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ASSEMBLY PROCESS IN OFF-SITE CONSTRUCTION: SELF-LOCK DEVICE AS A KEY TO A LEAN APPROACH

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ABSTRACT

The implementation of lean construction in off-site construction is an ongoing combination aiming to improve the efficiency and reduce all forms of waste in the construction industry. Modular construction offers a high level of off-site value creation, and consequently leaner processes associated to the well-known off-site construction advantages as waste management, shorter project timeline, improved health and safety conditions for workers, better quality control, optimal material handling, and efficient working stations. Nonetheless, the on-site activities needed to connect the modules are often identified as critical sources of waste. In response, many connecting devices and models for calculations were developed in recent years, but very few present an automated locking mechanism for modular connection. While most connecting devices include the use of fasteners that need to be manually fixed to complete the connection of modules, an automated connecting device could significantly reduce the quantity of on-site activities by including an engineered mechanism that ensures self-lock. This research aims to evaluate the impact on leanness of an automated connecting device as well as to present a new plug-in self-lock device.

KEYWORDS

Off-site construction, Modular assembly, Connecting Device, Automated locking mechanism, Waste management.

INTRODUCTION

Off-site construction (OSC) is characterized by the process of manufacturing components in-factory before their transportation and installation on the construction site. Components can be of many forms, but in this research, only the modular form is of interest. More precisely, Modular Construction (MC) is defined by the Modular Building Institute (MBI) as an off-site process, performed in factory setting yielding 3D modules that are transported and assembled at a building's final location. Hairstans (2015) has divided MC in four subcategories; uninsulated modules whose surfaces have first skin on

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only one side, insulated modules without finished linings, insulated modules with finished lining on one side (either internally or externally), and modules fully finished on all sides with integration of services (i.e. with electrical and mechanical services, windows and doors). The fourth subcategory is considered throughout this study.

While the fourth category refers to *fully-finished* modules, the reality is that some work is left to be done on-site because of assembly considerations. Indeed, to permanently assemble modules together on the construction site, workers need access to the structural posts of the modules in order to install fasteners and complete the linkage, which leads to modules showing unfinished areas. While MC factories were designed to achieve a lean production with organized work-stations, controlled environment, and accessible material and tools, the assembly process interferes with the in-factory level of completion that could be reached, consequently causing non-lean activities (e.g. repeating finishing steps on-site for the specific areas left unfinished). Indeed, Zhang *et al.* (2020) have extracted from the published literature all key performance indicators (KPIs) of OSC supply chain in economic, social and environmental aspects, and the on-site modular assembly cost and time were identified as two KPIs frequently identified by researchers, highlighting the importance of the assembly process in the overall OSC supply chain. The results section of this paper lists all sources of waste (as defined by LC theories) in the assembly process of the OSC supply chain.

With the aim of improving the modular assembly process, many types of modular joints have been developed by researchers and are currently used to fix modules together. To name a few, Sharafi *et al*. (2018), Chen *et al*. (2020), Annan *et al*. (2009), Loss *et al*. (2016), Sendanayake *et al*. (2019), Bowron *et al.* (2014), Park *et al*. (2015), and Dai *et al*. (2018) proposed new connecting devices. As illustrated in Figure 1, modular joints are typically located in the corners of the modules, which allows to concentrate connection in specific points and to concentrate external load of the buildings to these transfer points.

Nonetheless, the literature presents very few modular connection involving an automated connecting device (ACD) (Ferdous *et al.,* 2019). An ACD refers to a mechanical device permanently fixed in the structural framing of all modules, in which a locking system is automatically engaged when the module being assembled to the others has reached its final position. Such a device could eliminate all fastening operations currently needed to link modules together. This research aims to evaluate how an ACD can reduce sources of waste, since its value addition to the final building is not the connecting device itself, but all the sources of waste it reduces. This paper also presents a new ACD developed accordingly to the potential waste reduction identified.

