# Modelling and coordination of building design: an experience of BIM learning/upskilling

**Marcio Presente de Souza**
Institute of Architecture and Urbanism of University of Sao Paulo, Sao Carlos, Brazil, marciopresente@usp.br

**Beatriz Campos Fialho**
Institute of Architecture and Urbanism of University of Sao Paulo, Sao Carlos, Brazil, beatriz.fialho@usp.br

**Rita Cristina Ferreira**
Institute of Architecture and Urbanism of University of Sao Paulo, Sao Carlos, Brazil, rcferreira@usp.br

**Márcio Minto Fabricio**
Institute of Architecture and Urbanism of University of Sao Paulo, Sao Carlos, Brazil, marcio.m.fabricio@usp.br

**Ricardo Codinhoto**
Department of Architecture and Civil Engineering of the University of Bath, Bath, United Kingdom, rc784@bath.ac.uk

**Abstract**

The implementation of Building Information Modelling (BIM) in the Architecture, Engineering, Construction and Operations (AECO) industry requires multidisciplinary teams equipped with new technical and managerial skills. Professionals that are inexperienced or unfamiliar with the BIM design process face difficulties in transposing complex concepts into BIM modelling and coordination practices, despite governments, industry bodies, and academia's efforts. With this issue in mind, this article's objective is to present the teaching-learning strategies and tools adopted in a practical case of modelling an existing building on a BIM platform. In terms of method, a phenomenological approach has been taken to report on an exploratory didactic experience. The Cognitive Load Theory (CLT) was used to assess learning based on the authors' perceptions. The research has been structured into the following five stages: i. Literature Review; ii. Analysis of Brazilian and International BIM Standards and Guides; iii. Didactic exercise; iv. Experience Assessment; and v. Conclusions. The results reveal aspects of BIM processes that can be widely investigated in an academic environment, such as the BIM design and coordination process model, which can be explored as a tool in the BIM teaching-learning process. Also, difficulties related to teaching BIM management processes were identified, thus calling for different didactic approaches. The contributions made by the research come from reporting and analysing the process of learning complex BIM content from the perspective of inexperienced professionals. The work also contributes to the field through the BIM learning assessment proposal and the BIM process model resulted from the authors' practical experience.

Keywords: Project disciplines; Federated model; BIM coordination; Learning.

## *Introduction*

Despite the evident growth in BIM adoption by the AECO industry in different countries (Kassem & Succar, 2017; Succar & Kassem, 2015), the abstraction, transfer, and application of this knowledge in different cultural and organisational structures are not always effective. New professional skills are required to address innovative work strategies and the implementation of software and digital platforms in consolidated practices. Difficulties increase when the leading team lacks the experience and resources to support BIM implementation, as is usually observed in small- and medium-sized companies in the construction sector (Dainty et al., 2017; European Commission, 2019).

Such professionals' preparation for BIM is led by governments, industrial bodies, and academia through guidelines and regulatory material. International and Brazilian technical standards have been developed to define BIM concepts and principles to assist the AECO industry in the production and management of information over assets' life cycle (e.g. ISO 19650 and ABNT 15965 standards series). Various professional bodies have proposed frameworks and recommendations for the BIM work process. They focus on the needs of companies and professionals (e.g., the "BIM Project Execution Planning Guide" elaborated by Penn State University and the guide developed by the Brazilian Industrial Development Agency (ABDI)). Similarly, British institutions have been developing guides aimed at the academic education and training of professionals (CDBB, 2020; BAF, 2013). However, documentation's inconsistency and fragmentation represent an obstacle to learning and implementing BIM in work practices, especially for inexperienced professionals.

Given this context, the questions addressed by this work are as follows: What are the difficulties faced by inexperienced professionals in information management for the abstraction, transfer, and application of BIM knowledge? How can BIM learning by beginning professionals be assessed, particularly in an academic environment?

In answering these questions, the objective of this article is to present the teaching-learning strategies and tools adopted in a case of BIM usage. A practical case of modelling an existing building on a BIM platform has been developed as part of a postgraduate course. The didactic exercise involved the design and coordination of multiple disciplines and collaboration between different professionals.

The Cognitive Load Theory (CLT) was used for the subjective assessment of learning based on the authors' perception. By considering students' prior knowledge and balancing instructional teaching content and techniques, the CLT was considered appropriate for assessing BIM learning by beginners. The most valuable contributions of the work come from an understanding of the most difficult BIM concepts to abstract and apply in inexperienced professionals' practice.

## *Background*

The professional skills required by the AECO industry have significantly changed, with new functions and responsibilities arising from the emergence of BIM. Inexperienced professionals and students tend to believe that investments in technological infrastructure and software learning are sufficient for implementing BIM in organisations. However, these individuals face a dual challenge: consolidating the skills and technical knowledge necessary to explore the potential of BIM and, at the same time, learning new workflows and collaborative practices. The biggest challenge/obstacle in adopting BIM is related to people issues (Sacks et al., 2018). Specifically, cultural change has become the fundamental issue, imposing on people a broader view of the building construction process, and anticipating problems that are commonly left until the execution stage (ABDI, 2017).

Evidence shows that the identification and organisation of competencies facilitate the smooth adoption of BIM, clarifying which complex activities should be performed during interdisciplinary collaboration (Succar, Sher & Williams, 2013). These competencies are generated from the development of knowledge, skills, and attitudes that individuals can learn in specific contexts (Van Der Klink & Boon, 2003). Stimulating such learning is a significant challenge for academia and industry bodies, especially when dealing with professionals unfamiliar with the new BIM paradigms. In Brazil, data indicate that most companies are in the initial stages of BIM adoption (between 1 and 5 years of use) with a moderate level of expertise in their processes and technologies (McGraw Hill Construction, 2014). Similarly, BIM adoption in academia is still embryonic, despite the awareness of its potential benefits for Architecture and Engineering courses (Ramos, Costa & Mello, 2019).

Government actions have had a significant impact on the industry's awareness of BIM (Sacks et al., 2018). Countries in Europe, Asia and North America have well-structured plans requiring the use of BIM in public works, while Brazil has recently been developing dissemination strategies at the national level (Brasil, 2019, 2020). In 2018, the International Standardization Organization (ISO) published the ISO 19650-1 and 19650-2, setting the standards for organising AECO information oriented towards the design and development phases. The documentation provides wide-ranging content containing critical principles for understanding information management through BIM. In Brazil, the standardisation of collaborative work in BIM began with the translation of ISO 12006-2 (ISO, 2015) into the Brazilian context and the creation of the series of standards NBR 15965 (ABNT, 2017) - Parts 1 to 7, which establishes the terminology and classification structure for BIM, supporting the development of evaluation methods, work scopes and technical standards.

In addition to the normative documents, BIM guides play a fundamental role in transposing the local reality's central principles. A relevant example is the "BIM Project Execution Planning Guide" (CIC, 2010, 2011), that has supported the development of a series of Brazilian guides[1] to stimulate the discussion on BIM implantation in Brazil as supported by government decrees. But, the information needed to understand BIM processes and technologies is fragmented in the literature, requiring searches in normative documents and recommendations from specific agencies. According to the European Federation of Engineering Consultancy Associations (EFCA, 2019), many essential issues for BIM implementation in organisations are omitted in international standards, such as (i) implications arising from adding or subtracting steps in the suggested workflows; (ii) roles and responsibilities attributed to each professional; (iii) the ways of exchanging information between customers and suppliers; (iv) data processing and storage requirements; (v) quality control criteria for the use of the information; and (vi) clarity in implementation based on usage.

