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EDITED BY
AGOSTINO G. BRUZZONE
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CLAUDIA FRYDMAN
FRANCESCO LONGO
MARINA MASSEI
ADRIANO SOLIS

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BIM-ENABLED HEALTH & SAFETY ANALYSIS OF CROSS LAMINATED TIMBER ONSITE ASSEMBLY PROCESS

Tsvetomila Duncheva[a], Samer BuHamdan[b], Robert Hairstans[c], Mohamed Al-Hussein[d]

[a] [c] Edinburgh Napier University, Edinburgh, Scotland, UK
[b][d] University of Alberta, Edmonton, Canada

[a] m.duncheva@napier.ac.uk, [b]buhamdan@ualberta.ca [c]r.hairstans@napier.ac.uk
[d]malhussein@ualberta.ca

ABSTRACT
There is a global need for sustainable urban housing and offsite timber systems such as Cross Laminated Timber construction can be part of the solution to this need. However, the health and safety (H&S) impacts of CLT installation technologies have not yet been investigated utilising BIM enabled. This research project used a case study method to analyse the constructability of CLT panels installation and a System Dynamics (SD) simulation model was construed to analyse workers' time spent using hand tools for prolonged time, with potential health impacts. The results demonstrated that CLT installation H&S impacts could be correlated to CLT connections specification. These findings shine new light on Design for Safety (DfS) considerations for CLT medium rise construction with regards to social sustainability, in the context of urban residential buildings.

Keywords: Building Information Modelling/Management (BIM), Cross Laminated Timber (CLT), Social sustainability, Design for Safety

1. INTRODUCTION
Across the globe there is a race to provide housing for the enlarging population, the pressures for which are especially strong in the hotspots of economic growth, namely large cities. Urban centres of the likes of London, Boston, Bombay, Sydney and Beijing are all facing the challenges of population increase with higher rates than housing can be provided. In major cities in the southern hemisphere this trend has portrayed by the enlargement of informal settlements (King et al. 2017). One of the key strategies for coping with this urbanisation challenge is medium-density residential construction which needs to encompass all three sustainability branches; environmental, social and economic (UN 2016).

Offsite construction has been suggested as part of the solution to the housing crisis (Miles & Whitehouse 2013; Smith 2014). Mass timber construction in particular has the highest environmental sustainability credentials because of the high utilisation of a renewable resource, the production of which transforms CO_2 into O_2, namely wood. In addition, in offsite timber construction, a part of the building process is transferred from the building site to the factory environment, where there are opportunities for application of resource-efficient production methods developed in the manufacturing and automotive industries (Hairstans 2015; Womack & Jones 2003).

2. LITERATURE REVIEW
2.1. Offsite timber construction
With the change in production building method there are increased opportunities for automation, digitisation and control. As a result of these innovations, often cited offsite construction attributes are speed onsite, predictable costs and energy-efficient building fabric performance (Kamali & Hewage 2016; Dodoo et al. 2014). Moreover, an advantage of offsite construction with a high percentage of prefabrication, is improved safety, due to reduced need for working at heights and use of equipment for strenuous manufacturing and assembly tasks (Schoenborn 2012). However, the H&S aspects of the onsite assembly processes have been little discussed in previous research.

2.1.1. CLT for tall residential construction
Cross-laminated timber is a type of mass offsite timber system, in which lamellae are glued in perpendicular grain direction to each other (Hairstans 2018). CLT is an engineered-timber product, whose higher strength and stiffness properties allow for utilisation of engineered timber as the main superstructure material in increasingly tall buildings. For example, the 18-storey 53m-tall student accommodation building at the University of British Columbia, Vancouver, Canada combined Building Information Modelling/Management (BIM) with CLT construction to deliver the tallest timber building in the world at the time of writing (Fallahi et al. 2016). Furthermore, the construction of CLT buildings up to 150 meters in combination with a concrete core has been theorized for high-density urban environments (Van De Kuilen et al. 2011).

2.1.2. CLT modelling and optimization
There are many research studies on CLT production, and structural optimization. For example, Crawford and colleagues (2015) investigated the potential to produce

CLT from home-grown timber resources in Scotland, whereas Izzi and colleagues (2016) calculated strength factors of nailed CLT connections. In addition, the integration of shear tests for the lamination of CLT panels has been investigated by comparison of test results with desktop study calculation results, to propose practical testing methods and their specimen size considerations (Betti et al. 2016).