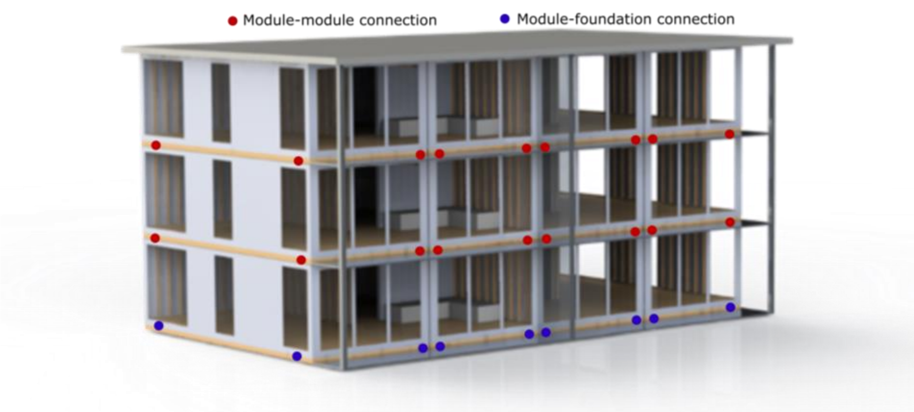


Figure 1: Typical location of modular joints to ensure vertical connection.

METHODOLOGY

To evaluate how an ACD can reduce sources of waste, the research approach is based on the development of appropriate Key Success Features (KFSs) to effectively manage Critical Waste Factors (CWFs) for a lean construction process through waste reduction. The CWF term is used in this paper to refer to specific characteristics of construction activities that are critical sources of waste. The methodology of the approach consists of five key phases: (1) identify CWFs through literature review and case study (field observations and interviews), (2) identify how to improve the CWFs by defining KSFs for an ACD, (3) design an ACD following state-of-the-art design methodology (2015), (4) evaluate the performance of the ACD with KSFs and (5) estimate the economic impact of the ACD.

More precisely, phase 1 consisted in field observations and interviews with members of OSC organizations combined with literature review. Field observations took place in Quebec, Canada, where modular construction is predominant with light-framed structures (Cecobois, 2020). The first project (study case A), located in Quebec City, involved a 24-unit residential modular building four stories high each containing seven light-framed modules (2019). The second project (study case B), located in the great area of Quebec City, involved a 6-unit residential modular light-framed building (2021). The in-factory visits took place in the factories of three different manufacturers, all located in Canada. During factory and on-site observations, many pictures and videos were taken for future consultation. Interviews were conducted with production managers, CEOs, and general managers of off-site manufacturers, as well as with a structure engineer, the CEO of an engineering group, and the director of creation of an architecture group. The literature review was divided in two major components: existing connecting devices for modular buildings, and lean construction principles. Phase 2 consisted in an analytical research approach to identify the key features the ACD must include in order to address the CWFs of the modular assembly process, while Phase 3 involved a state-of-the-art design methodology consisting of problem definition, design specifications, design iteration, prototyping, fabricating and testing. Phase 4 refers to a qualitative approach of evaluation, while phase 5 is predominantly based on assumptions.

RESULTS

CRITICAL WASTE FACTORS ON-SITE IN MODULAR CONSTRUCTION

In LC literature, Erikshammar *et al.* (2010) states that several elements must be managed to increase value in construction, such as waste reduction, quality, price and functionality, and more subjective elements such as design. The waste reduction approach defines eight forms of waste identified by Ohno as follows: Over-production, inventory, transportation, waiting, motion, over processing, rework, and not utilizing human resources (Howell, 1999). Table 1 presents how these forms of waste occur during on-site activities in OSC, with regard to on-field observations at both study cases A and B, interviews with OSC organizations members, and literature. Table 1 also presents association of these on-site activities with specific CWFs. A discussion follows.

