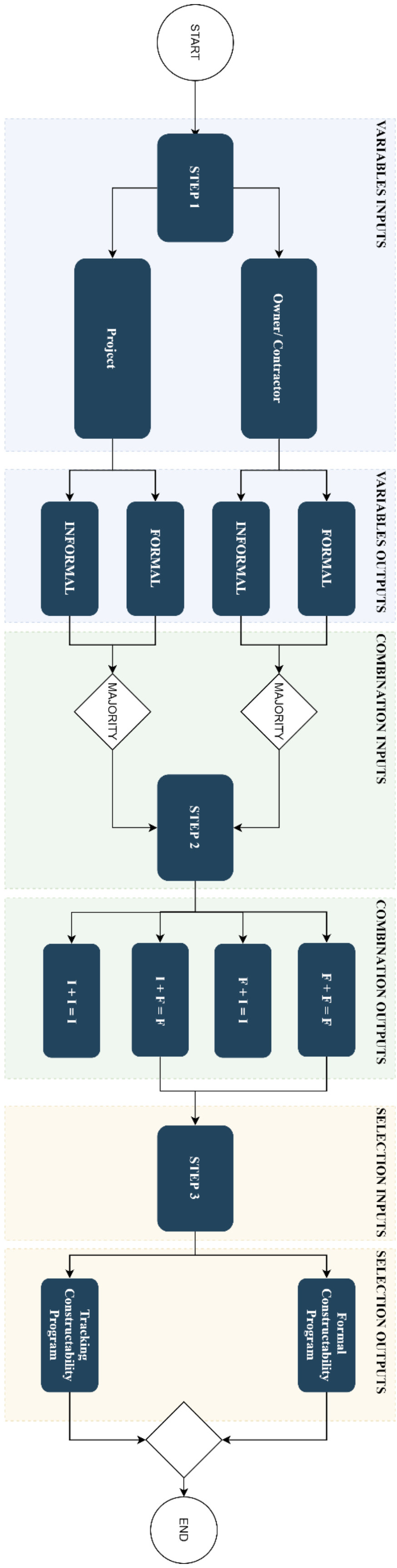

Figure 8-1. Constructability Formality Model
Source: own elaboration adapted from [26]

