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# Full-Scale Implementation of an Automated Connecting Device for Modular Construction

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**Abstract:** Modular construction is characterized by assembling volumetric units on site. Once assembled on site, the structural integrity of modular buildings highly relies on connections that provide essential performance against critical loading conditions. Connections significantly impact field assembly activities, and previous research has highlighted the importance of their functional performance. In this study, the researchers focus on implementing automated connecting devices in a full-scale experimental project. It presents the implementation of a self-locking inter-modular connector and an investigation of the benefits and limitations of its application in modular building systems. This study also investigates the use of connectors as attachment points for modular handling and lifting. It evaluates the pros and cons of combining a single device's connecting and lifting functions. The implementation of an automated connecting device in the building design process is covered as well as the evaluation of its impacts on architectural, structural, and functional considerations. Finally, the potential of automated connecting devices to improve modular building systems' overall performance and efficiency is assessed, and guidelines are identified to facilitate their adoption.

**Keywords:** inter-modular connection; self-locking joints; light-framed modular buildings; full-scale implementation; structural connection

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## 1. Introduction

The emergence of Industry 4.0, applied to construction, is marked by the automation and robotization of the construction process by new constructive environments in the form of intelligent factories as well as by the simulation, modeling, and digitalization of objects and projects [1]. This emergence has resulted in a sharp increase in construction research, one of the main areas being off-site construction [2]. Among the various forms of off-site construction, modular construction is the one whose assemblies delivered to the site show the greatest level of completion [3]. Methods for assembling prefabricated modules are currently the subject of intense research because inter-modular connections (IMCs) are a crucial part of off-site construction as they serve a prominent role in the structural integrity of modular building systems [4–13]. Rajanayagam et al. [10] reported 25 existent IMCs, out of which none fully met all the requirements for off-site construction, and argued that only automated or semi-automatic connections have the ability to resolve both constructional and functional requirements [10]. According to Rajanayagam et al. [10], full-scale field test studies for IMCs are required as they will significantly impact off-site construction and foster new opportunities to improve automation in construction.

From this perspective, two research groups recently proposed automated connecting devices (ACD) for off-site construction [14–16]. An ACD is a device with a self-locking mechanism where no human intervention is needed to secure the connection [14,16]. Having a mechanism that fulfills all the requirements for self-locking while being sturdy enough to support the loads encountered at the connection points is a complex and non-trivial task. The loads applied to structures vary depending on their geometry, location, and material used [17]. As modular units are likely to have more than one connecting point, ACDs must be manufactured and positioned accurately in a building. Picard et al. [16] highlighted that two opposing constraints exist within an ACD: first, to obtain self-connection, the ACD must include functional clearances between assembly parts. Second, for the connection to be treated as semi-rigid for seismic considerations, the ACD must present direct contact between surfaces and achieve an efficient load transfer while minimizing module displacement [8]. To achieve sufficient strength, stiffness, and ductility within a two-part connector located in two different modules, a factory must be capable of achieving high accuracy in positioning the connectors as well as controlling critical dimensions throughout the process, including a way to validate the connection [18]. While the quality of fabrication in off-site construction is often emphasized in the literature, very little research has quantified the dimensional control and accuracy commonly attainable in modular factories. Moreover, while in-lab testing took place in both Dai's and Picard's studies [14,16], no research has yet presented whether connection occurs when the ACDs are integrated in a real building, which makes the innovative concept still unproven. Hence, the main question is the following: can an ACD be successfully implemented in a full-scale building and provide the expected advantages?

Integrating ACDs in modular buildings is expected to affect many elements, namely the following: the general building design and design process, the production of adequate off-site work instructions (including shop drawings), the in-factory fabrication process, the inherent dimensional control required for installing the connectors, the insulation process, the on-site assembly process including modular preparation/handling, the connection itself (including proof-of-connection), and the completion level that can be reached. Without the full integration of ACDs in a real building, their functional performances are hypothetical and unverified. Full-scale testing was specifically recommended to cover this research gap [19]. Our research team, along with our industrial partners, have managed to address this issue. A full-scale experimental project was developed to assess the functional performances of the ACDs developed by Picard et al. [16].

Similarly to what was found in the literature, IMCs have also been targeted as a key feature to improve the overall off-site industry as part of a sectoral reflection led by the government of Quebec and its partners [20]. Consequently, this study aimed to provide the process required for the successful integration of ACDs in a light-framed modular building. The focus was on the dimensional positioning and alignment concerns, the integration of the ACD in the project drawings, the in-factory integration, and the on-site assembly process.

Achieving a full-scale experimental project that integrated an innovative technology while allowing the acquisition of qualitative data regarding the overall performances (including workmanship user experience, ease of use, etc.) required a methodology that combined social and technical sciences. The project realization had to be performed in a working environment where all individuals involved were aware of the general objective, which was to implement the ACD, reflect and react if needed, and observe its performance. Participatory action research (PAR) aims to offer a framework for creating knowledge that is rooted in the belief that those most impacted by research should take the lead in framing the questions, design, methods, and analysis and determining what products and actions might be the most useful in effecting change [21]. Consequently, by adopting the PAR methodology in this study, all major actors in the construction project (promotor, entrepreneur, manufacturer, and engineering firm) became stakeholders in our research [22]. Each actor involved in the full-scale experimental project contributed to creating a favorable context for carrying out field studies, which is consequent with the premise of the PAR methodology. The voluntary participation of stakeholders in the full-scale experimental project clearly demonstrates the industry's willingness to use ACDs and the acknowledgment that field studies must occur in the maturation process of developing innovations for construction.

This research is in alignment with current industry trends that emphasize automation and technological advancements. As the construction sector undergoes evolution, this study offers valuable insights into positioning automated connecting devices (ACDs) as a transformative technology, contributing to the ongoing modernization of construction practices. To address uncertainties surrounding their usability, this study showcases the successful integration of ACDs into a full-scale building. This not only highlights the feasibility of incorporating automated connecting devices into modular construction but also brings forth several noteworthy implications. These include insights into the extent of challenges associated with dimensional control during off-site installation, the additional architectural and structural constraints introduced, and the impact of on-site perturbations.

## 2. Method for Implementation and Observations

### *2.1. Full-Scale Experimental Project Overview and Key Activities for Implementation*

The experimental testing site was located in Lévis, Canada. This off-site construction project was a 8.5 m × 8.5 m two-story house comprising four modules and a concrete basement and was erected in September 2022. The participants in this research can be listed as the promotor, the general contractor, the module manufacturer, and the engineering firm. The project was specifically created for research purposes to achieve and observe the implementation of a new inter-modular connection.

The planning activities of the full-scale experimental project covered a design revision of the ACD presented in Picard et al. [16], the manufacturing of twelve ACDs for the full-scale experimental project, and the identification of quality control requirements for the in-factory implementation of ACDs. The realization process presented in this article follows the planning activities and begins with the virtual integration of ACDs into building design and drawings, followed by the off-site integration of the ACD during module manufacturing, and on-site building erection. The participants responsible for building models, renders, and drawings were the promoter and the engineering firm, while the module manufacturer fully carried out the off-site implementation. The general contractor fully carried out on-site activities such as the off-site preparation, foundation, and erection.

### *2.2. Observational Method and Expected Results*

The full-scale experimental project followed the PAR cyclic methodology of inducing a change/observe/reflect/adapt attitude in both the planning and the realization phases. However, its application differed in both phases since, throughout the realization phase, the results obtained from the planning phase were applied as changes to the regular off-site ecosystems and their implementation was observed. Consequently, in the realization phase, the research team became an observant rather than an active participant, and observational activities were planned following the PAR method [23]. To ensure that the observations lead to results that contribute to the general knowledge associated with ACD implementation, Table 1 presents the expected results for each activity and their associated observational method, based on the PAR methodology. All the expected results are presented in this article, and the appropriate section is referred in parentheses. For on-site erection, since many elements occurred simultaneously, various sources of visual footage were used. To observe the mechanism deployment of the ACD with detail, endoscopic cameras (model 86T-5MP from DEPSTECH, Hong Kong, China) were installed between the floor joists, with a 15 cm × 15 cm cut in the OSB sheathing to access the camera to capture real-time video footage. One drone (Mavic Mini from DJI, Shenzhen, China) was used for aerial footage, and two digital action cameras (HERO6 by GoPro, CA, USA) were installed with different angles inside and outside the building.