Table 1: On-site activities in OSC, associated forms of waste and identified CWFs

On-Site Activities	Forms of Waste	CWFs
Modular assembly	Waiting	(1) Co-dependence of crews (2) Poor rate of machine usage / workers usage (3) Need of coordination
Positioning of module	Rework	(4) Alignment unpredictability
Structural connection	Over Processing	(5) Load bearing relies on many systems
Modules completion (*interior finish at connection points*)	Transportation and handling	(6) Multiple handling of tools and material (7) Reduced productivity compared to off-site
Building completion and rework	Material Waste*	(8) On-site material waste management is poor

** A more explicit form was chosen to simplify understanding, referring to the Over-Production form of waste.*

CWFs (1), (2) and (3) associated to modular assembly were identified when observing the following activities on field. Figure 2 illustrates crews B to F pursuing their activities. Crew A moves trucks for modules delivery. Crew B unwraps the module and attaches it to the crane. Crew C attaches and manoeuvers the cables for rotation control. Crew D, located in nacelles, controls the alignment of the module, corrects inter-modular gaps if needed, un-attaches the rotation control cables and ensures lateral fixation on the façade edge. Crew E, located on the highest walkable surface of the building, ensures the lateral fixation on the ceiling edge. Crew F, located one story lower, installs fasteners to complete the vertical fixation of the modules at the floor-ceiling interface. As seen on field, D, E and F can work simultaneously but depend on B and C, while B and C can work simultaneously but depend on A. Since tasks of crews D, E and F are labor intensive, the co-dependency of crews induce major wait-times prior to repeating the whole process of module assembly. Wait-times are responsible for workers and machines being inefficiently used (*e.g. the crane for assembly not operating for long periods)*. Moreover, this kind of complex crew synergy requires great coordination, and occasional failure in coordination can lead to major waste.

CWFs (4) refers to the un-assisted alignment activities that leads to frequent need of rework due to angular or positional inaccuracy. The unpredictability leads to rework taking many forms: lifting the module to re-align, and/or misfit of partitions, and/or incongruous façade form.

Crew B **Crew C** **Crew D** **Crew E** **Crew F**

Figure 2: On-site pictures of crews B to F executing their specific tasks at study caseA.

CWF (5) refers to the labor-intensive connection tasks, which add limited value for the project owner. With the actual assembly methods, the building structural stability depends on the shear wall continuity at various locations: at the façade edge, ceiling edge, and floor-ceiling interface. This complex connection process is considered over-processing since a single complete connection that does not require shear wall continuity could significantly reduce the labor needed for assembly, and be concentrated in a discrete locations in the module.

CWFs (6) and (7) refer to the module completion tasks induced by the need of accessing the connection points, typically numbered as four to eight per module. When connecting devices are non-automated, access is required at interior surfaces to install additional fastening to withstand tensile loads. Compared to off-site where workstations contain the right tools and are located immediately next to the appropriate material supply point, on-site modular completion requires substantial material and tool handling from module to module. Module completion can include the installation and finish of the drywall, the application of primer and paint, finishing the flooring, fixing mouldings, etc. Moreover, on-site labor productivity is significantly lower than that of off-site (Bosnich *et al.* (2001).

CWFs (8) refers to solid waste generated on-site. While off-site material waste management facilitates the reduction of un-usable remains, and/or encourages its recycling and sorting, on-site remains are most likely wasted.

ANALYTICAL REVIEW OF EXISTING CONNECTING DEVICES AND ON-FIELD ASSEMBLY PROCESS

Bowron *et al.* (2014) invented a new non-automated connector for steel MC. They founded a corporation named Vector Bloc, located in Toronto, Canada and have already sold multiple units that were used in high-rise modular buildings. The core of their design involves a three part connecting device for steel-modular assembly. The ceiling part is located at the top corners of modules, allowing the extruded parts to insert into the hollowed-square structural beams. Permanent linkage of structural beams and the ceiling part is achieved with welds. The floor part is located at the bottom corners of modules, allowing the extruded parts to insert into hollowed-rectangular structural beams, permanently linked to the floor beams with again, welds. Gusset plates were designed to achieve lateral connection between horizontally adjacent modules, and are installed on-site. Hence, related on-site activities that follow the positioning of the first floor modules are depicted as follows:

1. Placement of the gusset plates when all horizontally adjacent modules are placed;
2. Installation of fasteners to fix the gusset plates (two bolts per module);
3. Placement of the second story modules;
4. Installation of fasteners to link all three parts together (two bolts per module);
5. Completion of the inside of the modules to hide connection access points;
6. Completion of the modular joining areas at all locations in the building (corridors, open-areas overlapping on more than 1 module, elevator, exterior sheathing and finish, etc.).