The analysis of the ISO 19650, the American guide (CIC, 2011), and the Brazilian guide (ABDI, 2017) corroborate part of EFCA (2019) statements. In fact, professionals' attributions are not covered in depth by the standards and differ in certain aspects among the main guides, thus demanding caution in the distribution of functions according to each professional's competencies and experience. Only basic information requirements for implementing BIM are provided for beginners, referring to infrastructure (i.e. hardware and software), and the reallocation of skills to accommodate new workflows. On the other hand, exchanges of information and deliverables are covered in detail, with examples of organisation forms, delivery protocols, and responsibility matrices.

Addressing the new demands of the industry imposed by the BIM design process, another critical challenge is training AECO professionals, especially in architects and engineers' academic education. More than providing relevant content for the market, educational institutions have been developing strategies and criteria for assessing BIM learning. According to Hu (2019), from 2014, the integration of BIM into the curricula of courses has been driven to cross-disciplinary collaboration, overcoming fragmented approaches: first, in the transition from Computer-Aided Design (CAD) teaching to BIM and, second, focusing on teaching specific tools for each course.

Previous studies have discussed BIM teaching based on Problem-Based Learning (PBL) approaches (Jin et al., 2018; Wu & Hyatt, 2016). Sacks and Pikas (2013) developed a framework to support BIM education, establishing expected content and performance levels in each undergraduate and postgraduate program phase. Besides, Barison and Santos (2010, 2014) proposed definitions and planning of content to assist teachers in implementing BIM in AECO courses. Similarly, Ruschel and Cuperschmid (2018) described a

[1] "Guia Boas Práticas em BIM" (ASBEA, 2013) developed by the Brazilian Association of Architecture Offices (ASBEA); the "Coletânea Implementação do BIM para Construtoras e Incorporadoras" (CBIC, 2016) proposed by the Brazilian Chamber of the Construction Industry (CBIC); and the "Coletânea Guias BIM" (ABDI, 2017) developed by the Brazilian Agency for Industrial Development (ABDI) in partnership with federal government.

pioneering initiative in Brazil to implement BIM in undergraduate courses. The authors proposed a curricular reform, introducing elective courses and changes in the content, prioritising multidisciplinary experiences and diversifying teaching-learning strategies (Ruschel & Cuperschmid, 2018). However, a limited number of publications have investigated the dynamics of collaboration for BIM teaching based on learning theories.

In 2013, the BIM Academic Forum UK (BAF) published the "Embedding Building Information Modelling (BIM) within the taught curriculum," which is a guide aimed at understanding the learning needs of undergraduate and postgraduate programmes in the UK. Among its contributions, the BAF (2013) presented learning content organised into three categories (learning and understanding, practical skills, and transferable skills) applicable at different stages of the course. Such content encourages structuring individual subjects and consolidating a consistent curriculum for the gradual learning of BIM. Another initiative was promoted in 2020 by the Centre for Digital Built Britain (CDBB) through the publication of the "UK BIM Framework Learning Outcomes" (CDBB, 2020) aimed at introductory training in BIM in the AECO industry context. The document proposes BIM learning indicators to assist professionals in improving information management according to the UK BIM Framework's propositions and the ISO 19650 series of standards. Unlike the BAF (2013), it presents a broader set of requirements for BIM learning, hindering its application in BIM professionals' academic education. However, structuring the techniques to assess BIM teaching-learning processes is necessary from a pedagogical point of view.

In this sense, the CLT can contribute to the qualitative assessment of BIM learning. The CLT aims to explain how a human being appropriates new knowledge and the cognitive processes associated with learning, based on the concepts of working memory and long-term memory (Sweller, Van Merriënboer & Pass, 1998). According to this theory, knowledge is first processed in working memory, which is volatile and limited. The working memory is responsible for processing the intrinsic load, which is derived from the learning content, and the extrinsic load, derived from the way the content is approached. Such knowledge is later "fixed" and consolidated in the long-term memory, becoming automatically accessible for problem-solving. Measuring cognitive load involves complex processes. However, its application can help to evaluate BIM learning. Sweller, Van Merriënboer and Pass (1998) discussed three categories for measuring cognitive load: subjective, psychological, and task based. Subjective techniques are generally qualitative, and their characteristics best address the needs of this research. In this way, a pedagogy knowledge orientation can contribute to greater effectiveness of learning new concepts, such as those demanded by BIM.

## *Method*

The research strategy is qualitative and exploratory with a phenomenological approach, describing individuals' experiences concerning a particular phenomenon and in a specific context (Creswell, 2014). In this work, a didactic exercise of BIM design and coordination is the phenomenon described. It involved developing, federating, and analysing architectural, structural, mechanical, and electrical digital models. The activities were conducted as part of a postgraduate course undertaken by two architects with basic BIM modelling knowledge and who shared designer and coordinator roles.

The course was delivered to 14 students over two weeks with 60 teaching hours involving theoretical and practical activities. The course's hybrid dynamics aimed to encompass the presentation of concepts in expository classes and the demonstration of their application in BIM software in practical classes. Given the diversity of professional backgrounds (architecture and civil engineering) and knowledge levels of BIM (basic, intermediate, and advanced) among students, a decision was made to use existing building projects to support modelling, design, and coordination activities. In this way, the research focused on learning new processes and technologies, not on disciplinary design knowledge. In addition to the BIM models, a reflective report about the process's practical challenges was produced for assessment.

The procedures for conducting the research were organised into the following five stages: i. literature review to establish a theoretical foundation; ii. analysis of national and international standards and guides to understand and structure the BIM project process; iii. a practical exercise covering project and coordination activities; iv. evaluating practical experiences, indicating lessons and recommendations; and v. conclusions, presenting the work's limitations and contributions and outlining future research opportunities.

The practical exercise included planning, modelling, and coordinating disciplines. Several guides were provided to the students, who autonomously decided which approach to take. In this work, the BIM Project Execution Planning Guide (CIC, 2010, 2011) supported the definition of the model uses and the corresponding process mapping. Although the document referred to the Business Process Modelling Notation (BPMN), nonconformities with the Object Management Group (OMG)[2] standards were observed. As a result, the software Bizagi[3] was selected for process mapping following BPMN standard notations. The technical and managerial requirements to produce project information were systematised in the "Exchange Information Requirements (EIR)," as suggested by ISO 19650 (BSI, 2018).

Modelling, federation, and verification activities were performed using Autodesk Revit 2019 software, selected due to the availability of native tools for all subjects and the free educational license. Based on the workflow suggested by Kirby, Krygiel and Kim (2018), the disciplines of architecture and structure were modelled in a single file. They composed the Integrated Model or Central File[4] to avoid overloads in processing the model and increase the efficiency of the process. The Central File then supported the development of the mechanical and electrical systems, generating the Federated Model[5]. Two tools were used to evaluate the Federated Model: The *Interference Check*, which detects possible conflicts between components of selected disciplines, gathered in an interference report; and *Model Checker* associated with the *Model Health Dashboard,* which identifies project delivery patterns and manages model integrity and interoperability (Moore, 2016). The report generated by the Model Checker uses parameters pre-established by the supplier (Autodesk, 2020). These are categorised by colour according to the status of the parameter (green = safe (desirable); yellow = demanding attention (potential warning); red = may cause problems in the file (danger zone); and grey = indifferent to the performance of the models).

Finally, the qualitative evaluation of the experience was based on the CLT and conducted through the learning indicators proposed by the BAF (2013) for postgraduate BIM courses. Although the CDBB (2020) is the most up-to-date reference on the topic, the BAF (2013) was selected to present more objective and applicable criteria in the context of this work. Three groups of learning indicators were adopted, namely, A. Learning and understanding, related to the industry context for BIM implementation, B. Practical Skills, involving individual capabilities to adopt and assess BIM tools, protocols, and principles, and C. Transferable skills, related to the cross discipline and team working at strategic, technical, and managerial levels.

