Developing a BIM and simulation-based hazard assessment and visualization framework for CLT construction design

Samer BuHamdan[1,*], Tsvetomila Duncheva[2], Aladdin Alwisy[3]

[1]Postdoctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta. E-mail: buhamdan@ualberta.ca

[2] Associate Lecturer, Edinburgh Napier University, E-mail: m.duncheva@napier.ac.uk

[3] Assistant Professor, M.E. Rinker, Sr. School of Construction Management, University of Florida, E-mail: aalwisy@ufl.edu

* Corresponding author. E-mail address: buhamdan@ualberta.ca

Abstract

One emerging trend in sustainable medium-density construction is the use of mass timber products such as Cross Laminated Timber (CLT), which is a novel approach that involves numerous connectors. Researchers have not previously investigated the potential health impacts of different connectors. This paper proposes a framework to correlate the specification of CLT connectors to the potential risk of exposure to Hand Arm Vibration Syndrome (HAVS). We also propose an innovative adaptation of the Location-Based Management System flow line by adding a health risk dimension. The usefulness of the proposed framework is tested using a cutting-edge case study building, the tallest timber building in Scotland. The contribution of this research is a novel appreciation of the impact on installers' Health & Safety based on the specified type of CLT connectors. With the methodology outlined in this paper, a HAVS variable can be added to design analysis to increase social sustainability in the built environment alongside other sustainability pillars. The findings are relevant to structural engineers, architects, key industry stakeholders, and researchers in the built environment.

Keywords: Social sustainability, Health and safety; Construction industry; Cross-Laminated Timber (CLT); Discrete event simulation; Building Information Modelling (BIM); Visualization; Design.

Introduction

Amid worsening housing crises across the globes, offsite construction is being floated often by researchers as a potential solution to the housing crisis (Miles and Whitehouse 2013; Smith 2014), due to its speed, energy-efficient performance predictability, and improved safety (Dodoo et al. 2014; Kamali and Hewage 2016; Schoenborn 2012). Indeed, these aspects, alongside others, such as improved productivity and increased use of digitization, are essential drivers for offsite use (Hairstans and Duncheva 2019). Among the various materials used in the offsite construction, mass timber is gaining increasing attention owing to its lower environmental impact, full availability, and lower cost. Cross-laminated timber (CLT) is a type of mass offsite timber system, in which lamellae are glued in perpendicular grain direction to each other (Hairstans 2018; Laguarda Mallo and Espinoza 2015). CLT is an engineered-timber product whose higher strength and stiffness properties allow for the utilization as the primary superstructure material in increasingly tall buildings (Kuilen et al. 2011; Yoo et al. 2019).

Research efforts have focused on the structural optimization of CLT panels. For example, Crawford and colleagues investigated the potential to produce CLT from home-grown timber resources in Scotland (Crawford et al. 2015). Izzi and colleagues calculated the strength factors of nailed CLT connectors (Izzi et al. 2016). Besides, 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 viability. Composite structures with CLT panels and supporting timber ribs can minimize the structural volume of CLT material for compliance with Eurocode 5 (EC5) (Stanić et al. 2016). Researchers outlined best-practice production methods, 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 the inclusion of façade elements in the factory manufacturing process have been shown to result in construction programme acceleration (Gasparri et al. 2015).

However, the socio-economic sustainability of the CLT construction processes has not been investigated with a focus on worker's efficiency and health impacts of CLT construction. Indeed, the majority of current occupational vibration H&S research has focused on the use of heavy-duty equipment such as electric breakers and rotary hammers (Cederlund et al. 2001; Edwards and Holt 2006). Others explored the ergonomics of different workstations and tools and how to assess hazards. The new emerging mass timber systems, such as CLT, have not received the same level of scrutiny by researchers.

Typical CLT connectors specified are wood and self-tapping screws, nails, bolts, and dowels, bearing type fasteners, and innovative fasteners (Mohammad et al., 2013). The common feature among these types of connectors is that they require the use of power tools such as nailing guns and impact screwdrivers, which, through exposure to vibration, can impact workers' health.

Hand-Arm Vibration Syndrome (HAVS, also known as 'white finger') was identified as a leading H&S concern within the trade of carpenters and joiners, who are responsible for completing the CLT onsite installation (ONS 2010). Research has revealed the clear connection between increased exposure to vibration tools among joiners and construction workers and the experience of HAVS symptoms (Palmer et al. 1999). The '99 report, produced for the Health and Safety Executive (HSE), is the latest available extensive such study. It 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. Besides, carpenters had a chance of 94.2% to be exposed to high-risk vibration in any one week. This high-risk may be correlated to the time spent using different tools per trade – in the case of carpenters nailing guns and impact screwdrivers resulted in exposure to HAVS 20.4% and 16.5% of the surveyed sample, respectively (Palmer et al. 2001). An average of 600 new cases is reported annually in the U.k., within the past ten years, as shown in Fig. 1 (HSE 2020a).