Optimization studies have also been conducted on CLT for economic factors. Composite structures with CLT panels and supporting timber ribs have been demonstrated to minimise structural volume of CLT material for compliance with Eurocode 5 (EC5) (Stanić et al. 2016). Best-practice production methods have been outlined in previous research, including finger-jointing, adhesive application and hydraulic or vacuum pressing, with emphasis on quality control procedures for guaranteed product speciation (Brandner 2014). Moreover, increases in the level of prefabrication of CLT panels by inclusion of façade elements in the factory manufacturing process has been shown to result in construction programme acceleration (Gasparri et al. 2015).

However, fewer studies have investigated the health and safety (H & S) aspects of CLT construction. Fire safety is one of the main H & S areas, which are limiting the opportunities for tall timber building construction. Specifically, more knowledge needs to be contributed to the areas of system-level fire performance, interfaces between CLT and composite construction systems and fire-stopping of openings for services within the CLT panels (Barber & Gerard 2015). Yet the impacts of CLT construction and specifically different connection options on onsite installers' health have not been the subject of previous studies.

2.2. Building Information Modelling/ Management

BIM interfaces with offsite construction methods through the increase in digitisation, automation and manufacturing in construction (Vernikos et al. 2014). BIM offers opportunities for increased understanding of site conditions during construction through analysis of site environmental factors and visualisation of the project, with risk levels as an overlay to 3D virtual models or 4D construction schedules (Hardin & McCol 2015).

For example, opportunities have been investigated to apply BIM technologies and process to automate fall prevention from slab edges using guard rails installation (Zhang et al. 2015). Moreover, regarding the question of how such technologies can be practically applied in construction management, previous research has found that onsite simulations have potential to be integrated with 'toolbox' meetings, at which teams are gathered to discuss the health and safety requirements prior to task start (Ganah & John 2015).

Further digitisation advances for BIM safety offer opportunities for improved safety management on construction sites online databases, virtual reality, overlaid 4D schedules and active instead of passive PPE enabled by sensing and warning technologies (Zhou et al. 2012). However, digital tools for the reduction of H&S risks through design are not as sophisticated as those for application during the construction stage. Process flowcharts have been suggested as simple yet effective tool to identify the drivers for potential safety hazards and remove them through Design for Safety (Malekitabar et al. 2016).

2.3. Construction safety simulation

The research studies outlined above investigated the optimization of CLT as a product or the integration of BIM practices with Safety management, however further opportunities for offsite systems H&S optimization lie in research of construction processes with the use of simulation models.

Although not focused on offsite systems, several research studies have investigated simulation models which aimed to capture the complexities of workers' safety behaviour on site (Goh & Askar Ali 2016; Guo et al. 2016; Mohammadfam et al. 2017). Because of the universal time over-runs of construction programmes, a significant factor which affects safety behaviour is the resulting pressure on workers to expedite their tasks and the co-relation between production pressure and accident occurrence has been proven through a System Dynamics (SD) model (Han et al. 2014).

2.4. The gap in knowledge

Overall, as Table 1 shows, there is gap in knowledge on the integration of the four outlined themes of CLT construction, BIM, Simulation Research Methods (SRM) and occupational health and safety.

Table 1: Literature review themes and gap analysis

Reference	CLT	BIM	SRM	H & S
(Fallahi et al. 2016)	✓	✓		
(Izzi et al. 2016)	✓			
(Betti et al. 2016)	✓		✓	
(Stanić et al. 2016)	✓		✓	
(Brandner 2014)	✓			
(Crawford et al. 2015)	✓			
(Barber & Gerard 2015)	✓			✓
(Gasparri et al. 2015)	✓		✓	
(Van De Kuilen et al. 2011)	✓		✓	
(Schoenborn 2012)	✓			✓
(Ganah & John 2015)		✓		✓
(Malekitabar et al. 2016)		✓		✓
(Zhou et al. 2012)		✓		✓
(Zhang et al. 2015)		✓		✓
(Goh & Askar Ali 2016)			✓	✓
(Guo et al. 2016)			✓	✓
(Han et al. 2014)			✓	✓
(Mohammadfam et al. 2017)			✓	✓

3. METHODOLOGY

The objective of the present research is to develop a decision support model to assist designers and project management evaluating the occupational hazards associated with CLT panels installation due to nailing and screwing efforts associated with a certain design of the structural connections between the panels.