In this work, the cognitive load was qualitatively measured according to the student's perception of the complexity of the content (intrinsic load) and their capability of understanding through the teaching-learning strategy (extrinsic load), based on the BAF indicators (BAF, 2013). A 5-level Likert scale was devised to assess learning as follows: Intrinsic Loads - from 1 (very little complexity) to 5 (very complex), with zero assigned for the content not covered; and Extrinsic Loads - from 1 (very facilitating) to 5 (very little facilitation), with zero not being applicable (See Table 1).

## *Results and Discussion*

### *Definition of BIM uses and process mapping.*

Understanding the purpose of the BIM model and the steps involved in the process is essential for planning and carrying out practical activities. Figure 1 depicts the BIM design and coordination process model related to the didactic experience, developed according to the CIC (2010, 2011) for design authoring and design

[2] https://www.omg.org/

[3] https://www.bizagi.com/pt/plataforma/modeler

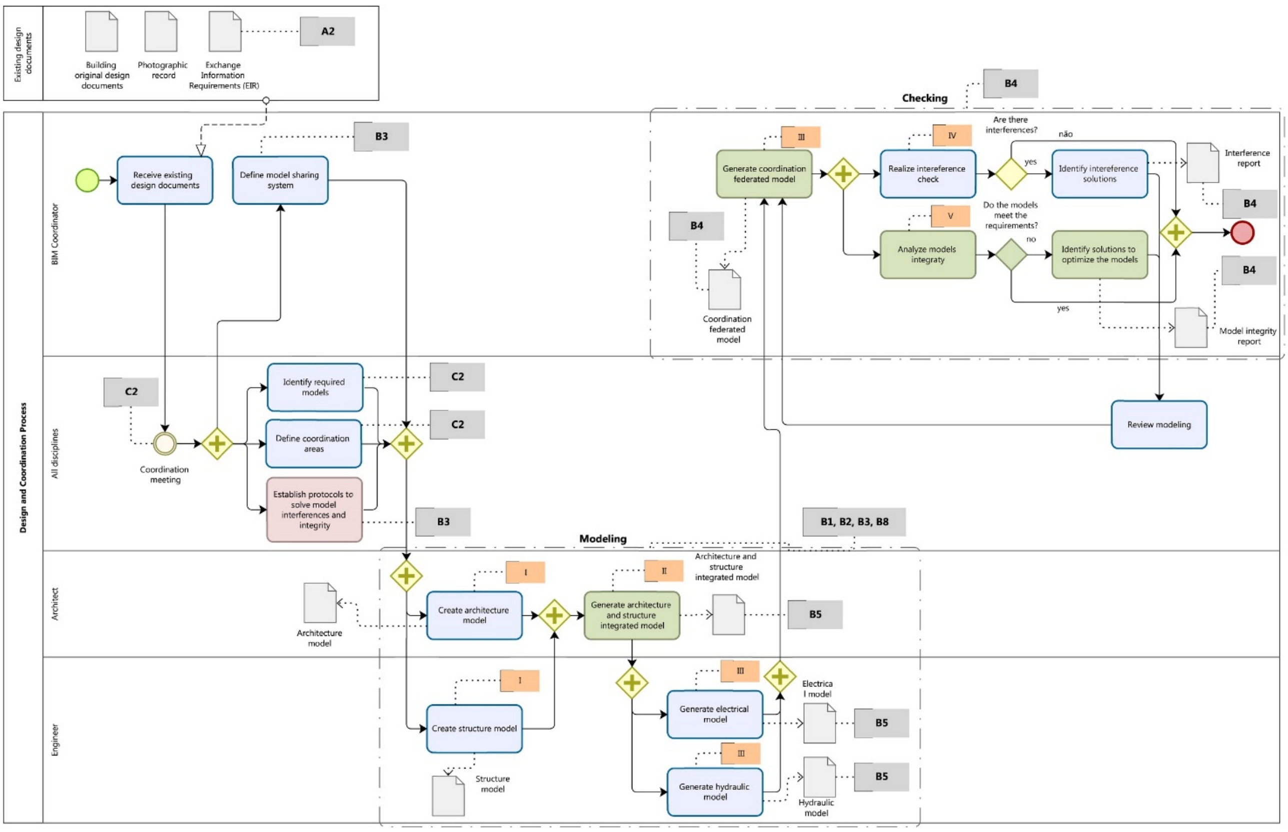
[4] The Integrated Model (Central File in Revit), integrates in a single file all the models of the different disciplines. The procedure for collaboration takes place by synchronizing the information generated by the different participants.

[5] The federated model is a solution in which the information for each discipline is modeled in separate files, making it possible to link the models on demand from the participants. The processing impact is reduced, since the individual properties are not merged into a single database, and different software can be used by each professional to fulfill their functions in the BIM process (BIM Initiative, 2019).

coordination uses. The model was divided into the following two processes: "Existing Project" and "Design and Coordination Process." In the "Existing Project", only the documentary products used for the project and coordination process were considered. The horizontal lanes displace the interaction among the stakeholders, for instance, the BIM Coordinator, responsible for managing the process; the Architect, concerned with the development of the architecture design; and the Engineer, responsible for the MEP and structure design.

The process starts with the BIM Coordinator receiving the Existing Project in 2D and triggering a meeting with the team to (1) "create the system to share the model", (2) "identify the required models", (3) "define the areas of coordination" and (4) "establish protocols to resolve model interference and integrity." Activities (1), (2) and (3) are described in the CIC (2010, 2011), while the authors added activity (4) to this didactic exercise. With these initial definitions made, the next step was modelling the disciplines of architecture and engineering. Once models were completed, the activities' verification was carried out mainly by the BIM Coordinator, who returned to the disciplines to review the modelling upon detecting problems in the project. A group of documents was generated at the end of the process, including: "architecture model," "structure model," "integrated architecture and structure model," "electrical model," "mechanicals model," "federated coordination model," "interference report" and "model health report."