**Table 1.** Observational method and expected results for each activity of the full-scale experimental project.

| Activity | Expected Results | Observational Method |
|---|---|---|
| 1. Integration in building model and drawings | (1.1) Identification of the strategy for ACD inclusion in the design<br>(1.2) Identification of guidelines for positioning the ACDs in the structure<br>(1.3) Identification of architectural design restrictions caused by ACDs<br>(1.4) Identification of the strategy for ACD inclusion in production plans<br>(1.5) Identification of critical dimensions for positioning ACDs | Real-time follow-up of building integration modeling (BIM)<br>Recurrent meetings with all participants |
| 2. Off-site implementation | (2.1) Identification of dimensional inaccuracies within the production line<br>(2.2) Analysis of the ACD's positioning accuracy | Presence of researcher in factory<br>Spreadsheet with critical dimensions to observe, measure, and note<br>Photos, videos, interviews with workers |
| 3. On-site erection | (3.1) General observations:<br>(a) Module parallelism with ground<br>(b) Module flexibility in XY plane<br>(c) Lifting by four eyebolts<br>(d) Module guidance during descent<br>(e) Positioning accuracy post lifting<br>(f) Interior finish post lifting<br>(g) Connection success rate<br>(h) Sound confirmation of connection<br>(3.2) Analysis of the connection success rate<br>(3.3) Proposal of acceptability thresholds | Team of observers: two videographers, one photographer, one timekeeper, two measurers<br>Spreadsheet with activities and associated time of realization<br>Spreadsheet with expected critical dimensions<br>Photos, videos, interviews with workers |

## 3. Integration in Building Model and Drawings

### *3.1. Strategy for ACD Inclusion in the Design*

As the construction process of modular buildings relies on many participants, the transmission of clear documentation is critical to limit errors and waste of valuable resources. Hence, creating a complete 3D model during the design phase is an increasingly common practice that can contribute to properly preparing a project. This practice is nowadays referred to as building integration modeling (BIM). In the full-scale experimental project, the engineering firm was responsible for modeling the project's structure with the inclusion of the ACDs, and the promotor was responsible for providing drawings of the project's architectural, mechanical, plumbing, and electrical details. Once the BIM model was completed, the general contractor was responsible for creating manufacturing plans for the factory. Figure 1 shows (a) the structural (partial) skeleton model, where the building volume is discretized in four modules with lifting axes, (b) the addition of architectural elements (e.g., walls, partitions, floors, doors, appliances) and the mechanical, electrical, and plumbing elements, and (c) the BIM family of parts for the ACD (e.g., ceiling and floor connectors). In Figure 1, it is possible to identify the ACDs that were integrated in the early stage of design planning from the beginning via a family of parts for BIM integration. The strategy for designing this full-scale experimental modular building was to integrate the structural design and ACD at the beginning of the process, prior to defining the building in details, since it was anticipated that their presence would affect other components.

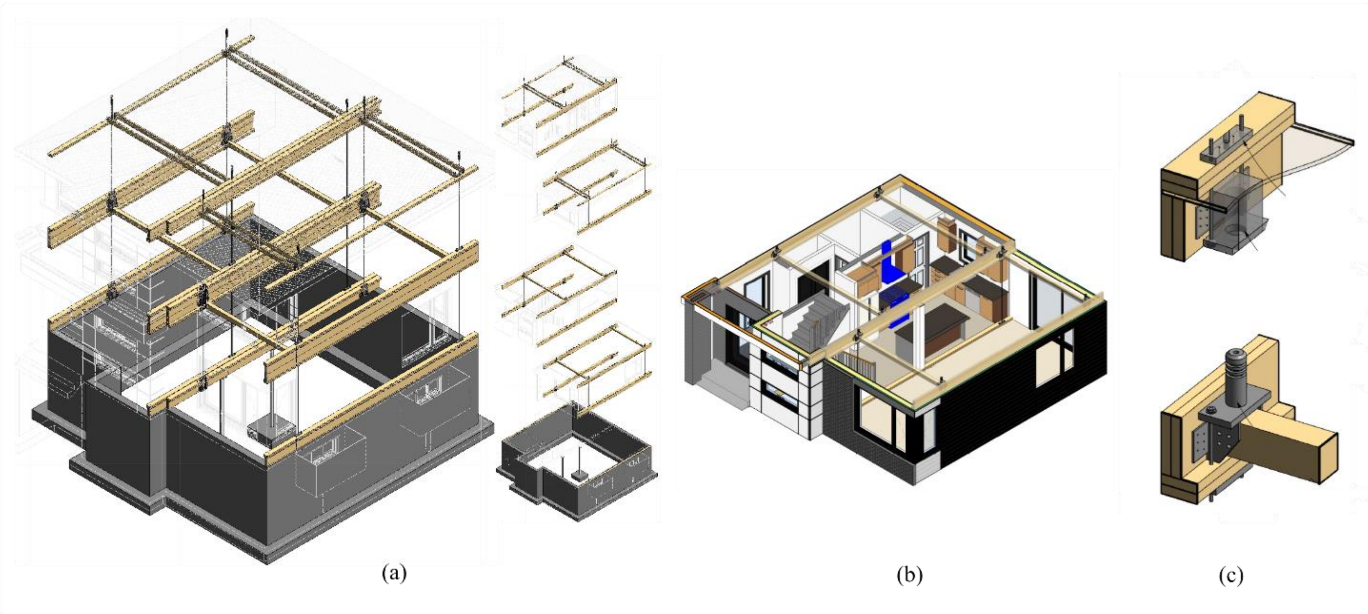


**Figure 1.** Inclusion of ACDs and lifting axes to plans: (**a**) structural skeleton; (**b**) architectural and mechanical/electrical/plumbing systems; and (**c**) BIM family parts for floor connector (hollowed) and ceiling connector (extruded).

### *3.2. Positioning the ACDs in the Structure*

To achieve the building design presented in Figure 1, the participants had to determine the positioning of the connectors throughout all the modules. Including ACDs in the BIM led to an easier understanding of the impact of positioning the ACDs in the building. Positioning the ACDs can become complex since numerous constraints are to be considered. The lifting of the modules can become a dominant constraint if the ACDs are expected to be used for lifting. Indeed, doing so requires a continuity between the floor and ceiling connectors within a module, while the connecting feature requires a continuity between two adjacent modules. Combining both features requires for this continuity to be kept throughout all stories. It was observed that this particularity added many restrictions to the design. As a result, it is recommended that the design process should always begin with positioning the lifting axes or cables to ensure safe lifting activities and streamline the architectural design. The constraints associated with the lifting of the modules are the following:

1. All lifting axes should be located on the most extended edges of a module, as most of the floor weight is distributed along these edges.
2. All lifting axes on either side of a module should be symmetrical for safe lifting.
3. The number of lifting axes should be determined with the total estimated weight of the module.
4. The geometrical center of all lifting axes should be very close to the gravity center of the module to ensure a proper load distribution.
5. The design team should evaluate module deflection and the maximum bending stresses caused by the chosen lifting configuration.

These constraints are highly restrictive when combined with ACDs. Regarding the ACD itself, the positioning should occur following these guidelines:

1. ACDs should be located according to the structural engineering plans where tension and/or shear loads occur.
2. ACDs should be located away from multi-level open areas (e.g., half-pace stairs).
3. ACDs should be located away from plumbing pipes and ventilation ducts.
4. ACDs should be aligned with 2 × 4-inch walls for proper installation (see Figure 1c).

### *3.3. Architectural Design Restrictions Caused by Combining ACDs and Lifting Axes*

This section was written to expose and recognize some design constraints induced by the use of the combination of ACDs and lifting axes. Figure 2a illustrates a bedroom area with the modular interface in the middle of a closet. With such a design, the lifting axis would need to be removed after on-site assembly, consequently adding undesirable on-site work. Figure 2b shows a window in a bedroom area located very close to an ACD and lifting axis. If the window was located further to the right, the design would need modifications to ensure complete clearance of the lifting axis. Moreover, the symmetrical lifting axis on the other side of the module lies in a partition wall designed in 2 × 4 wood lumber. This raises an issue since the lifting axis and ACDs used in this project need to be located in 6-inch-thick walls to be completely hidden. Figure 2c shows a half-pace stair located at the modular interface, causing interference with one ACD and causing an additional issue with the second ACD being in an open area (no wall). Finally, Figure 2d shows the open kitchen and dining room area where the countertop and lower cabinet interfere with the lifting axis.