The information required for the simulation process are fed from two input points; a database that is linked with a BIM model that contains geometrical information pertaining to the design and the user who provides information related to the design of the structural connections. The principles of this paper were validated during an in-depth qualitative interview with an industry expert in DfMA design and project management of CLT residential buildings

The overall methodology utilized in this research is presented in Figure 1.

Based on the provided information the simulation model emulates the entire installation process of the building, so the potential exposure time to occupational hazards can be evaluated and, therefore, the associated risk can be assessed. Once this information is known the designers and/or project management team can evaluate their practices accordingly to reduce the correspondent hazards.

3.1. The architecture of the simulation model

The simulation model uses discrete simulation in Simphony.Net environment to model the construction operations related to CLT panels installation. The model consisted of interconnected sub-modules, where each sub-module was responsible for a certain phase of the construction process.

3.1.1. Weather conditions sub-nodule (WCSM)

Craning operations are indispensable in offsite construction. These operations are sensitive to weather conditions, chiefly, wind speed and gusts that halt craning work when in excess of safe working limits. Accounting for weather conditions within the simulation engine is essential for the reliability of outcomes. For this purpose, the weather sub-module generates discreate events that follows the wind patterns prevailing in the area where the construction takes place (wind speed is modelled as a statistical distribution that is obtained from fitting the meteorological data). Once the wind speed of a generated incident exceeds the maximum allowable limit for craning it triggers the construction sub-module to stop craning operations until the wind speed goes back to the working limits. Figure 2 shows the weather sub-module used in the simulation model.

Figure 2: Weather conditions sub-nodule

3.1.2. Construction operations sub-module (COSM)

The core of the simulation engine is the construction operations sub-module, where the major effort of simulation is happening. As the purpose of developing the simulation model is to evaluate the health hazards associated with CLT installations, the focus of the COSM is on the installation task.

The simulation process begins once the panels are delivered on-site. Panels are usually delivered to the site following the installation sequence, except for some discrepancy that impose storing the panels until it is time for them to be installed. The COMS addresses this issue

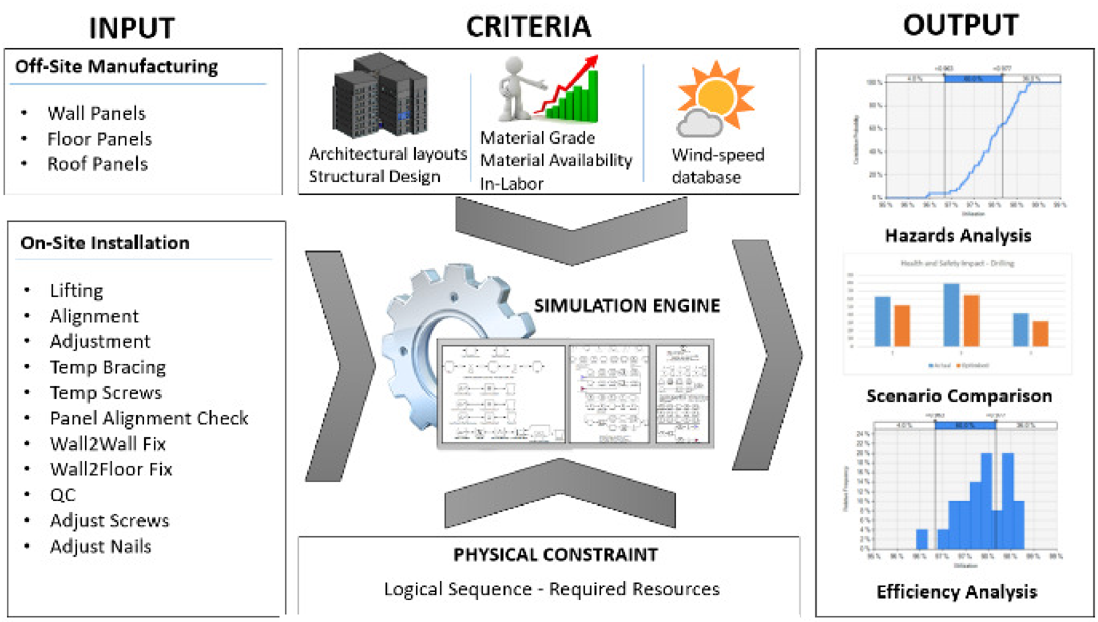

Figure 1: Research Methodology

using a probabilistic composition that assesses the likelihood of the wrong delivery of the panels and incorporates it to the correspondent sub-module. The next task for the COSM is to mimic the lifting process, where it interacts with the WCSM for safe-working conditions. Once the panels are in the designated place the next step is a nailing and/or screwing process to be fixed in place. The model simulates both process independently to allow for collecting more customized data. To simulate the installation process, the COSM requires the following input:

- the vertical (floor number) and horizontal (floor plan location) locations of each wall;
- the function of each wall (e.g. stability load bearing wall, non-load bearing wall, etc.)
- wall connection design per the function and location of the wall;
- wall geometry; and,
- productivity information for installation tasks.