Figure 1: BIM Design and Coordination Process Model

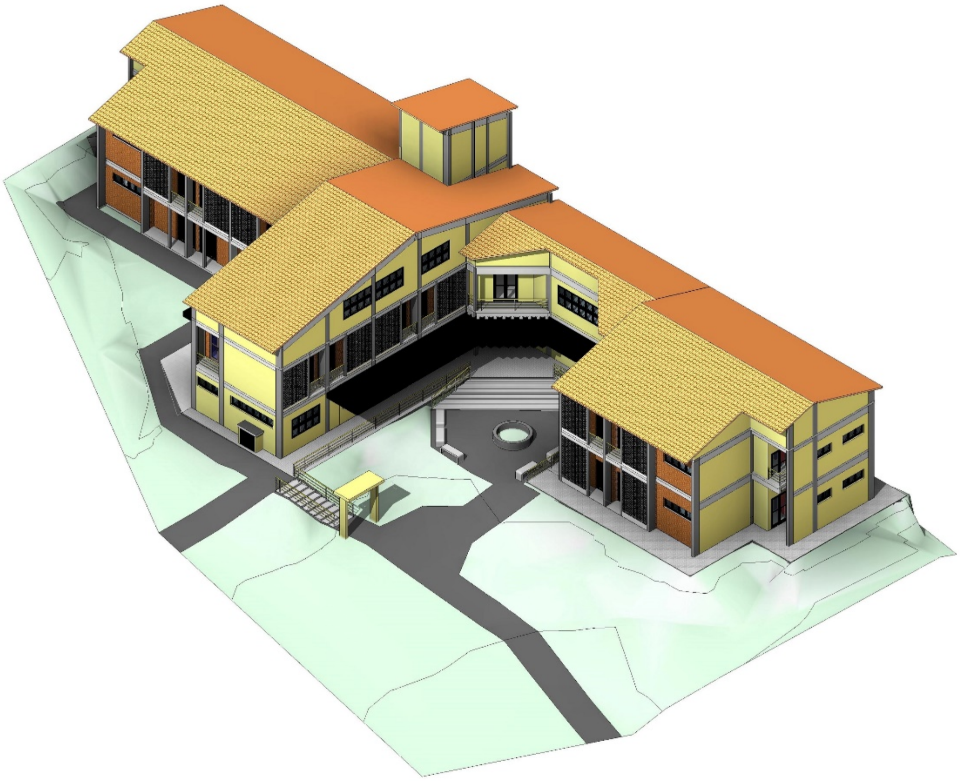



The Student Housing E building's original project on the USP campus in São Carlos-SP was selected for the activities. The project files of four disciplines (architecture, structures, mechanical and electrical installations) were provided in dwg. A visit to the building was carried out to map design solutions' visualisation and a photographic survey. All reference files, such as original projects, photos, and BIM models, were gathered in a shared folder on Drive, easily accessible by the participants.

## *Modelling*

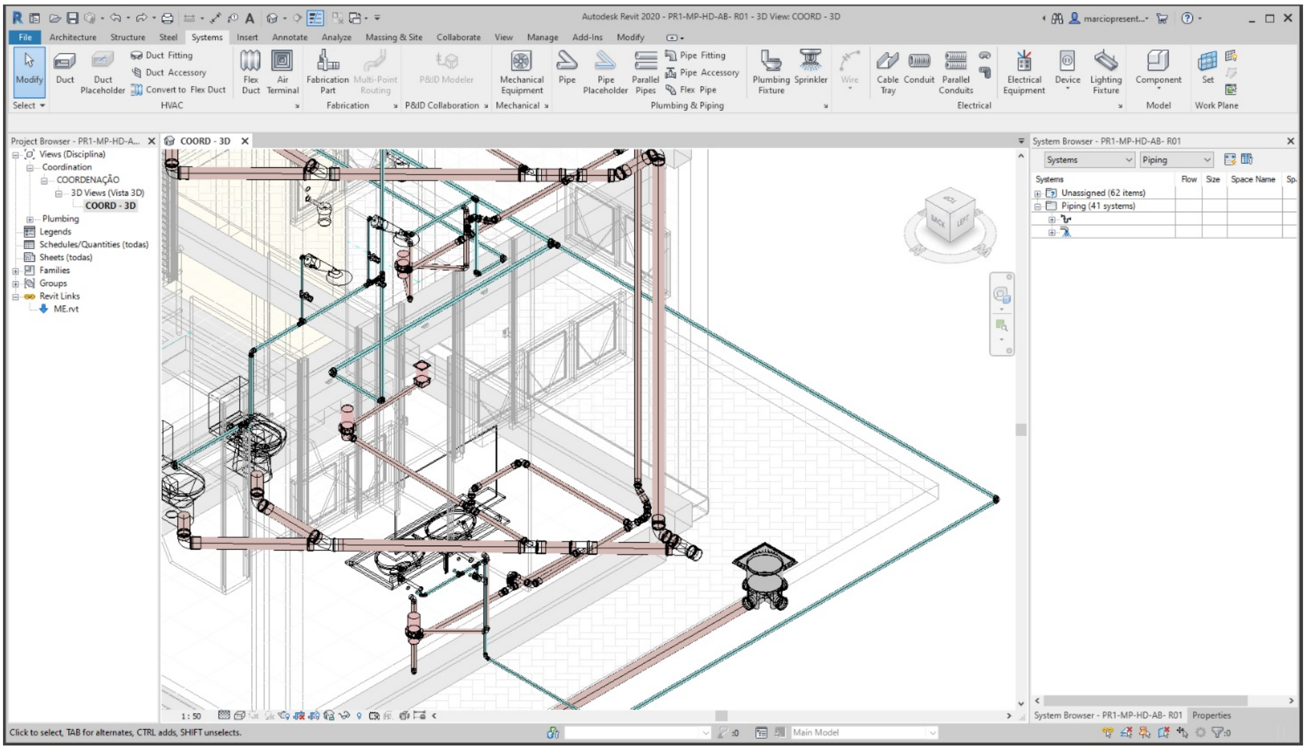
The architecture model was primarily developed, supporting the other disciplines. The architectural plans in dwg format were imported, guiding the positioning of the structural axes and the modelling of all components to comply with the project (Figure 2). For the development of the structural model, 2D formwork plants of all levels were imported, supporting the positioning of foundation elements, pillars, and beams. After that, the active BIM model was converted into an integrated model using the "central model" tool. That was achieved by using the "Worksets" functionality. Two standard Worksets were generated: the "Shared Levels and Grids", containing the original project's levels and axes, and the "Workset," with all the model elements. The resulting integrated architectural and structural model allowed for simultaneous and shared work between designers within either a local network or in the cloud (Drive).

Figure 2: Integrated Model - Architecture and Structure



The mechanical systems modelling was carried out based on the integrated architecture and structure model. It was inserted as a link in a template file of mechanical systems and organised into three sections in the Revit project browser: coordination, cold water, and sewage. This template facilitated the modelling process by separating each system's components and enabling the visualisation of sections in the coordination tab and updates to the files (Figure 3). The crucial point here was to obtain only references for positioning the pipes and sanitary pieces for modelling the ducts from the integrated model.

Figure 3: Coordination Section in the Mechanical Model



For electrical systems modelling, it was first necessary to understand the distribution of networks in the original project's building (Figure 4). As was the case in the mechanical model, the modelling of electrical systems started with the insertion of the integrated architecture and structure model in the template through a link, generating a linked model that could be constantly updated. Automated software solutions were used for the numbering and distribution of the circuits based on the original design (Figure 5).

Figure 4: Ground Floor Electric Plant of Original Design in dwg Format (Source: USP São Carlos Campus City Hall, 2019).