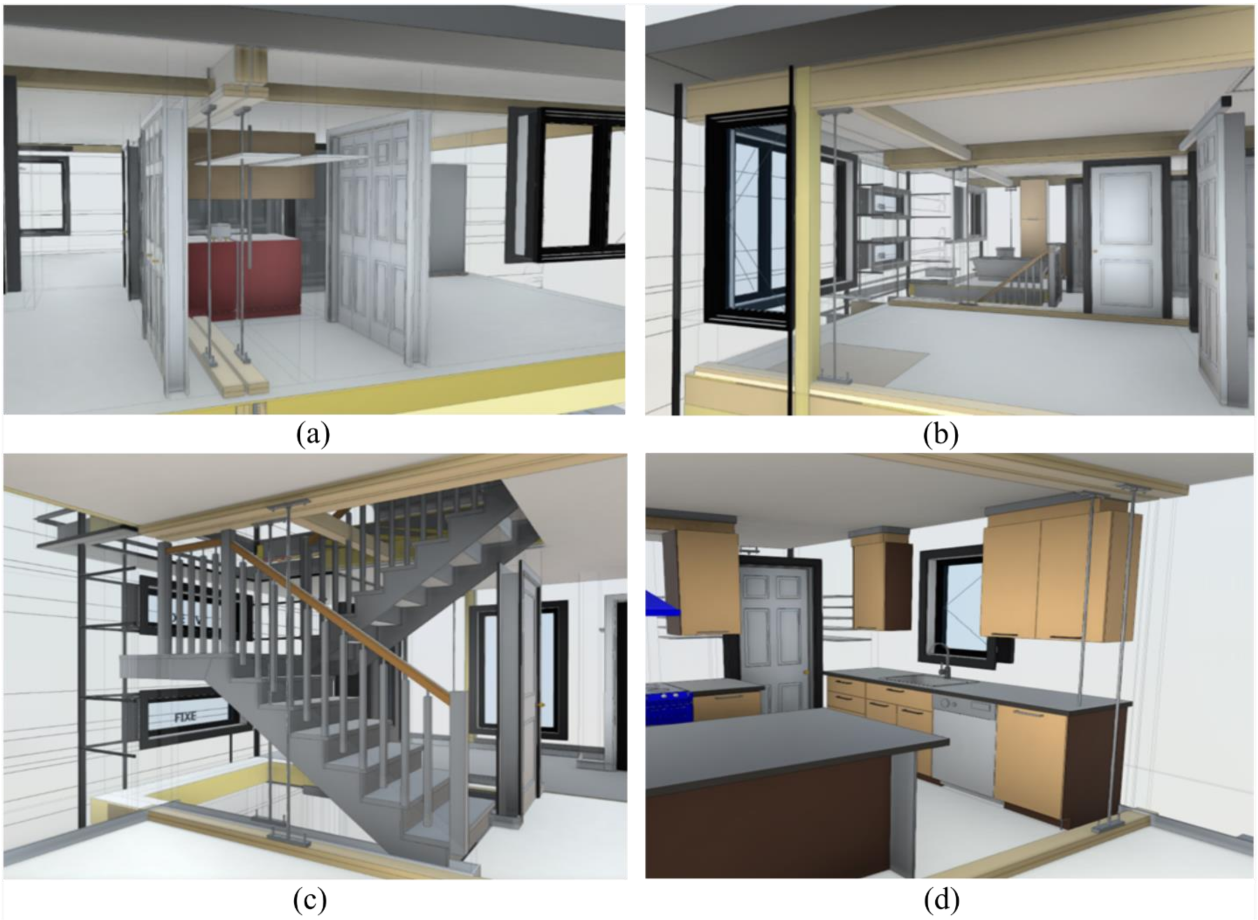


**Figure 2.** Observations and considerations of the use of an automatic connecting and lifting device in BIM modelling: (**a**) bedroom area, axes located in the closet; (**b**) bedroom area, axes located at the window limit; (**c**) open living room area, axes located in the open staircase; and (**d**) kitchen area, axes located through the countertop.

To summarize, in addition to the design guidelines for positioning defined in Section 3.2, the combination of the lifting axes with the ACD was observed to highlight architectural design restrictions with regard to the following elements:

1. Walls need to be dimensioned so that ACDs and lifting axes are hidden (in this case in 2″ × 6″ walls).

2. Windows and doors must be located away from the lifting axes.
3. Plumbing pipes and ventilation ducts must be located away from the lifting axes.

### *3.4. Identification of the Strategy for ACD Inclusion in the Production Plans*

To produce modules, manufacturing drawings are required in the factory at all workstations. Details of the ACD need to be included on all drawings to avoid problems. For example, if the plumbing drawings had been delivered without including the ACD, some pipe paths would have interfered with the ACD and, similarly, with the electricity and ventilation systems. From our full-scale implementation experience, it is recommended, as a result of the exercise, to perform an analysis of the factory workstations to understand at which workstation the ACDs should be installed, as these new elements challenge the status quo. In our experiment, detailed manufacturing drawings were provided with information on the ACD installation process. For the full-scale experimental project, the module manufacturer had distinct workstations for each task described in Table 2 and schematized in Figure 3.

**Table 2.** List of all workstation and associated activity in the factory of the module manufacturer of the full-scale experimental project.

| Workstation | Activity Description |
|---|---|
| 1 | Fabrication of the floor joists |
| 2 | Assembling the floor (cutting rim boards, positioning floor joists, squaring, sheathing, and fixing) |
| 3 | Fabrication of partition walls |
| 4 | Fabrication of exterior walls |
| 5 | Fabrication of ceiling or roof |
| 6 | Assembling the module (positioning of the walls and the ceiling and fixing) |
| 7 | Mechanical, ventilation, and plumbing systems' integration into the floor (basement station allowing access to the floor of the module from below) |
| 8 | Mechanical, ventilation, and plumbing systems' integration into the walls |
| 9 | Wall insulation and sheathing |
| 10 | Exterior doors and windows |
| 11 | Roof insulation and sheathing |
| 12 | Interior additions (kitchen and bathroom cabinets, appliances, etc.) |
| 13 | Module packaging and factory exit |

Workstation 7 was identified as being prone to the activities required to install the ACDs. When the modules arrived at workstation 7, the floor system was accessible from an underground access area, as illustrated in Figure 3, which allowed the installation of the floor ACD (hollowed part). Workstation 7 also provided access to the ceiling system via a platform, allowing the installation of the ceiling ACD (extruded part). Hence, one conclusion of this research is that the ACDs should be treated like conventional mechanical elements (e.g., HVAC, electrical, pluming) and should be planned at workstations dedicated to these elements.

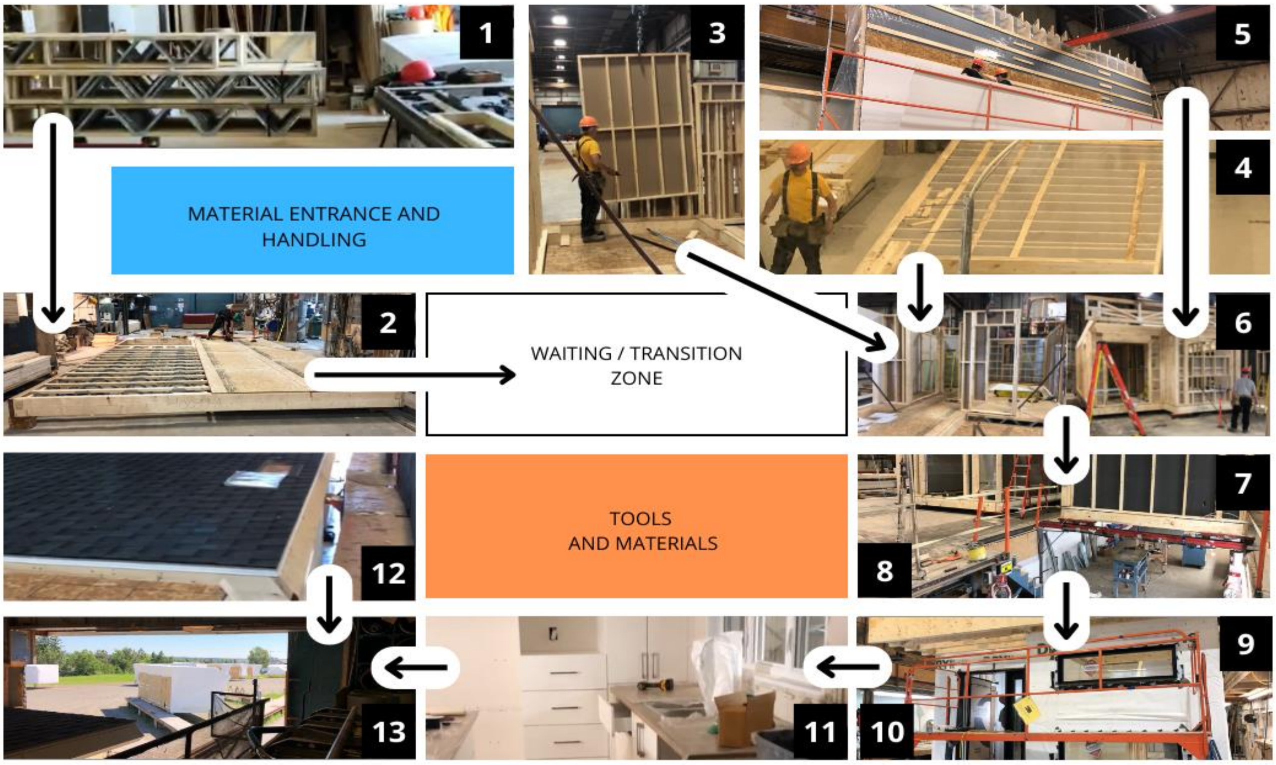


**Figure 3.** Module manufacturer of full-scale experimental project factory schematization with 13 identified workstations at specific locations.