Figure 3 shows the COSM in Simphony.Net Environment. The input for the simulation model, which was described previously, comes from two sources; a BIM model and the user. The following sections will discuss the information exchange with data sources.

3.2. Information exchange with data sources

The efficiency of utilizing simulation as a decision support tool is proportional to the ease of feeding the information pertaining to the various scenarios needed to be evaluated. As demonstrated in 2.1, except of the wind speed database and productivity information, the information required to simulate the installation process is related to the building. The size of the data pertaining to a certain building is proportional to the size and the complexity of that building, and the building grows in size and complexity, the manual acquisition of the required information by the simulation model gets harder. Therefore, the simulation engine is designed to retrieve the building-related infatuation from a BIM model, while productive and wind speed patters are input manually. Section 2.2.1 elaborates more on the link between the simulation model and BIM models. While Section 2.2.2 discuss user-fed information.

3.2.1. Linking BIM models with the simulation engine

BIM models contain accurate data about the building categorized per element. BIM authoring tools support export building data to databases management environments such as MS Access. On the other hand, Simphony.Net support generating entity with properties obtained from an external database. Therefore, MS Access is used as a medium between BIM authoring tools and the simulation engine, where BIM authoring tools export required information into a MS Access database, which Simphony.Net will use to generate entities with the building properties. The following information types are stored in the database:

- ID: a unique identifier from the BIM model, which is also used for horizontal location of the wall;
- type: indicates the function of the wall, which will further define the type of connections needed;
- length, where the generic information is stored; and,
- floor: to define the vertical location of the element.

This information is acquired for wall and floor panels. This link allows processing large amount of information pertaining to the building in almost no time, which

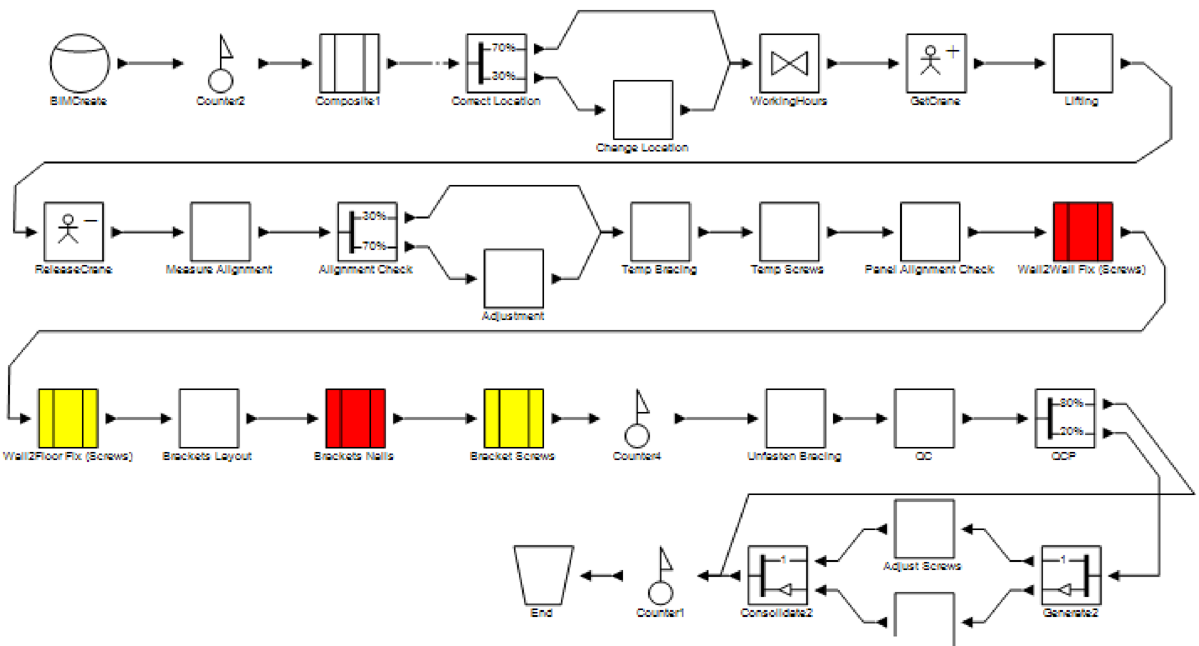

Figure 3: Construction operations sub-module

expedite the simulation process as it automates the input process. Furthermore, design nature in the construction industry has an iterative process, which in case of manual feed of information will burden the implantation of the developed model during assessment. Hence, the developed link with the BIM models relive this burden.