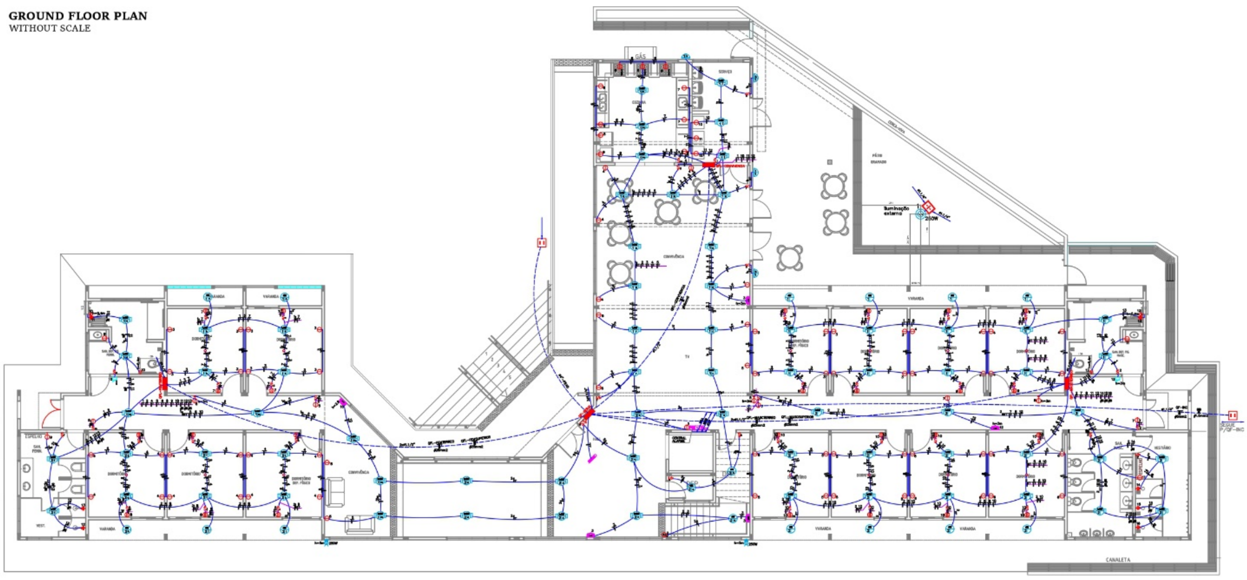
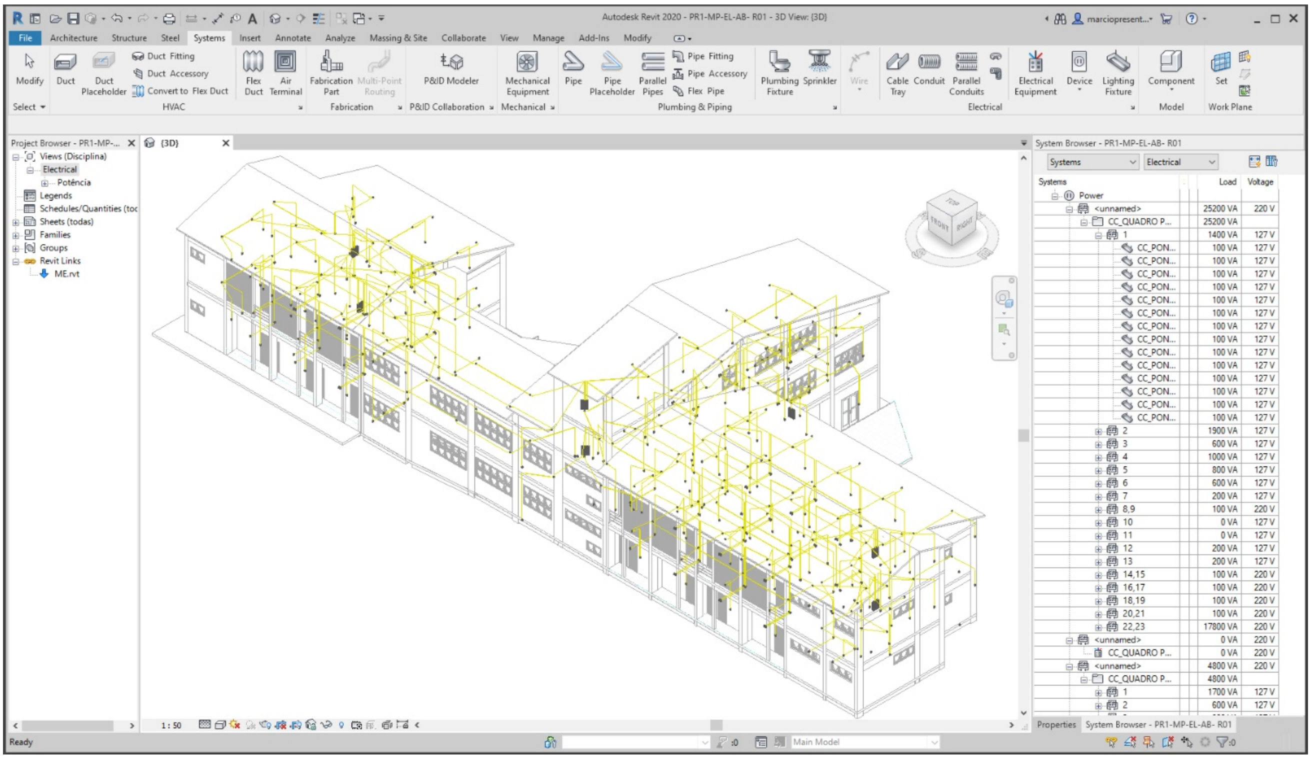


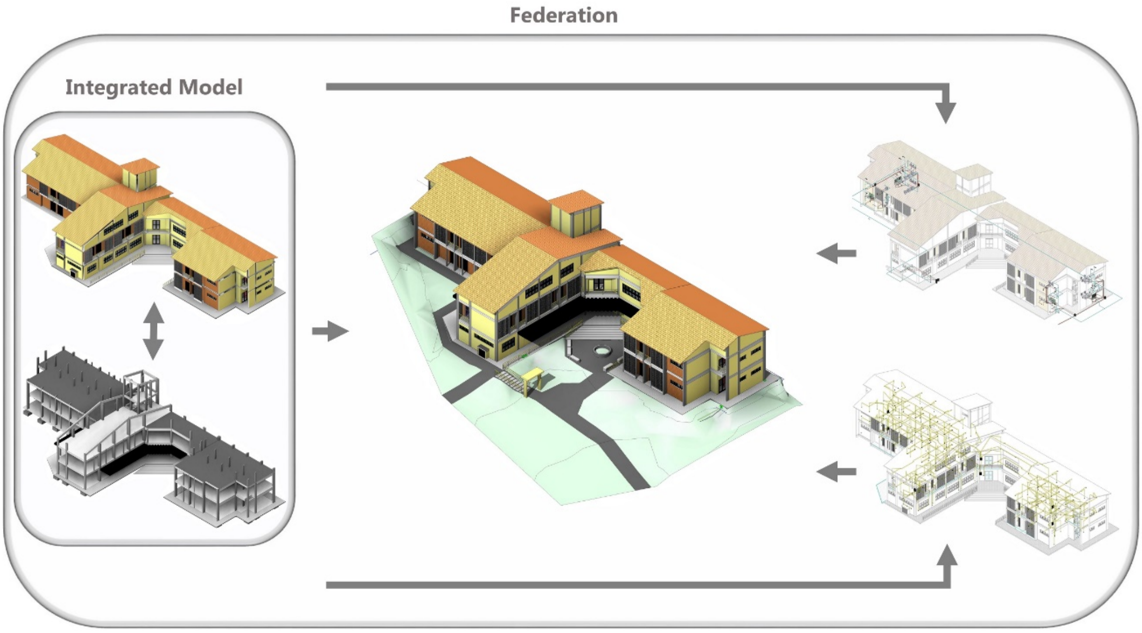
Figure 5: Modelling of Conduits and Circuit Boards in the BIM Electrical Model