The Vector Bloc products are often praised by literature because of the flexibility it offers despite its aim to standardize the modular assembly process. Indeed, the system can be combined with any post and beam dimensions and ensure vertical proper stacking for up to 60 stories high. While this innovation proposes a significant improvement to standardize the assembly process and achieve higher-rise buildings, it leads to question if an automated mechanism for vertical fixation can contribute to extend the lean benefits. What seems to oppose this innovation to LC principles is the need of a certain incompletion level of the modules, required for accessing the connection points. On this regard, Vector Bloc products can be compared to the Innov-144 connectors observed in Quebec, where the joints were non-standard as they were specifically designed for this project. It allowed the linkage of the modules through two metallic holders, one in a C shape containing the floor timber beams, and the other one fastened on the lower module wood post. When analyzing these two assembly solutions with the six forms of waste identified in Table 1, it seems obvious that the lean approach can still be improved through the development of an automated connecting device ensuring the vertical and lateral connection as well as maximizing off-site completion of modules while reducing on-site assembly activities.

IDENTIFICATION OF KSFS TO ACT AS DESIGN SPECIFICATIONS

Table 2 presents the results of an analytical exercise on identifying relevant KSFs to help reduce the impact of the CWFs identified and to act as design specifications for the ACD development.

Table 2: Identification of KSFs as design specifications to improve CWFs

CWFs	KSFs
Co-dependence of crews Poor rate of machine usage / workers usage Need of coordination	(k1) Automation of the locking mechanism
Alignment unpredictability	(k2) Ability to assist the alignment of the modules (k3) Ability to create predictability in module positioning
Load bearing relies on many systems	(k4) Integration of a complete load bearing system that includes shear, tension and compression
Multiple handling of tools and material Reduced productivity compared to off-site On-site material waste management is poor	(k5) Dissimulation of the ACD inside the framing to allow full interior completion of the module and reduce on-site work

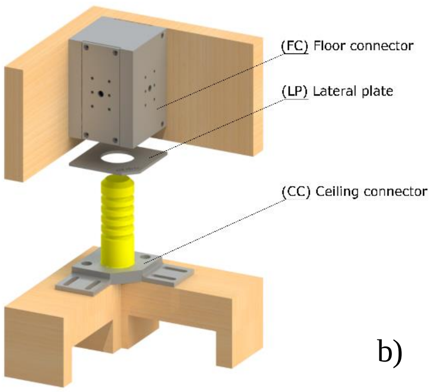
A NEW SELF-LOCK CONNECTING DEVICE

In accordance with the KSFs identified, an automated connecting device (ACD) was developed to increase the leanness of OSC processes. The proposed ACD, illustrated in Figure 3, is composed of a lateral plate (LP) and two distinct assemblies respectively named floor connector (FC) and ceiling connector (CC). The FC contains a triggering mechanism that induces self-locking only if the male member of the CC has reached its final position. The final position of the male member is reached when the module is sitting at the right position above the lower ceiling. More details about the functional and technical design specifications met when testing the ACD are presented in Table 3. The

ACD meets all the specified KSFs, starting with a fully automated vertical locking mechanism which significantly reduces assembly time by reducing wait-times, co-dependency of working crews and coordination needs. (k1). The ACD also requires no access to connection points by a complete dissimulation of the ACD inside the framing, hence maximizing the off-site completion of modules (k5). The ACD needs to be precisely positioned off-site in order to increase the predictability of modules positioning earlier in the process (k3), and the FC presents a conic entry that guides the cylindrical CC member to the right location, which contributes to facilitate the alignment of the modules (k2). Moreover, the ACD was designed to bear considerable loads in tension, compression and shear which are detailed in Table 3. The values for shear, tensile and compressive capacities were obtained from an experimental study led by Picard *et al.* (2022).