3.2.2. User-fed information

In cases where the information is required by the simulation engine is global (i.e. applies to all entities in the model), the user can manually input this information. The information that falls within the global nature is as follows:

- Productivity (labour-minutes per connection);
- connection design per panel type;
- distribution functions that predict wind speed patterns.

This information is input once per scenario and therefore the need for automation is not pressing and won't affect the ease of implementing the developed model. The statistical distribution of wind data generation is an area for further work in the research, which will be included in a subsequent journal publication.

The last section of the methodology deals with analysing simulation generated data.

3.3. Analysing simulation data for occupational health and safety by design

Research into hand-arm vibration syndrome (HAVS) has revealed the clear connection between increased exposure to vibration tools among joiners and construction workers and increased risk of HAVS (Palmer et al. 1999). This '99 report produced for the Health and Safety Executive (HSE) indicated that 4.2 million male and 667,000 female workers were exposed to hand-transmitted vibration at work, of which carpenters and joiners were the second-largest male group, after welders. The report findings demonstrated that there was a nearly 2 times higher rate of cold-induced finger blanching in carpenters and joiners than in workers not exposed to vibration tools. In carpenters and joiners the rate was especially high, between 1.89 and 3.37.

According to the HSE, more than 600 new people were reported to suffer from vibration 'white finger', cumulatively more than 7,500 people in the ten years between 2006 and 2015, shown in Figure 4 (HSE 2016). Other health problems associated with exposure to vibration are carpal tunnel syndrome and occupational deafness (ICE 2015). According the ICE, the only way designers can prevent Occupational Health and Safety Hazard such as HAVS, is by eliminating or reducing the 'need for workers to use hand-held vibrating tools or machinery. Specific to CLT projects this would translate as optimizing the screw connections in the superstructure.

It is speculated that the risk of HAVS and other occupational health and safety hazards associated with use of vibration tools in carpentry increases incrementally with the time spent using vibration tools, which can be measured as a percentage of overall labour-hours, as outlined in Equation 1.

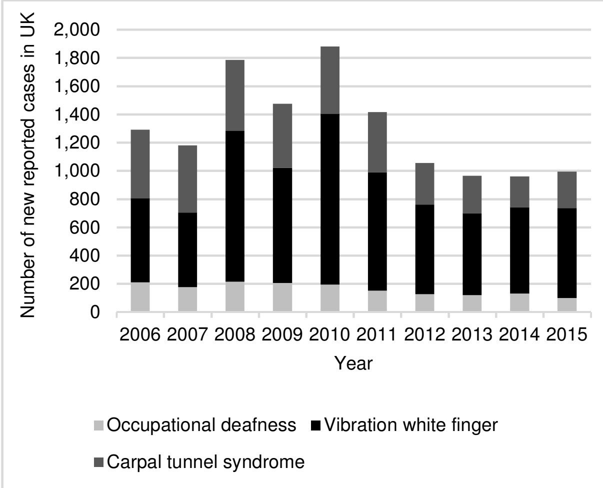

Figure 4: Health impacts associated with vibration tools. Authors' own graph based on data from (HSE 2016).

$$\text{\% time spent using vibration tools} = \text{\% increase in chance of HAVS symptoms} \quad (1)$$

The simulation model provides time information pertaining to the performed tasks based on input building data. The hazard associated with the screwing and nailing tasks are assessed based on (1) exposure times to nailing and/or screwing tasks and (2) number of the workers who are exposed to the mentioned tasks.

3.3.1 Limitations

To speculate more accurately how much the chance of HAVS increases with use of vibration tools, further research is needed in establishing the correlation between time spent using equipment and the likelihood of HAVS symptoms. For example, the number of carpenters and joiners working in construction in the latest year available year 2015 in the UK, needs to be compared to the number of reported HAVS cases. Moreover, the average time spent using vibration tools of carpenters and joiners on construction sites should be compared to the time spent using vibration tools in the case study building. In addition, not all connections will have an equal impact on the health & safety of workers, from the observations in this project it can be stated that connections at angles other than perpendicular to the surface are more strenuous. This approach will be the object of further study.