### 3.5. Identification of Critical Dimensions for Positioning ACDs

Figure 4 presents a CAD analysis of various dimensions' angular, horizontal, and vertical impact for a successful connection. To ensure a complete connection, the shaft of the ceiling connector must complete its insertion in the cavity of the floor connector. The vertical dimensional clearance between the shaft grooves and the gripper teeth was designed to be 1.16 mm (A) to minimize the displacement when the load shifts from compression to tension. Hence, a connection was deemed successful when the top surface of the shaft reached the highest position or up to 1.16 mm (A) lower, as can be seen in Figure 4. It was associated with a 30.5 mm (B) theoretical distance between the bottom plate of the floor connector and the bottom plate of the ceiling connector. In the case of an incomplete connection, the grippers deployed and hit the outer surface of the shaft without being aligned with the grooves. Such an incomplete connection can still withstand shear and compressive loads but would fail to withstand tensile loads. Figure 5b presents the horizontal tolerances on misalignment. The 70 mm diameter shaft (C) must adequately enter the 75 mm (D) bore of the floor connector, which allows a 5 mm tolerance on the horizontal positioning. Moreover, because the shaft has a significant length, level errors can cause important horizontal and vertical displacements at the highest surface of the shaft. Knowing that the length between the top of the ceiling connector's lower plate and the top of the shaft is 193 mm, a 1.15 degree (E) error at its base can cause a horizontal displacement of 4.64 mm (F) at its top, as shown in Figure 4. Similarly, the same 1.15 degree (G) error causes the top edge of the top groove to sustain a vertical displacement of 0.74 mm (H) and a horizontal displacement of 4.03 mm (I). Since a vertical displacement of 0.74 mm (H) represents 63% of the allowable vertical offset (A) and the horizontal displacement of 4.03 mm (I) represents 81% of the allowable horizontal offset, this highlights the importance of severely controlling angular dimensions when positioning the ACDs in the factory.

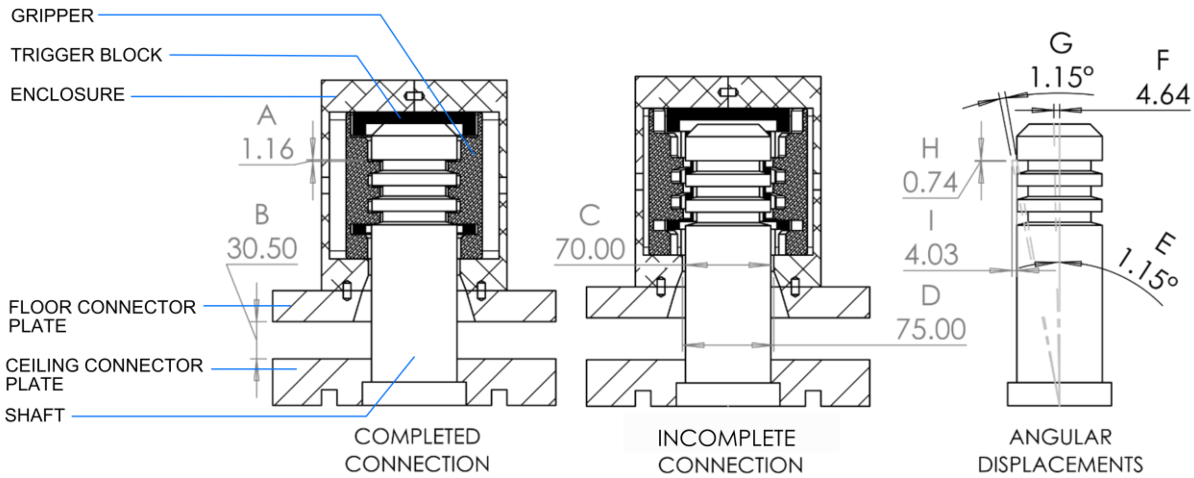


**Figure 4.** CAD analysis of functional gaps and clearances between floor and ceiling connectors for a successful connection.

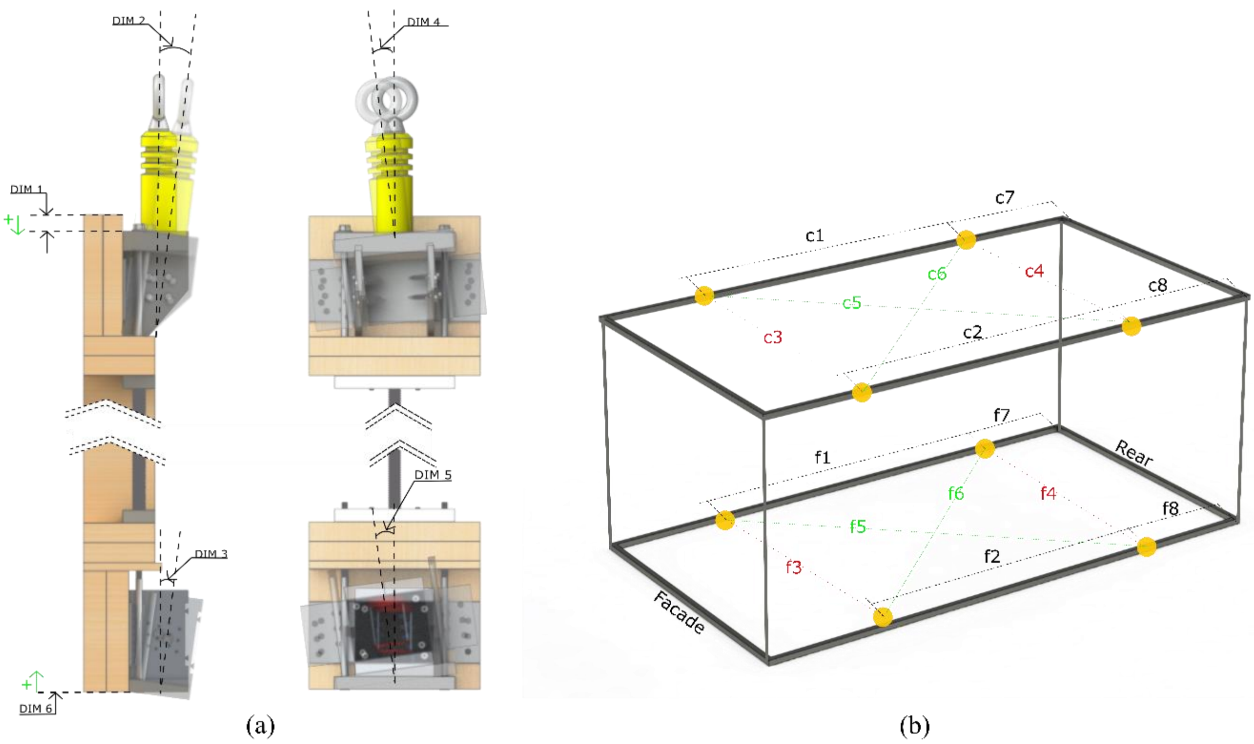


**Figure 5.** Critical dimensions for the accurate positioning of ceiling and floor connectors (**a**) on the vertical plane and (**b**) on the horizontal plane.

The previous analysis, combined with the module composition analysis, leads to identifying the important dimensions for ACD positioning that must be included in the drawings of the appropriate workstations to ensure the success of the self-locking mechanism during on-site assembly. The following dimensions, defined in Figure 5, must be specified and controlled: dimensions DIM1 to DIM6 for each ACD as well as dimensions c1 to c8 and f1 to f8 for each module. The dimensions shown in Figure 5a cover the vertical and angular critical dimensions, while the dimensions shown in Figure 5b, all located in the horizontal plane, dictate the positioning of the ceiling connectors relative to each other in the ceiling plane as well as the floor connectors relative to each other in the floor plane.

## 4. Off-Site Implementation

### *4.1. Identification of Dimensional Inaccuracies within the Production Line*

As a result of off-site observations, sources of error associated with each step of the manufacturing process were assessed and are presented in Table 3. Connection success is highly sensitive to positioning accuracy as floor and ceiling sub-assemblies are fixed on specific parts of a module that can exhibit dimensional errors. For instance, the back-plate of the floor connector was screwed to the inside surface of the floor rim board, which presented uncertainties in length, thickness, and flatness. Moreover, when positioning the floor connector, a contact must be created between the top surface of its lower plate and the surface of the floor rim board groove, but, in our study, a variation in the groove depth of up to 6 mm was observed. With regard to the squaring and flatness of the floor and ceiling perimeters, it was possible to observe a variation in the dimensions between workstations caused by the flexibility of the structure. On-site observations confirmed that the module flexibility could compensate dimensional errors in the floor and ceiling planes. Regardless of the flexibility, vertical errors that led to interference instead of a gap between rim boards were likely to be responsible for failed connections.