For comparison purposes, related on-site activities that follow the positioning of the first floor modules when using ACDs are depicted as follows:

1. Placement of the gusset plate when all horizontally adjacent modules are placed;
2. Placement of the second story modules;
3. Completion of the modular joining areas at all locations in the building (corridors, open-areas overlapping on more than 1 module, elevator, exterior sheathing and finish, etc.).

a) 

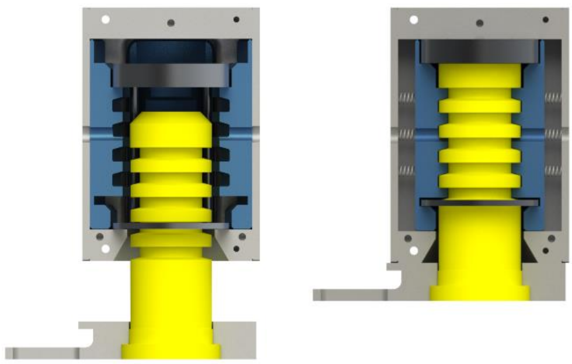
b) 

Figure 3: ACD device illustration, (a) identification of three major components floor connector, lateral plate, and ceiling connector, (b) cut-section in two states, prior to connection, and after connection.

Table 3: Design specifications of the ACD and resulting values

Characteristics	Resulting values	Comments
Movement of insertion	Vertical	The modules arrival on connecting site is always vertical.
Lock mechanism	Vertical and Automated	The mechanism replaces tensile bolts by restricting pull-out motion. Automation reduces workers activities at assembly.
Location	Adaptive	The ACDs can be located at the four corners of the module, or elsewhere if needed. They are located in the void space between the ceiling and the floor.
Module-mount offsite	Easy	The frame shape is adapted to the module type (*e.g.* light-framed module, steel module, concrete module, hybrid module).
Module alignment	Easy	The conic entry facilitates the alignment process.
Access needs	For lateral plate only	The connection needs access point for workers only on exterior surface of the ceiling, where the lateral plate is installed.
Unlocking	Possible	Holes on the sides of FC allow for bolt insertion, and when tightened, they compress the triggering springs and pull the locking clamps back in initial state. Ceiling opening is required.
Compression load path	Unaffected	Load concentrations at connecting points are avoided by allowing a continuous contact between rim joist and top plate of lower module.
Lateral fixture	Various plates	Three parts are designed for lateral fixture to accommodate all locations, as of the corner of the building (1-hole), the face of the building (2-holes), and the inside of the building (4-holes).
Tensile capacity	200 kN	Allowable for buildings up to 6 stories.
Compressive capacity	1000 kN	Designed to prevent collapse in case of beam failure (and load concentration).
Shear capacity	40 kN	Building response to lateral loads is a combination of ACD shear capacity and siding sheathing.

ECONOMIC ANALYSIS ON THE IMPACT OF THE WASTE REDUCTION

The lean processes inherent to OSC are responsible for a major increase in labor-productivity and resource usage. The optimization of workstations, the material and tools handling management, the jigs and standardized equipment for fast transformation of components, the controlled environment independent of weather hazards and more are believed to induce a major difference in labor-productivity. To quantify the cost difference between a task done off-site, and on-site, the hypothesis used assumes a 2:1 ratio of value creation per hour off-site to value creation per hour on-site. Differently said, the same task is believed to take twice the time to do on-site than it takes off-site. This 2:1 ratio is enhanced by the context of completing a module: since most of the tasks are started but unfinished at some locations (*e.g. drywall installing, finish, priming and painting)* it seems reasonable to believe it would take at least half the time to simply pursue the on-going task in-factory than to prepare tools and materials on-site and complete the task. Although it appears to be an optimistic ratio, the findings of Wandahl *et al.* (2021) state that on-site labor is being used at only 43% for direct work. Moreover, the rates of on-site workers is estimated to $65/h compared to $32/h for off-site workers in Province of Quebec (CEO of engineering group, 2022). Hence, the same 1-hour off-site task will cost $32 when performed off-site compared to $130 when performed on-site, which corresponds to 4-time increase between off-site and on-site.