4. CASE STUDY

An innovative CLT urban residential building was the case study selected to demonstrate the simulation methodology. This was the Yoker project, the tallest CLT building in Scotland at the time of writing at 7 storeys tall. The building site is situated on the north bank of the river Clyde and a small ferry is in operation, which takes passengers across to the opposite bank. The building is oriented along the north-south axis with a T shape, which maximises views over the river Clyde. The area of Yoker is mainly residential and its high street feature the characteristic of Glasgow red-stone tenement buildings as shown in Figure 5.

Figure 5: Yoker project in context. Courtesy of CCG.

4.1. Input data

4.1.1. Tasks duration

To account for the stochastic nature of the construction activity, a triangular distribution was used for the installation tasks durations. Table 2 shows the parameter of the triangular destructions used for each of the tasks.

Table 2: Duration of task used in the simulation model

Task name	Duration (Triangular Distribution Parameters in min)		
	Low	average	High
Correct location	0.5	1	3
Change location	2	5	8
Lifting	1	2.5	4
Measure alignment	0.25	0.5	1
Adjustment	0.5	1	2
Temp Bracing	1	2	4
Temp Screws	1	1.5	2
Panel Alignment Check	0.25	0.5	1
Wall2Wall Fix	NS*0.25	NS*0.5	NS*0.75
Wall2Floor Fix	NS*0.75	NS * 1	NS*1.25
Brackets Layout	NB*0.25	NB*0.5	NB*1
Brackets Nails	NN*0.25	NN*0.5	NN* 0.75
Brackets Screws	NS*0.25	NS*0.5	NS*0.75
Unfasten Bracing	1	1.5	3
QC	120	240	360
Adjust Screws	NS*0.5	NS * 1	NS*1.5
Adjust Nails	NS*0.5	NS*1	NS*1.5

Where;

- NS is the number of screws in one connection plate.
- NN is the number of nails in one connection plate.
- NB is the number of brackets to be installed on one panel.

4.1.2. BIM model

The BIM model of the building, shown in Figure 6, was prepared by the architects and was used to overlay the engineers' CLT model with the architectural model. As the model was delivered in IFC format the authors had to modify the definition of the element and added information to enable export to the developed database.

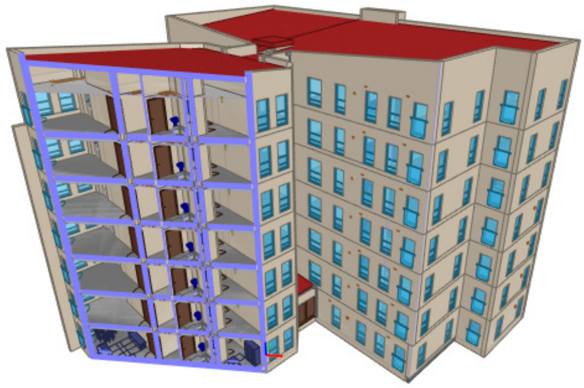

Figure 6: The BIM model of the case study building

4.1.3. Wind speed patterns

The site is located in the west outskirts of Glasgow and is to the south-west is exposed to the river. This is reflected in the wind rose diagram shown in Figure 7. The image shows that higher frequency and velocity winds are oriented from the SW, the same direction as the central axis of the building, facing the river. Wind data was sourced from an online weather database in the public domain (MeteoBlue 2018). Typically, in the area there are 34 days per year with wind speeds above 30 m/h, at which crane operations needs to stop, concentrated between November and March (5 months), with much fewer high-wind days in the spring and summer months.

During the installation of the CLT panels in the case study building 5 days were lost due to high winds. This is less than the typical 8 high wind days in the months March to May, and could be explained by some high wind days falling on non-working days, and/or a spring season with lower than usual wind frequency and velocity in 2017.