**Table 3.** Observations of manufacturing process and sources of error.

| Module Parts | Manufacturing Process | Sources of Error | Critical Dimension Impacted |
|---|---|---|---|
| Floor | Fabrication of the floor joists | Error in length: ±1.60 mm (±1/16 in) | f3–f4 |
| | Rim board groove cutting for the connector | Error in groove start: +0 mm, −6.35 mm (−1/4 in)<br>Error in groove end: +6.35 mm, −0 mm (+1/4 in)<br>Error in groove depth: ±3.18 mm (±1/8 in) | f1–f2–f7–f8<br>&<br>DIM6 |
| | Rim board cutting | Error in length: ±1.60 mm (±1/16 in)<br>Error in thickness and width: ±3.18 mm (±1/8 in)<br>Error in flatness: ±12.70 mm (±1/2 in) | f1–f2–f3<br>f4–f5–f6–f7<br>f8 |
| | Fixation of the floor joists | Error in distance between rim boards: ±6.35 mm (±1/4 in) | f3–f4 |
| | Fixation of the OSB panels | Error in floor squaring: ±12.70 mm (±1/2 in) on a diagonal | f5–f6 |
| Ceiling | Cutting and placement of ceiling joists | Error in length: ±1.60 mm (±1/16 in)<br>Error in thickness and width: ±3.18 mm (±1/8 in)<br>Error in flatness: ±12.70 mm (±1/2 in)<br>Error in squaring: ±12.70 mm (±1/2 in) on a diagonal | c1–c2–c3–c4<br>c5–c6–c7–c8 |

### *4.2. Analysis of ACD Positioning Accuracy*

Scheme 1 presents the errors measured during the quality control of ACD positioning in factory. This scheme presents the mean and max errors obtained on all the eight in-plane dimensions identified in Figure 5b. The mean and max errors were computed regardless of whether they were measured in the ceiling (*c*) or flooring (*f*) systems, as depicted by the cf-prefix on the scheme labels. From this scheme, it is possible to observe that the greatest errors are found in dimensions 3, 5, and 6 and are of magnitudes up to 8.45 mm.

In addition to the in-plane critical dimensions presented in Scheme 1, six other dimensions referred to as DIM 1 to DIM6 for vertical and angular positioning were identified as being critical. For all ACDs, the target values were 28.5 mm for DIM1, 0° for DIM2 to DIM5, and 0 mm for DIM6. The results obtained for DIM 2 to DIM5 were all within a deviation of ±1.15°. Inversely, DIM 1 and DIM 6 presented more errors and were observed to be harder to control. Hence, the measured values of DIM1 varied between 25.4 and 31.75 mm, while the measured values of DIM6 varied between 0 and 4 mm.


**Scheme 1.** Dimensional control for positioning the connectors, in-plane dimensions.

## 5. On-Site Assembly

### 5.1. General Observations

On the day of assembly, the site preparation and foundation were completed, the crane was installed, and the modules had already been delivered. The modules' production had been completed three months prior, and each of the four modules was stored in an outdoor area and placed on six trestles. This resulted in an increase in moisture content of the wood component since wood is a hygroscopic material. The moisture increase led to dimensional variations, and the placement on trestles led to a light creep in the floor structure. Before the assembly day, the engineering firm had prepared a lifting procedure stating the required gear for lifting and the path of the lifted loads. When facing the building, the modules were installed from right to left. Among the twelve connections which needed to be observed during assembly, eight were located on the first and second floor interface, and the remaining four were on the first floor and foundation interface. To minimize compressive forces within the module during lifting, a spreader beam of appropriate dimensions was selected to ensure verticality of the lifting cables. The selected spreader beam had extensible legs, covering a range of rectangles having short sides from 2.5 to 3.8 m and long sides from 3.3 to 5.5 m. A first configuration of 3.3 m × 5.5 m was required for lifting the right modules (1 and 3) and a second configuration of 4.3 m × 3.8 m was required for lifting the left modules (2 and 4). Both configurations are presented in Figure 6 as well as the identification of the ACDs. In addition to minimizing compressive forces within the module, the spreader beam also contributed to stabilizing the module and improving its parallelism with the ground. The weight of modules 1 to 4 was 98 kN, 96 kN, 89 kN, and 104 kN, respectively. Figure 6 also identifies each module's estimated center of gravity, attributable to the geometry of the modules and the location of all the different loads inside the module (windows, doors, partition walls, etc.).

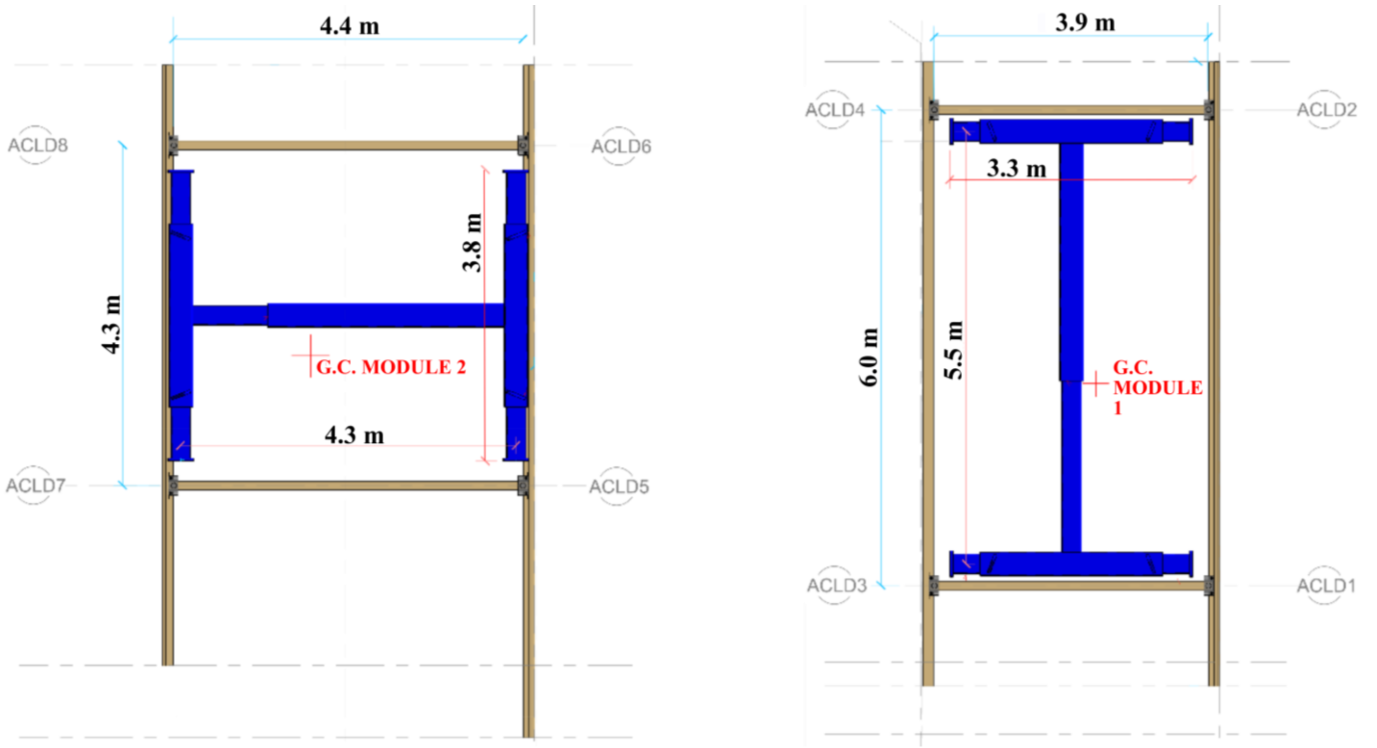


**Figure 6.** ACDs positions in the left and right modules, center of gravity, and spreader beam configurations for lifting.

Figure 7 presents all the critical steps during the assembly day, including the (a) testing of the lifting equipment, crane, and parallelism with the ground, (b) the installation of module 1, (c) the installation of module 2, (d) the installation of module 3, (e) the installation of module 4, and (f) the complete façade once the modules were unwrapped and the hinged roof had been deployed. Overall, each module lifting took approximately 10 min to rig, lift, position, and un-rig. Nonetheless, long delays were observed between module liftings. Many activities not related to connection slowed down the process, which can be summarized as follows: (1) usage of a new lifting method which required additional precautions; (2) un-wrapping of the modules; (3) management of temporary walls; (4) ceiling preparation for the next module; and (5) column installation in the basement.

As the assembly day was rainy, the modules were unpacked cautiously, unpacking only the central division during lifting. Thus, after the completion of the first floor, it was necessary to unpack the ceiling to prepare for the arrival of the second floor. This method was inefficient and slowed down operations. Wrapping and unwrapping activities should be designed and planned in advance for an efficient use of the ACD. In addition, in our experience, central dividing walls were installed temporarily to provide additional rigidity during transport. Removing the OSB panels of the temporary walls also slowed down the process. This step should be redesigned to take full advantage of the quick installation process. Finally, installing a support column in the basement was carried out simultaneously with the installation of the first module to ensure adequate compressive stress-bearing capacities of the assembly.