*Federation of Models and Checks*

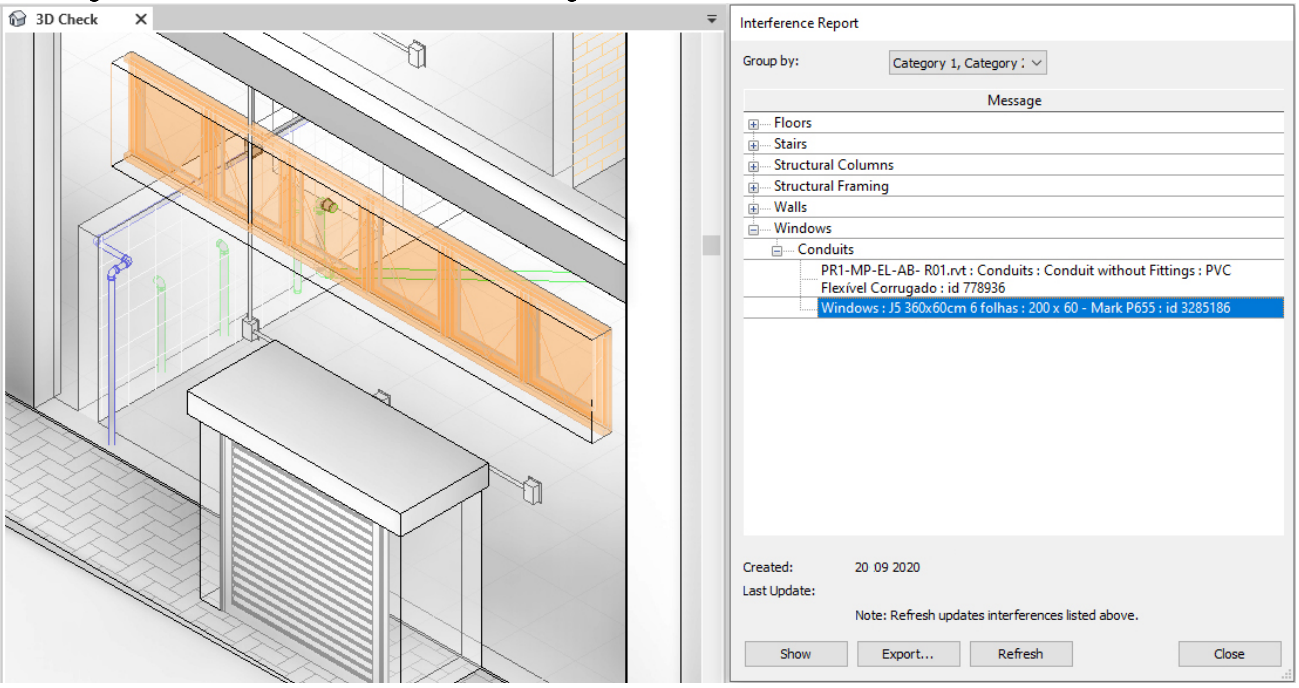
The federated coordination model was produced by linking the integrated architecture and structure model with the mechanical and electrical models in a single file, supporting the verification of interferences and the integrity analysis (Figure 6). In Revit, interference checking among disciplines can be performed using the "Interference check" native tool. This tool enables the user to define which families in the models (imported or linked) will be applied for conflict detection.

Figure 6: Perspective of the Four BIM Models Making Up the Federated Coordination Model in the Centre



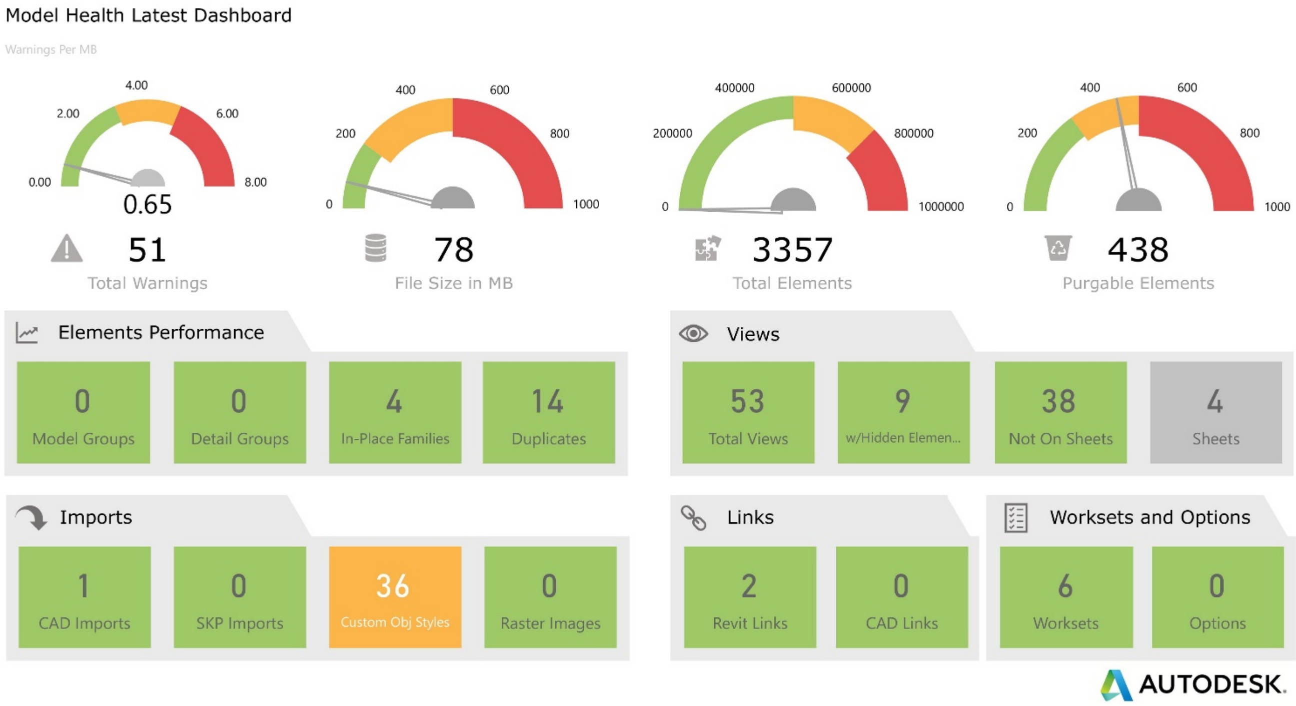
Given the existence of only two disciplines, a rapid test and validation process was conducted. The first verification was carried out between architecture and structure in the integrated model. Architectural elements (i.e., columns, floors and walls) were excluded from the verification, considering that their integration with the structural elements corresponds to a constructive characteristic of the adopted constructive system and does not amount to a design interference. The second verification involved the integrated model and the mechanical and electrical models. Among the conflicts, most results showed incorrectly positioned components, such as the intersection of a conduit with a window (Figure 7), information that was not registered in the original project.

Figure 7: Interferences Identified between the Integrated Model of Architecture and Structure with the Electric Model




The federated coordination model was used to identify project delivery patterns and manage the models' integrity and interoperability, which are critical aspects of the process's performance. The Model Checker tool was used to generate the model's compliance report, as shown in Figure 8. The parameters "Total Warnings", "File Size in MB", and "Total Elements" presented desirable indices regarding the number of elements, warnings, and the size of the model. On the other hand, the parameter "Purgeable Elements" in yellow revealed a high number of elements not used in the project. Plausible results regarding the "Elements Performance" were also observed. The "Imports" field shows in yellow 36 Custom Object Styles, possibly linked to files in dwg format during modelling. Concerning the "Views" parameter, 38 Not On Sheets views were identified, indicating that the model is incomplete. Finally, the "Links" and "Worksets and Options" parameters relate to the solutions used to create the federated model.

Figure 8: Compliance Report Generated by Model Checker




*Evaluation of teaching experience*

The BIM learning indicators proposed by the BAF (2013) and the CLT concepts were used as a qualitative tool to evaluate the reported experience. As shown in Table 1, the indicators were structured into three groups (A. learning and understanding; B. practical skills; and C. transferable skills) and assessed by the participants according to the complexity level of the content (intrinsic load) and the facilitation level of the teaching-learning strategy (extrinsic load).