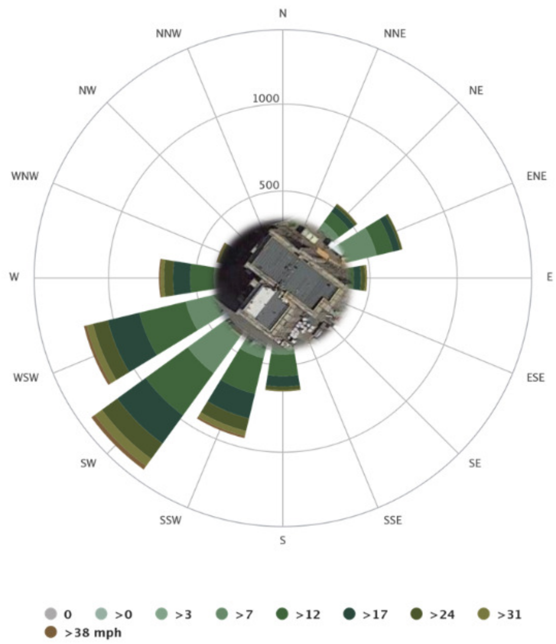

Figure 7: Case study building in wind rose context

4.2. Simulation output

The model is set to run 100 times, where Figure 8 shows finish times of the project through the multiple runs. The installation duration is 52,711min with a 95% confidence interval of [52471,52951]. On the other hand, Table 3 demonstrates the percentage of the total project duration that was spent on screwing and nailing of panels. As per Equation 1, the increase in the HAVS symptoms can be estimated as per Table 3. Considering the information pertaining to the increase in the HAVS symptoms, decision makers can adjust the design of the connection between the panels to reduce the likelihood of having HAVS symptoms.

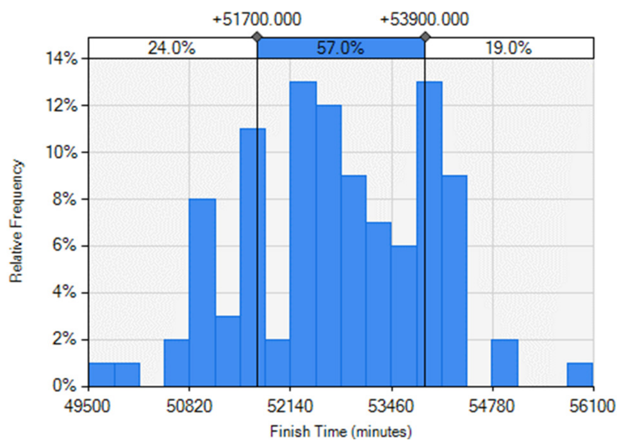

Figure 8: Finish times of the project

Table 3: Presentation of screwing and nailing tasks

Task	**Average Utilization**	**Standard Deviation**	**Maximum Utilization**
Screw Floor 0	2.10%	0.10%	2.30%
Screw Floors 1,2,3	92.10%	1.20%	95.10%
Screw Floors 4,5,6	37.80%	1.40%	41.20%
Nailing Floor 0	31.60%	1.20%	34.40%
Nailing Floors 1,2,3	23.10%	1.00%	26.40%
Nailing Floors 4,5,6	24.00%	1.10%	26.30%

Table 4: the increase in the HAVS symptoms

Task	Increase Percentage
Screw Floor 0	2.10%
Screw Floors 1,2,3	92.10%
Screw Floors 4,5,6	37.80%
Nailing Floor 0	31.60%
Nailing Floors 1,2,3	23.10%
Nailing Floors 4,5,6	24.00%

ANALYSIS AND DISCUSCUSSION

To interpret the meaning of these results, it should be noted that the CLT installation was sequenced in to phase, first the panels were installed using temporary connectors by half the team, and then connections were finished by the rest of the team members. Therefore, only the CLT panels assembly was on the critical path and has a higher rate of completion compared to the connectors finishing. With view of the differences in skill requirements and the criticality of the tasks, the panel assemblers were senior in expertise, whereas the second connections crew were junior and were in training. These associations were revealed during a qualitative validation interview with an industry expert.

Therefore, most of the effect of these results would have been experienced by the most junior staff, subjected to the highest number of repetitive tasks. However, further research would be needed to decipher the correlation between individuals' use of vibration equipment and their respective likelihood of HAVS symptoms development. Such studies could perhaps be undertaken using emerging technologies such as smart watches, smart safety helmet and others (Robinson et al. 2016). With view of the urgent need for recruitment of new talent in the construction industry underpinned by the skills gap in construction, this approach seems anti-productive. If those training to become construction professionals are exposed to monotonous tasks which potentially increase the likelihood of H&S impacts, even if substantial dampeners are used to mitigate the H&S impacts, the nature of the task at hand may discourage the new entrants in the construction industry. A recommendation is made that the necessary practice in precise, accurate and quick connections installation is complemented with utilisation of technology such as Augmented Reality BIM to overlay (Hardin & McCol 2015). Their responsibilities can moreover be enhanced by providing young trainees with tablets and training on how to input daily component-based progress statuses, reflected in 5D BIM models, showing 3D + Time + Completion Status, which could be reflected using different colour schemes. A similar visualisation approach has already been proposed in the context of energy utilisation visualisation.