Table 4 presents the general observations associated with specific characteristics and scores whether the results are satisfactory or unsatisfactory for ACD implementation based on our quantitative examination. The criteria for satisfactory or unsatisfactory results are described within the observations' column of Table 4. The scores (satisfactory or unsatisfactory) are based on the subjectivity of the research team and project participants who have been actively participating in the modular construction industry for several years.

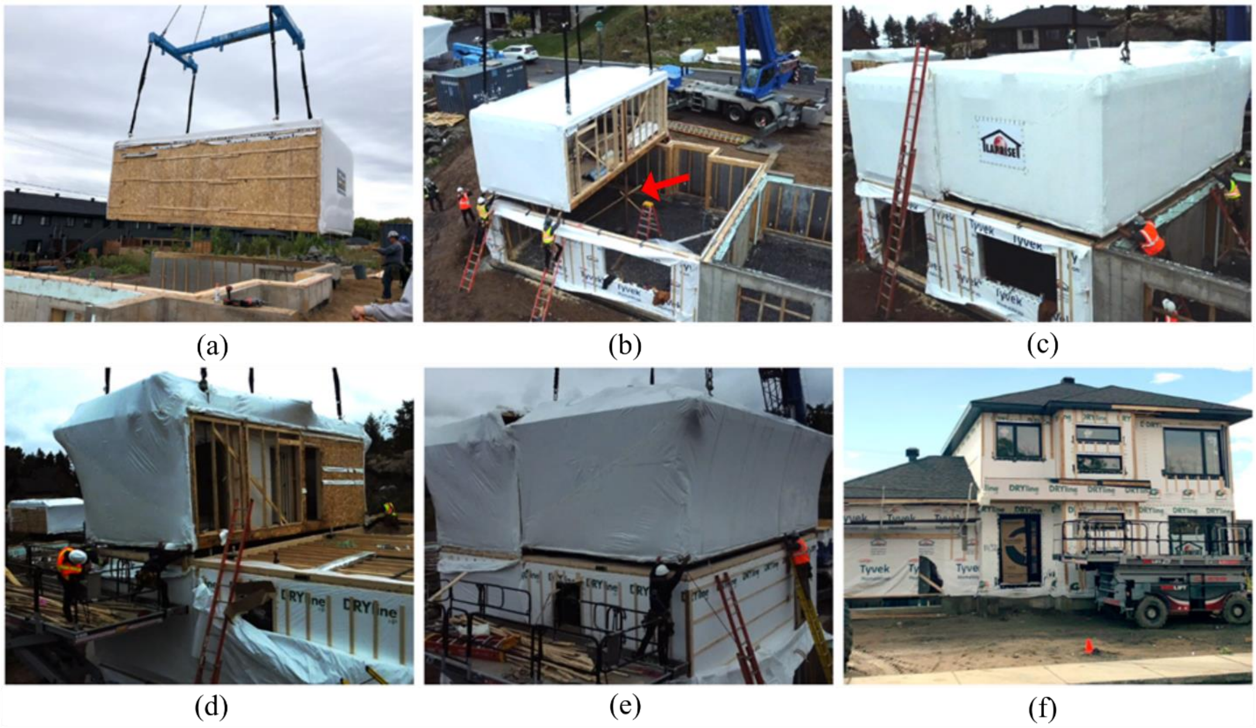


**Figure 7.** Overview of the on-site assembly process of the full-scale experimental project: (**a**) testing of the lifting equipment; (**b**) rear view of module 1 installation; (**c**) rear view of module 2 installation; (**d**) rear view of module 3 installation; (**e**) rear view of module 4; and (**f**) façade of completed assembly.

**Table 4.** General observations associated with specific characteristic and associated scores.

| Characteristic | Observations | Score |
|---|---|---|
| Module parallelism with the ground | To ensure a smooth simultaneous insertion of four shafts in the flooring connectors, the module should be lifted as parallel as possible to the ground. As highlighted in Figure 7, the center of gravity of the modules was offset from the geometrical center of the module. This eccentricity caused a rotation of the module around the crane hook, leading to one side of the module being higher than the other one. To compensate this rotation, shackles were added on the higher side, which extended the length of the lifting cables and rotated the module back to parallelism; this can be very dependent on the lifting crew's competences. | Satisfactory |
| Module flexibility in XY planes | Section 4.2 depicts a few critical dimensions presenting important deviations (up to 8.45 mm). Interferences were expected during assembly, but the module showed a sufficient flexibility to compensate these errors. The analysis of the endoscopic cameras' footage combined with the visual observations of workers confirmed that the shafts of the ceiling connector did enter smoothly in the floor connector for all twelve ACDs. Hence, the module compliance allowed dimensional compensation for up to 8.45 mm on linear dimensions. | Satisfactory |
| Lifting by four eyebolts | The unanimous opinion of the on-site workers stated that the installation and uninstallation of the eyebolts used for lifting was an easier attaching operation than the traditional practices normally used. | Satisfactory |

**Table 4.** *Cont.*

| Characteristic | Observations | Score |
| --- | --- | --- |
| Module guidance during descent | The unanimous opinion of the on-site workers stated that the conic surfaces of the shaft and the floor connector bore significantly facilitated the module's positioning. They eliminated the risk of failing the positioning of the module. | Satisfactory |
| Positioning accuracy post lifting | Lifting by the ceiling connector could induce variations in dimensions 2 and 4 since tensile loads were not expected to be strictly vertical at all times during lifting. Dimensions 2 and 4 were verified with a spirit level on site post lifting for both modules 1 and 2, and no significant variations with the in-factory measurements were observed. | Satisfactory |
| Interior finish post lifting | The lifting activities with the ACDs combined with lifting axes did not induce any cracking, warping, or breakage of the interior finish elements. Many pictures were taken before and after the lifting to compare the state of the elements. This is a significant step towards the long-term objective of maximized interior completion off site. | Satisfactory |
| Connection success rate | The connection was completed for only 2 of the 12 ACDs. Section 5.2 covers the analysis of this criterion. | Unsatisfactory |
| Proof of connection | For experimental purposes, the front plate of the floor connectors was see-through to observe and analyze the connection. Visual confirmation would not be possible for non-experimental purposes as no access trap would be present in the floors, and the connection should be sound confirmed only. The workers detected a total of nine sound confirmation of connection, while only two were successful. Section 5.2 covers the analysis of this criterion. | Unsatisfactory |

### *5.2. Analysis of the Unsatisfactory Criteria*

The ten incomplete connections are all attributable to incomplete shaft insertion in the connector. In some cases, the missing vertical displacement was small enough to trigger the mechanism and partially engage the grippers, while, in other cases, no trigger occurred. Outdoor storage of the modules on trestles for three months resulted in creep, dimensional variations due to moisture levels, and planarity errors. This led to interference during assembly between the ceiling and the floor perimeter module rim boards, preventing ten shafts from being inserted. Such interference could easily be avoided with an adequate vertical positioning of the connectors that would foresee the impact of creep, moisture contents, and planarity errors and the addition of a compliant member (such as an acoustic membrane) between the modules. Revised positioning is proposed in a later section.

Table 5 presents the detailed observations for all twelve connections in the building, with specific observations on the trigger block deployment, the left gripper displacement, the right gripper displacement, the visual signs of friction, and the approximated vertical error. The ACDs were numbered according to Figure 6, and an *F* prefix was added to the connectors in the foundation. To qualify a connection, 1 indicates a successful connection, and 0 indicates an incomplete connection. For trigger block displacement, L indicates that only the left side has reached the final position, R indicates that only the right side has reached the final position, 0 indicates that the trigger block has not engaged in the grooves of the grippers, and 1 indicates that the trigger block has reached the final position. For gripper displacement, 1 indicates a complete displacement, 0.5 indicates a half-way displacement, and 0 indicates the initial state. For qualifying interference in the XY plane, visual signs of surface wear (visible in Figure 8c) were observed on the surface of the shaft: 0 indicates absence of visual signs of friction, 0.5 indicates that visual friction is visible on some but not all the teeth, and 1 indicates that visual friction is visible on all the teeth. Nonetheless, a zero value for visual friction does not necessarily indicate the total absence of interference, since only a quarter of the shaft was visible for observation.

Finally, the missing vertical displacement column is a qualitative evaluation based on distance interpolation on pictures. Figure 8a shows the completed connection of ACD F2, similar to ACD 3, while Figure 8b shows the tilted trigger block of ACD 8, with the right trigger half deployed and the left trigger at the initial state. Figure 8c shows black marks of surface wear on all the teeth of ACD F7, which indicates that the connector did contribute to guiding the module's descent into its final position.