Table 1: Results of the Assessment of Learning Indicators

| **Criteria** | **Very Little Complex > Very complex (1 to 5) or not addressed (0)** | **Index** | **Very Facilitator > Very Little Facilitator (1 to 5) or not applicable (0)** | **Index** | **Assessment** |
|---|---|---|---|---|---|
| **Teaching-Learning Group** | **Intrinsic Load (content)** | | **Extrinsic Load (teaching-learning strategy )** | | |
| A. Learning and understanding | 1. Collaborative working, BIM, information management and its application in the built environment | 5 | Exposure of the concepts of federated model, integrated model and single model. Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design. | 2 | Very complex<br>Facilitating |
| | 2. Commercial implications – contractual/legal | 4 | Elaboration of Exchange Information Requirements (EIR). | 2 | Complex<br>Facilitating |
| | 3. De-risking projects through BIM and risk management | 4 | Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design. | 4 | Complex<br>Little Facilitating |
| | 4. Understanding nature of current industry practice | 5 | Exposition of theoretical classes and multidisciplinary practical experience of collaboration. | 4 | Very complex<br>Little Facilitating |
| | 5. Client value – soft landings | *0* | *Not applicable.* | *0* | *Not applicable.* |
| | 6. Business value / value proposition | *0* | *Not applicable.* | *0* | *Not applicable.* |
| | 7. Understanding supply chain management | *0* | *Not applicable.* | *0* | *Not applicable.* |

| | | | | | |
|---|---|---|---|---|---|
| | 8. Lifecycle management of BIM | *0* | *Not applicable.* | *0* | *Not applicable.* |
| **B. Practical skills** | 1. Demonstrate ability to adopt different platforms | 4 | Integrated use of Revit, Excel and PowerBI software for modeling, federating and verifying models. | 2 | Complex<br>Facilitating |
| | 2. Critically judge/evaluate various BIM tools/applications | 4 | | 3 | Complex<br>Strategy Adequate |
| | 3. Protocols/inter-operability/standards | 5 | Definition of technical and managerial parameters for BIM modeling and coordination, definition of protocols to resolve interferences and perform the model integrity analysis and creation of a system for sharing the model. | 3 | Very complex<br>Strategy Adequate |
| | 4. Capability evaluation | 3 | Integrated use of Revit, Excel and PowerBI software for modeling, federating and verifying models. | 2 | Neutral Complexity<br>Facilitating |
| | 5. Change in way projects are to be delivered | 4 | Delivery of the detailed models by discipline, as well as the Integrated Model and the Federated Model. | 2 | Complex<br>Facilitating |
| | 6. Visualisation of large data sets | 4 | Using the Federated Model. | 2 | Complex<br>Facilitating |
| | 7. Lean principles and links to BIM | *0* | *Not applicable.* | *0* | *Not applicable.* |
| | 8. Use of BIM enabled technology | 4 | Integrated use of Revit, Excel and PowerBI software for modeling, federating and verifying models. | 2 | Complex<br>Facilitating |
| **C. Transferable skills** | 1. Project level application | *0* | *Not applicable.* | 0 | *Not applicable.* |
| | 2. Cross discipline and team working | 5 | Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design. | 2 | Very complex<br>Facilitating |
| | 3. Importance of effective communication and decision making | 4 | Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design; coordination meeting; identification of the required models and definition of information for the models of the disciplines; definition of coordination areas; development of a schedule for coordination. | 2 | Complex<br>Facilitating |
| | 4. Process mapping and BPR (Business Process Re-Engineering) | 4 | Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design. Process mapped based on BIM Project Execution Planning templates (CIC, 2010, 2011). | 1 | Complex<br>Very Facilitator |
| | 5. Change management and cultural gap | 4 | Multidisciplinary practical experience of collaboration, modeling and BIM coordination of building design. | 3 | Complex<br>Strategy Adequate |
| | 6. Masters level thinking – strategic/technical/ managerial | 5 | | 4 | Very complex<br>Little Facilitating |
| | 7. Ability to assess barriers to BIM at various levels | 5 | | 4 | Very complex<br>Little Facilitating |

Legend

| Intrinsic Load (content) | | Extrinsic Load (teaching-learning strategy ) | |
|---|---|---|---|
| Very Little Complex | 1 | Very Facilitator | 1 |
| Little Complex | 2 | Facilitating | 2 |
| Neutral Complexity | 3 | Strategy Adequate | 3 |
| Complex | 4 | Little Facilitating | 4 |
| Very complex | 5 | Very Little Facilitator | 5 |

Concerning the learning and understanding group, the content of (1) was evaluated as very complex, and its teaching strategy was deemed facilitating. Meanwhile, the content of (2) was considered complex, and its teaching strategy was deemed facilitating. The content of (3) was assessed as complex, while its teaching strategy being a little facilitating. Similarly, the evaluation of item (4) considered the content very complex and the strategy a little facilitating. In both cases, difficulties were faced in addressing the BIM domain's practical issues within the academic context, such as risk management and industry changes. Items (5), (6), (7) and (8) were disregarded in the assessment because they were not addressed in the course. The development of skills might be improved by expanding the experience to other stages of the design process and phases of the life cycle (e.g., strategic definition, construction, and operation). Moreover, benefits might be expected from more significant interaction between the participants and the industry environment, such as internships and visits to companies, discussions with multidisciplinary teams working in BIM, and specialised professionals' lectures.

Practical skills (Group B) had the highest concentration of good learning indicators. The participants considered the content complex and the teaching strategy facilitating for items (1), (5), (6) and (8). The adoption of integrated platforms for modelling and coordination (i.e., Revit, Power BI, Google Drive) enabled the development of practical skills for tool operation, the visualisation of large volumes of data, and the delivery of products in the required format (e.g., templates and reports). The exercise also stimulated criticism and validation of the process models standards from a practical perspective. For (2), the content was assessed as complex, and the teaching strategy was facilitating. The former assessment was due to the difficulty encountered in critically evaluating all the tools through an exercise only focused on the design process stage.

The learning of practical skills throughout the collaboration process is noteworthy. The participants' difficulties in using some tools were solved with the support of tutorials and online forums, within the time limits of the exercise. A pertinent example here was the process of modelling sanitary fitting families, which was initially carried out by the architectural designer in the integrated model, generating joint problems that hindered mechanical modelling activities. The solution adopted by the mechanical designer was to replace these families with others that met the project specifications in the integrated model. This work could have been better performed with the definition of protocols for the insertion of families in the initial moments of planning activities or even using native software tools to control and monitor objects' insertion in the models.

Students also experienced some difficulties in modelling the electrical systems. The first such obstacle involved understanding the two-dimensional drawings in the floor plan and details of the distribution boards. This representation hampered the comprehension of the logic of circuit numbering and the paths taken by the conduits, rendering it time-consuming for the professional to read and interpret the project. Another obstacle stemmed from automated software solutions for the numbering and generating of circuit paths and editing the load capacity in specific installations. Software restrictions on editing conduit paths within a circuit compromised the accurate documentation of existing designs, leading to disagreements about the original design. During the defining of some luminaire circuits' points, for example, warning messages indicated a load exceeding that recommended by the Brazilian standard NBR 5410 (ABNT, 2004). It was then up to the designer to analyse each item and check if there was any oversizing in the original project's specifications, thus generating rework. These restrictions revealed the need for a broad knowledge on the designer's part about the relevant technical standards and the settings of these parameters in the software, which represents a demanding requirement for beginners in BIM.

Regarding practical skills (4), the content's complexity was considered neutral, and tools supported the teaching strategy facilitated since the evaluation of the project and the BIM models for checking interference and assessing the model's integrity. For example, interference was verified within architecture and structure models. These included a window overlap with a pillar, resolved by consulting the original design to ascertain the elements' position and how these fitted into the model. Besides, upon visiting the building, the participants noticed that some interferences identified in the models had probably been solved during the building's construction. Difficulties in visualising information in two-dimensional drawings might have contributed to the late identification of these conflicts, which could have been mitigated with BIM models' support in the design phase.