Importantly, the results suggested that the screws on Floors 1,2 and 3 could have imposed the highest H&S risks to the CLT installers and a correlation is hypothesised between the high number of complex connectors on those floors and their H&S impact. However, a careful examination of the differences in detailing with consideration for structural requirements will be the object of further study by the authors.

5. CONCLUSION

Using cross limited timber as construction material is gaining increasing recognition from construction practitioners and researchers due to its low environmental impact and improved levels of constructability, and with the increasing demand on CLT in the construction project it is important to assess the H&S aspects associated with CLT installation. Therefore, this paper utilizes Building Information Modelling with discrete event simulation to develop a decision support model that assist designers and project management teams to evaluate the potential H&S hazards during CLT installation that are associated with a certain design. With the help of the developed model, designers can test the compliance of their design with health and safety regulations and modify according to the findings, and as a result the implementation of CLT becomes safer and more appealing for a wider range of contractors and owners, improving the sustainable practice in the construction industry.

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AUTHORS BIOGRAPHY

Tsvetomila Duncheva is a Research Assistant at the Centre for Offsite Construction + Innovative Structure, working on multiple projects, whose main aims are to mitigate the skills shortage in the UK construction industry and to facilitate collaboration between offsite timber companies in Scotland. Mila is now completing her PhD on measuring and comparing the productivity of panelised, mass timber and volumetric offsite timber systems. To achieve this Mila extracted best practice information from international leaders in volumetric in the UK, mainland Europe and Canada. This PhD study is funded through an 'Engineering the Future' scholarship from the University of Strathclyde and supervision is provided through collaboration with the University of Glasgow. Beforehand Mila completed a BA (Hons) Architecture degree with distinction at the University of Kent, Canterbury. Mila undertook two architectural assistant internships in her home country Bulgaria on residential architecture design and BIM integration, respectively. Through the combination of education and practice Mila completed her RIBA Part I training in 2013.

Samer BuHamdan is Post-Doctoral Fellow at the University of Alberta as part of NSERC Industrial Research Chair in the Industrialization of Building Construction. Samer's research utilizes building information modelling (BIM) to evaluate the interactions and inter-relationships among components of a project. This deep study of system components serves as the foundation for the development of a dynamic approach to project planning considering time and costs as targets. The result is the development of a decision making model in the context of complexity theory that captures the long-term quantitative effects of engineering decisions as well as the qualitative aspects of human behaviour. It is expected that the principles underlying this research can be extrapolated to explain and predict the behaviour of any component in a complex system in which there are many competitors and limited resources.

Dr. Robert Hairstans is an Associate Professor and head of the Centre for Offsite Construction + Innovative Structures (COCIS), a team with specialist knowledge in the field of timber technologies and engineering adding value to the supply chain with an emphasis on offsite (modular) prefabrication. His research interests include wood innovation, structural timber systems, offsite manufacture and modular construction with an emphasis on delivering more sustainable communities. Dr Hairstans has delivered over £1M of research, commercial and knowledge exchange activities working in collaboration with industry, academia and external organisations. Dr Hairstans is Co-Chair of the international Modular and Offsite Construction Summit and academic lead of Offsite Solutions Scotland (a local industry timber offsite community of practice employing over 1000 people). His most recent book publication is “Mass Timber: an introduction to solid laminate timber systems”.

Mohamed Al-Hussein is a professor at the University of Alberta, Hole School of Construction Engineering, and a highly sought researcher and consultant in the areas of construction automation, lean construction, process improvement, equipment selection and utilization, CO2 emission quantification and reduction, urban development, and building information modelling. Dr. Al-Hussein’s current research initiatives include prototyping of automated and semi-automated machinery for fabrication of steel and wood-framed construction components, application of lean and ergonomic principles to improve the safety and productivity of industrialization construction operations, and development of plant layout and process improvement measures for panelized and modular construction. Dr. Al-Hussein holds the NSERC Industrial Research Chair in the Industrialization of Building Construction, and is Director of the Nasseri School of Building Science and Engineering. Dr. Al-Hussein’s research has been published in well over 200 peer-reviewed journals and conference proceedings.