**Table 5.** Details of connection for all twelve ACDs.

| ACDs | Connection | Trigger Block | Left Gripper | Right Gripper | Visual Friction | Missing Vertical Displacement (mm) |
|---|---|---|---|---|---|---|
| F1 | 0 | L | 0.5 | 0 | 0 | 4 |
| F2 | 1 | 1 | 1 | 1 | 0 | 0 |
| F7 | 0 | L | 0.5 | 0 | 1 | 2 |
| F8 | 0 | R | 0 | 0.5 | 0 | 4 |
| 1 | 0 | L | 0.5 | 0 | 0.5 | 3 |
| 2 | 0 | 0 | 0 | 0 | 0 | 8 |
| 3 | 1 | 1 | 1 | 1 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 6 |
| 5 | 0 | L | 0.5 | 0 | 0 | 2 |
| 6 | 0 | 1 | 0.5 | 0.5 | 0 | 5 |
| 7 | 0 | 0 | 0 | 0 | 0 | 8 |
| 8 | 0 | R | 0 | 0.5 | 0 | 3 |

(a) (b) (c)

**Figure 8.** Three ACDs in the full-scale experimental project: (**a**) complete connection (ACD F2); (**b**) incomplete connection (ACD 8); and (**c**) incomplete connection with visual signs of interference on all the teeth (ACD F7).

As observed in Table 5, seven of the ten incomplete connections presented a tilted or complete displacement of the trigger block. A tilted displacement can be attributed to errors in dimensions 4 and 5. As depicted in Section 3.5, an offset of 1.14° can lead to a 0.74 mm vertical displacement in the top teeth. Consequently, the top surface of the shaft can apply a not-centered force on the trigger block, resulting in a tilted displacement. From what was observed, if the shaft pursued its displacement, the trigger block tilted back and reached the final position. A further design revision should include a vertical guidance element to avoid tilting the triggering block. In addition, all of the grippers that were released (either from the tilted or complete displacement of the trigger block) deployed until they reached the outer surface of the shaft. This means that the housing inside the floor connection designed for the translation of the grippers offered appropriate functional gaps. This also explains that the sounds detected by the workers were associated with the impact caused by the gripper reaching the outer surface of the shaft, rather than the internal surface of the teeth. Hence, a detected sound can originate from both a complete or an incomplete connection that follows the trigger block's full or tilted displacement and can confuse the qualifying of a connection. Nonetheless, the actual design of the gripper comprised a chamfer on the top edges of the friction surfaces with the trigger block, which pushed the mechanism too early and induced a sound under an incomplete connection. Eliminating the chamfer would allow the sound-confirmation criterion to be satisfactory since the mechanism would be triggered only when the shaft reaches its final position. The chamfer was designed to facilitate resetting the mechanism for reuse after disassembly by guiding the trigger block toward the center. Nevertheless, as depicted earlier, with the addition of a vertical guiding element to avoid tilting, the chamfer would not be required.

Regarding visual signs of friction or wear, both ACD F7 and ACD1 presented some minor signs of friction. In the case of ACD1, this was attributable to the 7.94 mm difference between c3 module 1 and f3 module 3 (see Table 4). In conclusion, all incomplete connections can be attributed to the vertical position and, more precisely, to the target values of DIM 1 and DIM 6. The MVD column of Table 6 shows that the vertical insertion of the shaft was left incomplete by an average of 4.5 mm, varying from 2 to 8 mm.

**Table 6.** Obtained experimental values for critical dimensions.

| Acceptability Thresholds | | Interface Modules 1 and 3 (mm) | | Interface Modules 2 and 4 (mm) | |
|---|---|---|---|---|---|
| | | In-Factory | On-Site | In-Factory | On-Site |
| 1 | $\lvert c1 - f1 \rvert$ | 1.6 | 4.8 | 1.6 | 6.4 |
| 2 | $\lvert c2 - f2 \rvert$ | 0 | 3.2 | 0 | 3.2 |
| 3 | $\lvert c3 - f3 \rvert$ | 8.0 | 3.2 | 3.2 | 1.6 |
| 4 | $\lvert c4 - f4 \rvert$ | 3.2 | 3.2 | 0 | 6.4 |
| 5 | $\lvert c5 - f5 \rvert$ | 8.0 | 4.8 | 8.0 | 8.0 |
| 6 | $\lvert c6 - f6 \rvert$ | 8.0 | 0 | 6.4 | 12.7 |

### *5.3. Proposal of Acceptability Thresholds*

This section proposes acceptability thresholds (AT) to control the positioning accuracy of ACDs in the factory. The acceptability thresholds were developed to emphasize the relation between the critical dimensions. More precisely, ATs 1 to 6 were set to ensure that the shaft-to-shaft distances in the ceiling plane corresponded to the cavity-to-cavity distances in the floor plane. AT 7 was set to ensure a complete vertical path. Finally, ATs 8 to 11 ensured that the angular errors in both sub-assemblies were small enough to allow a full connection.

Table 6 presents the obtained values for critical dimensions during our full-scale implementation. The results show that ATs 1 and 2 led to small deviations since those dimensions were located within a single rim board. ATs 3 to 6 led to more significant deviations, but, nonetheless, all twelve connectors achieved a smooth shaft insertion, which indicates that the measured deviation is acceptable. Moreover, the comparison of in-factory and on-site values shows that the XY plane of modules was flexible and changed dimension depending on how the module was supported. Deviations of ATs 7 to 11 are not presented in this table since the sensitivity of the on-site measures was not acceptable.

According to the experimental results, Table 7 presents the proposed acceptability thresholds for implementing ACDs. ATs 1 and 2 were fixed to 5 mm since no flexibility can compensate for the deviation within a single rim board. ATs 3 and 4 were set to 8 mm since face-to-face rim boards are linked with floor joists that can lightly compensate deviations. ATs 5 and 6 were set to 12 mm since diagonals on light-framed modules show great flexibility. AT7 was set to 20.5 mm to allow for flatness variation in the rim boards. As depicted in Figure 4, a full insertion of the shaft led to a 30.5 mm gap between the plates of the ACD, to which an additional clearance of 10 mm was added following the results of the experiment (chosen slightly larger than the maximum MVD value in Table 6). Indeed, it is preferable to have clearance between the rim boards rather than incomplete connections. To conclude, ATs 8 to 11 were set accordingly, with the precision level being used throughout the in-factory installation, which showed that a 1.15° error led to acceptable vertical and horizontal offsets. This 1.15° value was selected because spirit levels are calibrated so that a 2% slope slightly moves the bubble until it touches one of the outer lines. When the spirit level is pressed on the shaft, a 2% slope represents a 1.15° slope.

**Table 7.** Proposed acceptability thresholds 1 to 11.

| Proposed Acceptability Thresholds | | | |
| --- | --- | --- | --- |
| 1 | $\lvert c1 - f1 \rvert < 5$ mm | $DIM1 + DIM6 < 20.5$ mm | 7 |
| 2 | $\lvert c2 - f2 \rvert < 5$ mm | $-1.15° < DIM2 < 1.15°$ | 8 |
| 3 | $\lvert c3 - f3 \rvert < 8$ mm | $-1.15° < DIM3 < 1.15°$ | 9 |
| 4 | $\lvert c4 - f4 \rvert < 8$ mm | $-1.15° < DIM4 < 1.15°$ | 10 |
| 5 | $\lvert c5 - f5 \rvert < 12$ mm | $-1.15° < DIM5 < 1.15°$ | 11 |
| 6 | $\lvert c6 - f6 \rvert < 12$ mm | | |

## 6. Discussion

This full-scale implementation took place in the Quebec modular construction context with stakeholders interested in integrating automated connecting devices in the off-site building industry. It was observed that the industry must adapt some of its practices for the effective adoption of ACDs, particularly in terms of the dimensional control of modules. Automating certain processes could improve dimensional repeatability and reduce the impact of human error. In addition, the use of positioning templates or other manufacturing tools could make it easier for workers to install ACDs. The industrial partners involved in this project recognized the importance of such projects in enhancing the industry and were satisfied with the advantages of using these devices. Moreover, they have expressed their interest in conducting additional full-scale projects, which demonstrates the relevance and the potential of a technological breakthrough concerning ACDs. The cottage constructed during this full-scale implementation has become a private property within the months following its assembly, making long-term observations unlikely.

Future research should focus on the long-term behavior of ACDs and their impact on building performance, such as the presence of vibrational/acoustic discomfort, dew point positioning under winter conditions, and laboratory testing to characterize seismic behavior. Moreover, additional thoughts need to be put into developing a validation process that would certify the proof-of-connection.