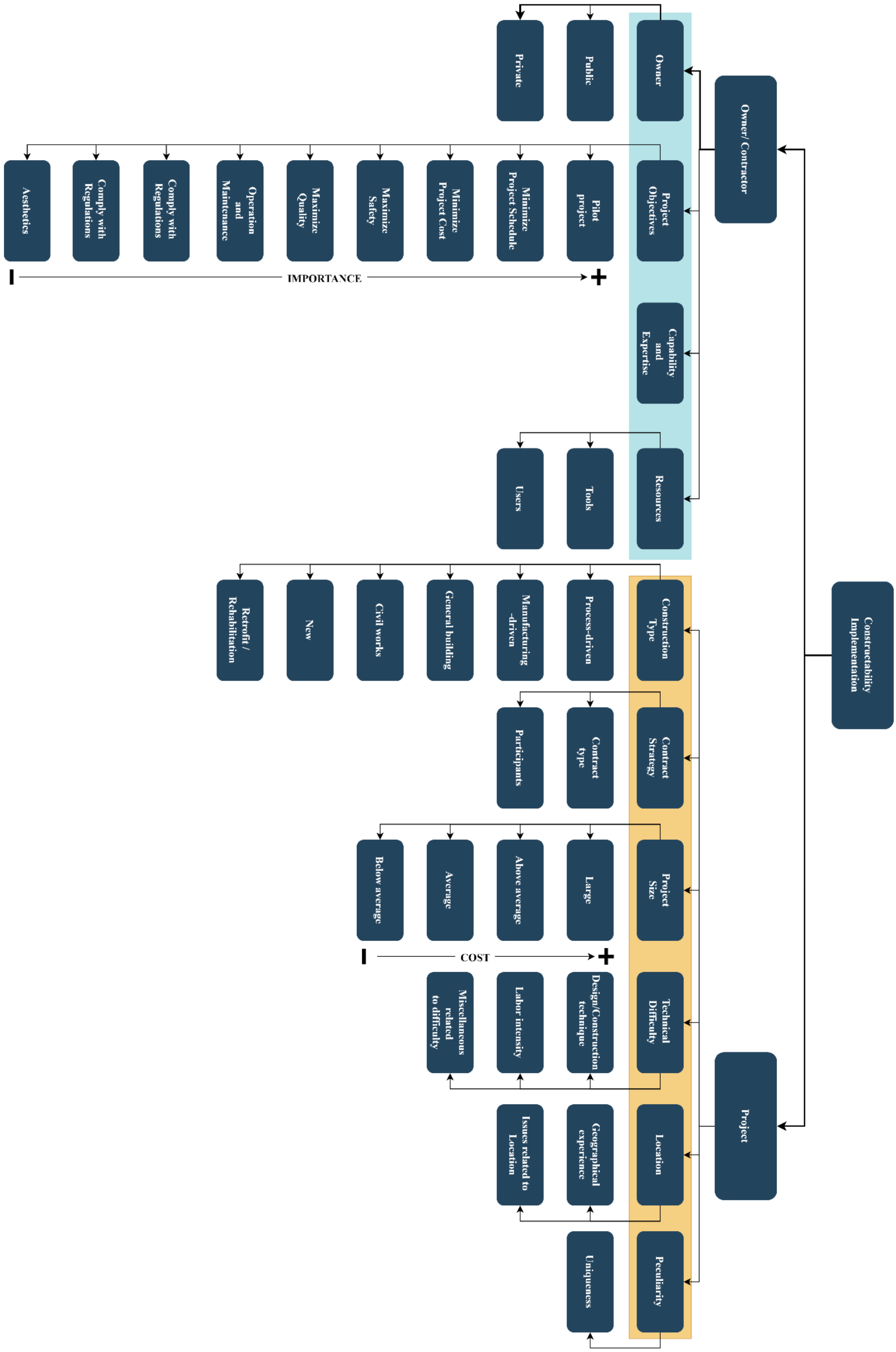

Figure 8-2. Step 1 Constructability Formality amplified version.
Source: Own elaboration based on [26].

Table 8-5. Constructability Information Model (CIM).

Constructability Information Model Structure (CIM)		
Categories	Description	Attributes
Design rules	The impact of a concept into the design.	**Design applicability**: Economic impact of the concept.
		Constraints and suggestions: Layout, dimensions, and details.
Performance	The properties of a concept into the construction productivity.	**Results**: Describe performance compared to other than can produce a similar result. • Cost • Production rate • Quality • Safety
		Impacts: Describe the influence it has on the concept performance. • **Direct:** o Complexity o Method o Interdependency • **Indirect:** o Level of automation o Location o Process o Uncertainty
Lessons Learned	General information about the project.	Intention of improvement
		Result of improvement
		Problem avoidance mindset
Resource Constraints	The requirements of the concept used.	**Information**: Type and detailed information needed for the concept. • Construction • Coordination • Tolerances • Extra details
		Skills: The amount and type of personnel abilities for applying the concept. • Technical

		• Managerial • Operational
		Time: The amount of it considers the preparation and coordination in terms of management, planning and design processes.
		Equipment: The type and amount of construction equipment.
		General conditions: Considers the special needs for the concept to be applied, such as spatial conditions, services, or systems.
		Tools: The type and amount of construction tools.
		Space: The analysis of the site layout for the different construction access.
		Material: The type, amount, and delivery rate for construction materials.
		Energy: The type and amount of energy used for the concept.
External Impacts	Impact on external sources if the concept is implemented.	Environmental
		Site neighbours
		Infrastructure

Source: Adapted from [25].

(II) QUALITY ASSURANCE

Architectural Detailed Design BIM	Structural Detailed Design BIM	MEP Detailed Design BIM	Merged model at Preliminary Design, Detailed Design, Construction and As-Built stages
- BIM in agreed version - BIM includes defined stories - Building elements & spaces modelled separately in each story - BIM includes required building elements - Building elements modelled using correct objects - Building elements include types - No excess building elements - No overlapping or doubled building elements - No significant clashes between objects - No conflicts between structures in architectural and structural BIM - BIM includes GFA spaces objects - Space areas match space program - BIM includes spatial reservations for MEP - Space height defined (including suspended ceilings) - Shape and size of spaces matches with walls - Spaces do not overlap - All spaces have unique IDs	- BIM in agreed version - BIM includes defined stories - Building elements defined separately in each story - BIM includes required building elements - Building elements modelled using correct objects - Building element types are as agreed - No excess building elements - No overlapping or doubled building elements - No significant clashes between objects - No conflicts between structures in architectural and structural BIM - No conflicts between penetrations in architectural and structural BIM - Columns and beams converge - MEP penetrations & reservations included in structures	- BIM in agreed version - BIM includes defined stories - Components defined separately in each story - BIM includes required components - Components modelled using correct objects - Components belong to a correct system - System colours are defined systematically - System colours are defined systematically - No excess components - No overlapping or doubled components - No significant clashes between components - No clashes between MEP disciplines - No clashes between M&E and electrical BIM - Components fit into their spatial reservations - No clashes between M&E, architectural and structural BIM	- All agreed models available - Models represent the same design version - Models are located in the correct coordinate system - No conflicts between vertical shafts and MEP systems - No conflicts between horizontal reservations and MEP - No conflicts between suspended ceilings and MEP - Penetrations of columns OK - Penetrations of beams OK - Penetrations of slabs OK