The completion level of modules were observed to be of approximately 60% throughout on-field observations in study cases A and B. However, it has been reported that the level of completion can reach up to 80% off-site in the Swedish OSC environment, with the Timber Volume Element (TVE) method (Hook *et.* Stehn, 2008). Considering 10% of activities will be needed for building completion (junction areas of modules) with, or without the use of ACDs, there is a 10% to 30% additional completion that can be potentially reached with the use of ACDs.

The following paragraph sets an example of cost variation induced by off-site completion level and use of ACD in assembly activities. The example is illustrated in Figure 4. If constructed off-site or on-site, the material cost will not sustain a major difference, hence noted independent. Transportation is also independent of the ACD usage, as well as the building completion, which corresponds to approximately 10% of the module completion (*e.g.* esthetic continuity in halls and corridors, at façades, etc.). The labor cost, for its share, highly depends on the level of completion off-site and the remaining task to be completed on-site. Taking as example that a 60% off-site completed module induces a $20K labor cost, and following the 4:1 ratio highlighted previously, the remaining 30% can either cost $10K if done off-site, or $40K if done on-site. The cost of completion activities become $30K apart with, and without ACD. The waste reduction associated with KSF (k5) is substantial and highlights the potential impact of using an automated connecting device in MC.

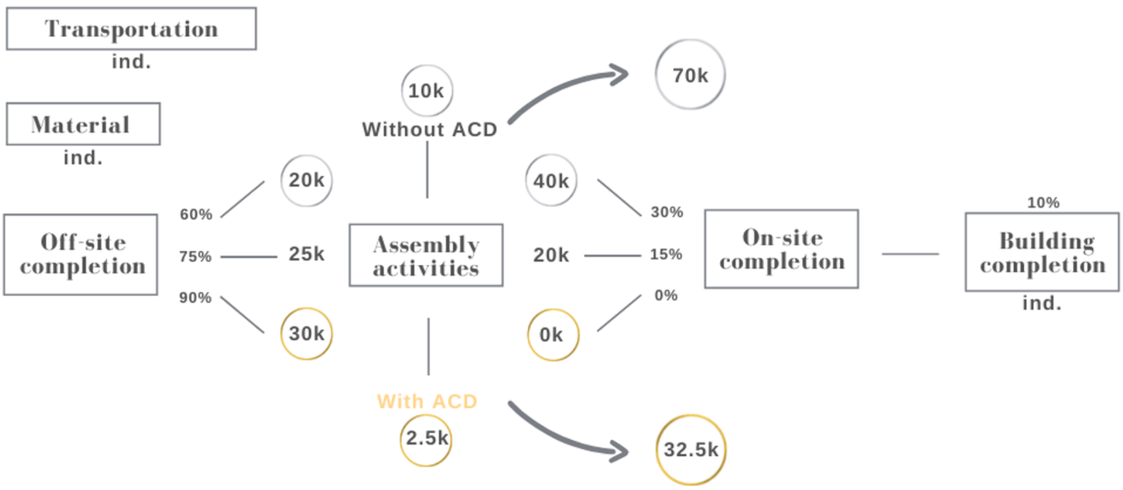


Figure 4: Economic example of the impact of using an ACD.

On the other hand, the waste reduction associated with KSFs (k1), (k2), (k3), (k4) is harder to evaluate and less predictable. Field comparison of similar buildings being built with, and without ACDs could help quantify the waste reduction in terms of assembly time. Indeed, all four KSFs are expected to facilitate the assembly process and consequently reduce the assembly time. Based on field observations only, the wait-times, the connecting operations of Crews D, E and F as well as the lack of coordination are assumed to represent 75% of the work-time. Hence, assembly process is estimated to be four times quicker with the use of ACDs, leading, again, to major cost reduction.

Sutrisna *et al.* (2019) presented the findings of their work on the off-site manufacturing cost analysis based on three study cases in Australia. To compare with this research, all cost components values were divided by the number of modules involved in each study case, mean values were computed, converted to CAD$ and are presented in Table 4.