### *6.1. Implementation of Automated Connecting Devices in the Building Model and Drawings*

The full-scale implementation has shown that implementing automated connecting devices to a building model and drawings does not significantly change the workload for designers using BIM. Implementing ACDs used exclusively for connection purposes also has a limited impact on the architecture of the buildings as they are entirely hidden in the flooring/ceiling system, as are other mechanical components (e.g., HVAC, electrical, plumbing). On the other hand, implementing ACDs combined with lifting axes induced many additional design constraints in our project that impacted the feasibility of some floor layouts. Constraints in the architectural design were associated with the required continuity of the ACD from the floor up to the ceiling through a lifting rod that had to be hidden in a wall.

### *6.2. Implementation of Automated Connecting Devices in Off-Site Activities*

Our observations pointed out that the implementation of ACDs has a significant impact on off-site activities. The difference between the installation process of ACDs with and without lifting axes was not significant, since installing the lifting axes was a fairly rapid operation. While the complete installation of ACDs was observed to be time-consuming, it is believed that, in the context of implementing new practices, the novelty highly contributes to longer realization times. It can also be attributed to the ACDs' installation process itself, which is task-intensive, as well as to the extensive dimensional control required during installation.

It has been observed that controlling 16 in-plane dimensions and 6 in-axis dimensions is a difficult and time-consuming task with manual methods. For future research, ACDs' implementation could integrate vision-based methods to evaluate whether the implementation is facilitated [24]. Vision-based methods paired with a proper inspection program could be used to implement acceptability thresholds and flag issues. Moreover, future research should propose design revisions or assembly methods that enable one to reduce the quantity of critical dimensions to control. Such research could significantly improve the off-site implementation of automated connecting devices. The results of our full-scale implementation led to proposing acceptability thresholds, summarized as follows:

1. High accuracy can easily be reached within a single rim board. The associated acceptability thresholds (AT1 and AT2) must not present a deviation greater than 5 mm.
2. High accuracy was not easily reached between rim boards because of joists' and trusts' length variability. The associated acceptability thresholds (AT3 and AT4) must not present a deviation greater than 8 mm.
3. The module stiffness (flexibility) created significant variation in the diagonal dimensions. The associated acceptability thresholds (AT5 and AT6) must not present a deviation greater than 12 mm.
4. To ensure connection and avoid interference caused by poor flatness of the rim boards, the vertical dimensions should be more conservative to accommodate for variabilities in the rim boards. Consequently, the associated acceptability threshold (AT7) should not exceed 20 mm. This AT is likely to create a functional gap between rim boards that will compensate flatness errors in the rim boards. The functional gap should be anticipated and a method to fill this gap (e.g., urethane, compliant lining, acoustic pad) should be planned in the project.
5. Verification of angular dimensions has proven to be efficient with the spirit level (indicating $\pm 1.15^\circ$). The associated acceptability thresholds (AT8 to AT11) must not present a deviation greater than $\pm 1.15^\circ$.

### *6.3. Observations during On-Site Activities with the Usage of Automated Connecting Devices*

Our observations during on-site implementation led to a better understanding of automated connecting devices' functional performances and requirements. The design of the ACDs relied on various characteristics that needed to be observed during on-site activities. The following list of characteristics showed satisfactory results:

1. An eye-based parallelism of the module with the ground was attainable and sufficient to avoid interference during descent.
2. The module flexibility in the XY plane was sufficient to compensate differences between ceiling and floor dimensions, which allowed smooth shaft insertion for all twelve connectors.
3. Lifting by four eyebolts has proven to be very efficient, and the workers interviewed after the on-site activities stated they enjoyed and recognized the value of this lifting method.
4. The descent and positioning of the module was guided by the conic surfaces of the connectors, which resulted in an easier connection process and a reduction in errors in module positioning.
5. Lifting by the shafts did not induce angular differences on DIM2 and DIM4 caused by tension eccentricity, which confirmed that this lifting method does not interfere with the connection ability.

6. The lifting did not affect the interior finish: no warping or damage was detected during our observations.

On the opposite, the following elements need further attention:

1. The connection confirmation by sound detection was unreliable in this project since incomplete connections transmitted impact sounds. Sound confirmation was easily heard by workers and could successfully confirm connection in future projects if chamfers are removed from the upper edges of the grippers. Future research should be conducted to assess the risk and responsibility undertaken by structural inspectors when connection is only confirmed by sound in a construction project. As depicted by Dai et al. [14], the seismic performance of a self-lock connector is insensitive to connection completion. This mitigates the risk associated with incomplete connections and, therefore, increases the likelihood of settling for a sound-only confirmation of connection. Nonetheless, a proof-of-connection validation method is required for the large-scale adoption of ACDs in off-site construction efforts.
2. The success rate of a full connection was 2/12, mainly attributable to the vertical positioning of the ACDs. The positioning prescribed in the production plans for off-site installation did not foresee dimensional variations caused by moisture content and creep when the modules were stored outside on trestles for a long period. Off-site and on-site observations allowed the research team to identify the vertical clearance required to overcome the geometric and dimensional variability in the wood elements (creep and moisture content variations). Future projects should prescribe new vertical dimensions for positioning, and the research team is confident that the success rate of ACDs can reach 100%.

To summarize, using ACDs in construction comes with notable advantages and challenges. On the positive side, ACDs enhance efficiency by reducing manual labor and assembly time, ensuring precise and consistent connections between modular elements. They facilitate thorough off-site manufacturing, aligning with the industry's trend toward modernization and technological advancements. However, the implementation of ACDs requires an initial investment and introduces complexities in dimensional control during off-site installation. Combining ACDs with lifting axes may impose architectural constraints, influencing the design and layout of modular components. On-site perturbations, such as variations in moisture content, can impact the success rate of ACD connections, making their effectiveness project-specific and requiring careful adaptation to different contexts and structures.

As a result of this research, we suggest that industry professionals should combine the introduction of ACDs into modular building with the modernization of equipment for installing ACDs as well as the equipment used for controlling the quality of dimensional accuracy. From this experience, the factory in which the modules were fabricated had very limited technological tools to ensure dimensional control. The usage of traditional methods for positioning the ACDs within the acceptability thresholds was proven to be difficult.

## 7. Conclusions

This study aimed to perform the implementation of ACD in a full-scale experiment and observe the entire process. This research presents experimental data on how inter-modular connections with automated connecting devices can be used and what are the main issues to address in future projects. This study covers the research gap identified by Rajanayagam et al. [10] and Lim et al. [19] concerning the implementation of automated connecting devices into full-scale buildings. This full-scale implementation focused on wood light-framed modular buildings and showed that automated connecting devices have a significant potential to facilitate the assembly process of modular construction. The results of this study can be summarized as follows.

(1) The functional outcomes of self-locking connectors that many researchers expected were proven conclusive: elimination of on-site manipulation for connection, maxi-

mization of the completion level off site, reduction in module positioning errors, and faster erection.
(2) In addition, this research demonstrated that the concept of an automated connecting device for modular construction, often questioned regarding its feasibility of meeting the required dimensional accuracy in factory, is a functional and viable concept, since connection did occur during the full-scale experimental project.
(3) Nonetheless, this research has shown that controlling the position of multiple connectors within a module in factory is task-intensive and can add complexity to the off-site manufacturing process.
(4) The full-scale implementation has also shown that implementing automated connecting devices in a building model and drawings does not significantly change the workload for designers using BIM.
(5) On-site perturbations such as moist content, creepage of beams, and parallelism with the ground of the module during lifting should be given attention during assembly.

This work also explored the possibility of combining the connecting and lifting activities inherent to modular construction through a single device, and the pros and cons of combining ACDs with lifting axes were reported. Modular lifting activities in light-framed modules can benefit from standard lifting devices since the planning of lifting operations is task-intensive regardless of the connection method. However, combining connecting and lifting features created additional constraints in the architectural design that can become an obstacle when adopting this technology.

### 7.1. Future Research

Future research should focus on the long-term behavior of ACDs and their impact on habitation, such as the presence of vibrational/acoustic discomfort, dew point positioning under winter conditions, and laboratory testing to characterize seismic behavior. Sound-only confirmation of connection should be more studied to reach a high level of reliability and minimize risk for structural engineers. Future research should also explore the viability of using vision-based methods paired with an inspection program to facilitate off-site dimensional control during ACD installation and explore design revisions or assembly methods that would reduce the number of critical dimensions to control.

### 7.2. Limitations of This Study

The analysis of manufacturing tolerances presented in this paper is applicable for light-framed wood structures only, since the manufacturing tolerances for other types of structures differ. Moreover, the flexibility observed within the modules is also inherent to light-framed wood structures only, as well as the analysis inherent to combining the lifting and connecting features, since the behaviour of other types of structures subjected to lifting and handling loads differs. Finally, long-term observations were not pursued on the building following its assembly. Consequently, the long-term behaviour of the automated connecting device was not characterized.

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## List of Abbreviations

| | |
|---|---|
| ACD | Automated connecting device |
| ACLD | Automated connecting and lifting device |
| IMC | Inter-modular connection |
| PAR | Participatory action research |

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