The conformity assessment generated by the Model Checker (Figure 8) helped identify opportunities for improving the model, contributing to the proposed collaborative process's efficiency. Desirable rates for Total Warnings, File Size in MB, and Total Elements favoured the exchange of information between designers and integration among files. Although good indexes were observed for the Elements Performance parameter, duplicate elements and modelled families had to be avoided because they would have overloaded the file. Similarly, for the Views parameter, it would be recommended to arrange views to facilitate an understanding of the project among stakeholders, even though many views do not impact the file size. Among the parameters classified in yellow, the high number of Purgeable Elements negatively impacted software performance, which could have been minimised with the exclusion of these elements. Likewise, Custom Object Styles could be reduced using links instead of files imported from AutoCAD, thereby improving the model's performance, and reducing file size.

Regarding practical skills, according to the evaluation of item (3), its content was considered very complex, and the teaching strategy was deemed adequate. As discussed in this study, BIM standards have been developed by governments, academia, and industry bodies worldwide. However, given the complexity of the topic and the chain of involved stakeholders, defining consistent references can be challenging. In the proposed exercise, the use of only proprietary software for modelling and coordination of all disciplines eliminated interoperability problems. Also, requirements defined in the EIR and the process model supported the collaborative work between participants. Meanwhile, item (7) was disregarded in the assessment since it was not addressed in the discipline.

Finally, transferable skills (Group C) were assessed. Item (1) was disregarded in the assessment because it was not addressed in this discipline. The content of (2) was considered very complex, while the teaching strategy was deemed facilitating. Although transversal disciplines' interaction is challenging from a technological and procedural perspective, the participants considered the exercise a learning facilitator, supporting their comprehension of complex concepts. Elsewhere, (3) was assessed as complex. The teaching strategy was deemed to be facilitated by the participants, whom all considered the team meetings effective for developing communication and decision-making skills. The process mapping (item 4) was evaluated as complex, although it was supported by theoretical framework templates (CIC, 2010, 2011) and the Bizagi modelling software. For (5), concerning cultural change, the content was considered complex and the teaching strategy adequate, supporting the identification of prejudicial market practices for the effective adoption of BIM (e.g., the verification of design interferences in the model only solved in the building's construction stage). Regarding (6) and (7) were evaluated as very complex and minimally facilitated by the adopted teaching strategies. Difficulties in learning these items can be explained, in part, by the pragmatic approach to the experience, which used existing projects to develop modelling and coordination activities.

In general, the participants considered the experience satisfactory from an academic and professional point of view. The learning assessment reinforced the relevance of a hybrid teaching approach, connecting the theoretical content with the development of strategic, managerial, and training protocols in computational tools to make the best use of the BIM design and coordination process. However, there is a need for greater alignment concerning the time and sequence of the content presented to the student's cognitive ability to learn new concepts. Attention should be given to complex intrinsic loads (content) through a facilitating strategy, such as PBL.

## *Conclusions*

The theoretical and practical investigations undertaken by this study have made essential contributions to BIM teaching and learning. The analysis of the selected BIM standards and guidelines showed that, although complementary, their application in the BIM process depends on the professionals' skills and the organisational environment in which they work. Although the guides assist in understanding basic concepts set by technical standards, very complex concepts are only understood following the gaining of experience in carrying out the activities described in these materials, which requires significant effort from beginner professionals. Based on the model's design and coordination activities, the exercise aimed to establish a collaborative BIM work environment consistent with AECO practices, assisting students in developing strategic, managerial, and technical skills. The structuring of BIM processes, the modelling of disciplines and the analysis of models together form a cohesive cycle of the BIM work process, enabling the comprehension, even if partial, of the roles, played and responsibilities assumed by designers and coordinators in the market context.

In the practical exercise, the first challenge regarding applying guides and standards involved the definition of BIM uses and the development of the BIM design and coordination process model (Figure 1). To do so, the detailed process map templates of the BIM Project Execution Planning Guide supported the proposed activities. Remarkably, the BIM use process maps recommended by the CIC (2010, 2011, 2019) have been widely reproduced by Brazilian guides (ABDI, 2017). Although mentioning the use of BPMN, these templates do not comply with international standards. It is essential that BPMN is correctly applied in BIM process models, enabling the use of information in automation processes by computer professionals (e.g., machine learning) and facilitating integration with other knowledge areas. Another challenge was the definition of requirements for modelling and coordination among the participants, structured according to the EIR, which proved insufficient for conducting the exercise. In a future exercise, the Master / Task Information Delivery Plan– (MDIP / TIDP) documents could also be explored during the course, deepening the investigation of information delivery plans.

The beginner designers' workflows revealed some difficulties and benefits in the collaborative process of BIM modelling and coordination. Some problems solved during the exercise, such as the incompatibility between sanitary families, restrictions of editing of electrical circuits, and the interference between systems, had arisen due to the students' lack of experience with the coordination of processes with the support tools in the software. A review of each designer's planning and assignments and a deepening of the domain of the functionalities of the specific tools for each discipline could mitigate such problems. Among the benefits, the models' three-dimensional visualisation helped the designers understand the solutions and the interfaces connecting systems. The verification of interferences proved to be a fundamental benefit of the process, mainly due to the ability to foresee conflicts between the structural and the mechanical and electrical systems. As demonstrated in the compliance report, the federated model's good performance was directly related to the individual decisions made in the modelling of each discipline and in the strategy used to integrate the models. This finding reinforces the importance of the prior definition of the technical and managerial requirements that support all the collaborative process.

Concerning the BIM design and coordination process model (Figure 1), serving as more than a planning resource, its development played two crucial roles in the BIM teaching-learning process: first, supporting the organisation of the processes associated with the BIM use and the identification of technological and deliverable tools; and second, pointing out the learning indicators associated with each activity in the process. By presenting a synthesis of the experience, the model contributes to enhancing knowledge in the following two ways: from a practical point of view, guiding inexperienced professionals in structuring similar BIM design and coordination processes; and, from a theoretical point of view, assisting teachers in identifying learning opportunities through didactic activities.

The didactic experience revealed the need to review some of the assumptions commonly adopted in courses that aim to teach BIM using approaches based on a mixture of theoretical and practical classes. The study showed that students boosted their knowledge in relation to what they had previously mastered during the experience. However, their comprehension of complex concepts and specific software features was impaired, which demonstrates a cognitive overload of working memory. One of the reasons for this might be the time restriction on the processing and applying of knowledge content (intrinsic loads), given the compact format of the discipline (extrinsic loads) taught in two weeks of face-to-face classes. Another reason might be the limited interface with professionals and the industry's organisational environment. This could be overcome by establishing a collaborative environment beyond the university's boundaries, engaging experienced professionals from the industry to share experiences in lectures or effectively participate as consultants in the course.

*Limitations and Future Work*

There is some difficulty in teaching BIM management processes to AECO professionals in an academic environment. Many of the necessary skills can only be acquired from practical activities in the construction industry. In this research, obstacles were partially overcome by adopting existing building projects, thus focusing on modelling and collaboration processes rather than developing design solutions. On the other hand, the following opportunities for future research have emerged: first, to conduct teaching exercises with team members from distinct backgrounds (i.e. architecture, civil engineering, or MEP), thereby stimulating collaboration; second, testing multiple BIM software, reflecting the current reality of the industry; third, to investigate other strategies for structuring the modelling and federation process in addition to the one used in this work (summarised in Figure 6 and based on the suggestion of Kirby, Krygiel and Kim (2018)); and, fourth, to expand the learning assessment criteria beyond the CLT and the BAF (2013), conducting surveys with a larger group of students to ensure the statistical reliability of the data.

It should be noted that the postgraduate course in which the study took place served as a background for reflections on the entire learning process described. The course activities ended with the delivery of the BIM models, while the BIM design and coordination process model and the learning assessment framework attributable to a group of students and teachers' joint efforts. In addition to the teaching-learning experience, the study reinforces the significance of academia's role in spreading multiple layers of knowledge required by professionals to understand BIM.

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