Table 4: Construction cost in Sutrisna *et al.* study case, mean values

Cost Components	Mean Value (CAD$)	% of Total Cost
Module manufacturing cost (72% completion)	44.3K	71.9%
Module transferring cost (transport, unwrapping, attaching, lifting and connecting activities)	2.9K	4.7%
On-site Construction cost (module and building completion)	12.7K	20.6%
Engineering / permits / fees	1.7K	2.8%
Total cost / module	61.6K	100%

To compare with the results of this paper, the impact of an ACD is evaluated by computing the hypothetical total cost/module if off-site completion was maximized to 90%. The findings of Sutrisna et al. (2019) state that for the study-case under consideration, on-site construction cost represented 20% of the total cost and allowed for 28% of the module completion. By interpolation, if on-site completion was reduced from 28% to 10%, the cost would reduce from $12.7K to $4.6K. Following the 4:1 rule, the $8.1K reduction in the on-site cost corresponds to an $2K increase in the off-site cost, since 28% of the tasks will be done two times quicker, at a two times smaller hour-rate.

Hence, the savings associated to an 18% higher off-site completion are estimated to $6.1K per module. This represents a 10% cost reduction of the total cost/module since the mean total/cost per module of their findings is $61.6K. In addition, the module transferring cost of $2.9K can also be reduced to contribute in improving the total cost reduction.

CONCLUSION

The implementation of lean construction principles to the off-site construction industry is of growing interest in the literature and while many researchers have pointed out the connecting systems for modular linkage as a critical waste factor, few have evaluated its impact on the project cost nor have tried to identify a potential way to improve its efficiency. This research aimed to evaluate the impact on leanness of using an automated connecting device for modular assembly as well as present a new plug-in self-lock connecting device. The methodology consisted in five key phases: (1) identify CWFs through literature review and case study (field observations and interviews), (2) identify how to improve the CWFs by defining KSFs for an ACD, (3) design an ACD following state-of-the-art design methodology (2015), (4) evaluate the performance of the ACD with KSFs and (5) estimate the economic impact of the ACD.

The critical waste factors identified are the following: co-dependence of crews, low rate of machine usage / workers usage, need of coordination, alignment unpredictability, load bearing relies on many systems, multiple handling of tools and material, reduced productivity compared to off-site, on-site material waste management is poor. The key success features identified are the following: (k1) automation of the locking mechanism, (k2) ability to assist the alignment of the modules, (k3) ability to create predictability in module positioning, (k4) integration of a complete load bearing system that includes (tensile, compressive and shear capacity), and (k5) dissimulation of the ACD inside the framing to allow full interior completion of the module and reduce on-site work.With its automated locking mechanism (k1), the ACD allows to reduce on-site connection activities from six to three, and allows to maximize the off-site completion of modules to up to 90% (k5). Moreover, its conic entry and precise positioning in factory helps assist the alignment of the modules (k2) and helps to create predictability in the positioning (k3). Finally, the ACD can bear important loads, as of 200 kN in tension, 40 kN in shear, and 1000 kN in compression (k4). When estimating the impact of the ACD on total project cost, the usage of an ACD in the Australian study cases studied by Sutrisna *et al.* (2019) leads to the possibility of reducing the total cost per module by up to 10%.

This research highlights the potential impact of automating the modular connecting systems on the reduction of sources of waste in the modular assembly process of OSC. To confirm the results of this study, field analysis shall be conducted to confirm hypothesis and confirm the cost of similar buildings built with, and without an ACD.

REFERENCES

Abdelhamid, T., El-Gafy, M.A., & Salem, S (2008). Lean Construction: Fundamentals and Principles. *The American Professional Constructor – Fall 2008.*

Annan, C., Youssef, M., & El Naggar, M. (2009). Experimental evaluation of the seismic performance of modular steel-braced frames. *Engineering Structures, 31*(7) 1435–46. https://doi.org/10.1016/j.engstruct.2009.02.024

Bajjou, M., & Chafi, A. (2020). Identifying and Managing Critical Waste Factors for Lean Construction Projects, *Enginnering Management Journal, 32*(1), 2-13. https://doi:10.3390/su12114460

Bowron, J., Gullifor, J., Churchill, E., Cerone, J., & Mallie, J. (2014). Modular building units, and methods of construction and transporting same (United States, Patent No. US 9,458,619 B2).

Cecobois. (2013). Guide technique sur la construction modulaire en bois, Centre d'expertise sur la construction commerciale en bois, Québec, Canada.