Figure 8-3. Quality assurance checklist for Detailed Design.
Source: [50]

Project:

Contractor:

Request For Information (RFI)

To:	Issued Date:
From:	Requested Reply Date:

RFI Description:

Reference / Attachments:

Receiver's Reply:

By: ______________________ **Signature:** ________________ **Date:** ____________

NOTE: This reply is not an authorization to proceed with work involving additional cost, time or both. If any reply requires a change to the Contract Documents, a Change Order, Construction Change Directive or a Minor Change in the work must be executed in accordance with the Contract Documents.

Figure 8-4. RFI format example.
Source: Hermosillo format sample

Tables (10)

Name	Type	Schema
ActionTaken		CREATE TABLE "ActionTaken" ("ActionTakenID" INTEGER, "ActionTitle" TEXT, PRIMARY KEY("ActionTakenID"))
ActionTakenID	INTEGER	"ActionTakenID" INTEGER
ActionTitle	TEXT	"ActionTitle" TEXT
BuildingElements		CREATE TABLE "BuildingElements" ("BElementsID" INTEGER, "ElementName" TEXT, "Discipline" TEXT, "IssueID" INTEGER, "BIMCategory" TEXT, "BIMFamiliy" INTEGER, "BIMType" INTEGER, "ProjectID" INTEGER, PRIMARY KEY("BElementsID"))
BElementsID	INTEGER	"BElementsID" INTEGER
ElementName	TEXT	"ElementName" TEXT
Discipline	TEXT	"Discipline" TEXT
IssueID	INTEGER	"IssueID" INTEGER
BIMCategory	TEXT	"BIMCategory" TEXT
BIMFamiliy	INTEGER	"BIMFamiliy" INTEGER
BIMType	INTEGER	"BIMType" INTEGER
ProjectID	INTEGER	"ProjectID" INTEGER
Causes		CREATE TABLE "Causes" ("CauseID" INTEGER, "CauseTitle" TEXT, PRIMARY KEY("CauseID"))
CauseID	INTEGER	"CauseID" INTEGER
CauseTitle	TEXT	"CauseTitle" TEXT
Constructability		CREATE TABLE "Constructability" ("ConstructabilityID" INTEGER, "ConstructabilityTitle" TEXT, PRIMARY KEY("ConstructabilityID"))
ConstructabilityID	INTEGER	"ConstructabilityID" INTEGER
ConstructabilityTitle	TEXT	"ConstructabilityTitle" TEXT
Employee		CREATE TABLE "Employee" ("EmployeeID" INTEGER, "LastName" TEXT, "FirstName" TEXT, "Department" TEXT, "JobTitle" TEXT, PRIMARY KEY("EmployeeID"))
EmployeeID	INTEGER	"EmployeeID" INTEGER
LastName	TEXT	"LastName" TEXT
FirstName	TEXT	"FirstName" TEXT
Department	TEXT	"Department" TEXT
JobTitle	TEXT	"JobTitle" TEXT
Issues		CREATE TABLE "Issues" ("IssueID" INTEGER, "IssueTitle" INTEGER, "ConstructabilityID" INTEGER, "KnowledgeID" INTEGER, "IssueDescription" TEXT, "ActionTakenID" INTEGER, "Date" TEXT, PRIMARY KEY("IssueID"))
IssueID	INTEGER	"IssueID" INTEGER
IssueTitle	INTEGER	"IssueTitle" INTEGER
ConstructabilityID	INTEGER	"ConstructabilityID" INTEGER
KnowledgeID	INTEGER	"KnowledgeID" INTEGER
IssueDescription	TEXT	"IssueDescription" TEXT
ActionTakenID	INTEGER	"ActionTakenID" INTEGER
Date	TEXT	"Date" TEXT
Knowledge		CREATE TABLE "Knowledge" ("KnowledgeID" INTEGER, "KnowledgeDescription" TEXT, "SourceID" INTEGER, PRIMARY KEY("KnowledgeID"))
KnowledgeID	INTEGER	"KnowledgeID" INTEGER
KnowledgeDescription	TEXT	"KnowledgeDescription" TEXT
SourceID	INTEGER	"SourceID" INTEGER
Project		CREATE TABLE "Project" ("ProjectID" INTEGER, "ProjectName" TEXT, "Location" TEXT, "Year" TEXT, "TypologyID" INTEGER, PRIMARY KEY("ProjectID"))

Figure 8-5. Structure from the Constructability Knowledge Database in DB Browser for SQLite.
Source: own elaboration