Chen, Z., Wang, J, Liu, J., & Cong, Z. (2020). Tensile and shear performance of rotary inter-module connection for modular steel buildings. *Journal of Constructional Steel Research 175*(1), https://doi.org/10.1016/j.jcsr.2020.106367

Dai, X., Zong, L., Ding, Y., & Li, Z. (2018), Experimental study on seismic behavior of a novel plug-in self-lock joint for modular steel construction. Engineering Structures, 181(1) 143-164, https://doi.org/10.1016/j.engstruct.2018.11.075

Erikshammar, J.J., Bjornfot, A., & Gardelli, V. (2010). The ambiguity of value. *Proceedings IGLC-18, July 2010*, Technion, Haifa, Israel.

Ferdous, W., Bai, Y., Ngo, T.D., Manalo, A., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings – A state-of-the-art review. *Engineering Structures 183*(1), 883-893. https://doi.org/10.1016/j.engstruct.2019.01.061

Hairstans, R. (2015). Building Off-Site. *Journal of the national institute of building sciences, April 2015*, Edinburgh Scotland.

Hoesseini, M.R., Martek, I., Zavadskas, E.K., Aibinu, A.A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction, 87*(1), 235-247. https://doi.org/10.1016/j.autcon.2017.12.002

Howell, G. A. (1999) What is lean construction – 1999. Proceedings IGLC-7, *Annual Conference of the International Group for Lean Construction (IGLC7).*

Loss, C., Piazza, M., & Zandonini, R. (2016). Connections for steel-timber hybrid prefabricated buildings. Part II: Innovative modular structures. *Construction and Building Materials Volume 122*, 796-808. https://doi.org/10.1016/j.conbuildmat.2015.12.001

Marte Gómez, J.A., Daniel, E.I., Fang, Y., Oloke, D. & Gyoh, L. (2021). Implementation of BIM and Lean construction in offsite housing construction: evidence from the UK. Proc. 29th *Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 955–964, https://doi.org/10.24928/2021/0122

Picard, L., Blanchet, P. & Bégin-Drolet, A., (2022). Assembly Solution for Modular Buildings: Development of an Automated Connecting Device for Light-Framed Structures. Buildings 2022, 12, 672, https://doi.org/10.3390/ buildings12050672

Park, K., Moon, J., Lee, S., Bae, K., & Roeder, C. (2015). Embedded steel column-to-foundation connection for a modular structural system. *Engineering Structures*, *110*(1) 244-257. https://doi.org/10.1016/j.engstruct.2015.11.034

Sendanayake, S.V., Thambiratnam, D.P., Perera, N., Chan, T., & Aghdamy, S. (2019). Seismic mitigation of steel modular building structures through innovative inter-modular connections. *Heliyon* *5*(2019). https://doi.org/10.1016/j.heliyon.2019.e02751

Sharafi, P, Mortazavi, M, Samali, B, & Rohagn, H. (2018). Interlocking system for enhancing the integrity of multi-storey modular buildings. *Automation in Construction 85*(1) 263-272. https://doi.org/10.1016/j.autcon.2017.10.023

Sutrisna, M., Cooper-Cooke, B., Goulding, J. & Ezcan, V. (2019). Investigating the Cost of Offsite Construction Housing in Western Australia. *International Journal of Housing Markets and Analysis, 12* (1), 5-24. ISSN 1753-8270

Tafazzoli, M., Mousavi, E., & Kermanshachi, S. (2020). Opportunities and Challenges of Green-Lean: An Integrated System for Sustainable Construction. *Sustainability 2020, 12*(11), 4460. https://doi:10.3390/su12114460

Wandahl, S., Neve, H.H., & Lerche, J. (2021). What a waste of time. *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29)*, Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 157–166. https://doi.org/10.24928/2021/0115

Zhang, Y.D., Yang, Y., Pan, W., & Pan, M. (2021). Key Performance Indicators of Offsite Construction Supply Chains: A Review. *38th International Symposium on Automation and Robotics in Construction (ISARC 2021)*, ISBN 978-952-69524-1-3.