<Insert Fig. 1 here>

Cumulatively, this equated more than 6,230 new HAVS cases in the U.K. between 2009 and 2018, and on average, over the past three years, circa 10% of these were among construction workers (HSE 2020b). In the U.K., in the latest available statistics for 2018, 66,700 people worked as joiners, among whom 14% may be hypothesized as experiencing HAVS using data from the ’99 survey sample, equalling more than 9,300 people (ONS 2017; Palmer et al., 1999). HAVS typically impacts the daily lives of exposed workers, including intolerance to cold, needles-type pain, challenges in performing simple tasks such as the use of manual tools and handwriting (Cederlund et al. 1999; Handford et al. 2017). Therefore, HAVS is a significant concern in the carpentry trade and should be mitigated to increase the social sustainability of CLT construction.

The present research proposes a framework that utilizes discrete event simulation (DES) and Building Information Modelling (BIM) to assess and visualize health hazards related to the CLT construction operations, with particular focus on HAVS. Through this work, we aim to provide a platform that helps to integrate H&S into design analysis, which is expected to increase the social sustainability of CLT construction.

In the next section, we discuss the research methodology, present the proposed framework, and test its usefulness. The methodology section is followed by the conclusion where we outline the research’s contribution to knowledge and its limitations.

Research methodology

To design the intended risk assessment and visualization framework, we follow a modified version of Blessing and Chakrabarti’s Design Research Methodology (Blessing and Chakrabarti 2009), where the development endeavours follow three phases:

1. Phase I- Criteria definition, in which the authors identify the requirements and success criteria the developed framework must fulfill;
2. Phase II-Design and development, where we translate the identified requirement into a practical solution, and finally,
3. Phase III- Testing, in which we test the usefulness of the developed framework.

Phase 1- Criteria definition (PI-CD)

This phase is concerned with identifying a list of criteria that can be used to develop the health assessment and visualization (HA&V) framework and evaluate its merits. The PI-CD began with interviewing our industrial partners to understand better the challenges within their practice and list possible requirements that will increase the practicality of any developed solution.

This was a two-stage semi-structured interview process, conducted as part of doctoral work on offsite construction multi-factor productivity measurement (Duncheva, 2019):

- site observations of CLT installation followed by an interview with the installation team's head carpenter (questions are in Appendix A); and,
- interviews with the architects and structural engineers on the connection between structural design and constructability (questions are in Appendix B).

The identification of HAVS as a potential health hazard in CLT panels installation came from the head carpenter's answers to questions 7 and 8, about possible risks and challenges. During the interview, the head carpenter introduced the concept of HAVS (colloquially referred to as 'white finger') and described their symptoms in detail, including numbness and pain in cold weather. They continued with concerns that some of the specified connectors could cause similar effects on fellow carpenters due to their density (reaching up to 100mm centres with 30 nails per connector) and complexity (8×220mm screws installed at a 45° angle and 150mm centres). This personal and professional experience sparked the idea of investigating further the impact of HAVS on the carpentry trade (described in the introduction) and having interviews with the design team to further understand the connection between design, constructability, and health & safety.

In the second stage, the interviewees (architects and structural engineers) pointed out that lack of a mechanism that allows assessing the hazards inherited in a given design inhibits the design team's ability to incorporate health-related hazard assessment into the design practice. The architects and engineers expressed their interest in a hazard assessment tool that:

- supports team collaboration by maintaining efficient communication within and outside of the design team;
- allows for multiple hazard assessments; and,
- allows for a concurrent evaluation and display of hazards with the design development.

Using the identified set of criteria, we, then, moved to review the state-of-art literature in search of an application that fulfills the determined requirements. The next subsection summarizes the review effort.

Review of safety-in-design applications

Technology has proven considerable importance in helping decision-makers to mitigate the potential hazards related to the proposed design at an early phase, chiefly with the use of Building Information Modelling (BIM). BIM interfaces with offsite construction methods through the increase in digitization, automation, and manufacturing in construction (Vernikos et al. 2014). BIM offers opportunities for increased understanding of site conditions during construction by analyzing site environmental factors and visualizing the project, with risk levels as an overlay to 3D virtual models or 4D construction schedules (Hardin et al. 2015). For example, Zhang et al. (2015) investigated the application of BIM technologies to automate the process of fall-prevention, mainly from slab edges, using guard rails installation. Ganah and John (2015) found that onsite simulation can be integrated with ‘toolbox’ meetings, at which teams discuss the health and safety requirements before commencing the task. Indeed, digitization within the BIM environment offers 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).

The studies outlined above investigated the optimization of CLT as a product of integrating 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 that aimed to capture the complexities of workers' safety behaviour onsite (Goh and Askar Ali 2016; Guo et al. 2016; Mohammadfam et al. 2017). Because of the persistent time over-runs in construction projects, 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 (S.D.) model (Han et al. 2014).

The presented literature leads to the conclusion that there is a lack of applications that meet the previously identified practitioners' expectations and allow them to effectively incorporate H&S into design processes.

Moving forward, the criteria identified through the conducted interviews are used to guide the development of the HA&V framework.

Phase II- Design and development (PII-DD)

It is essential, prior to presenting the developed framework, to elaborate on how the identified features are translated into technical requirements. BIM is a widely used technology in the construction industry across almost all phases of the project life cycle, from design to commissioning and operation. Designers use BIM to develop their models and drawings, while construction personnel utilizes it to facilitate construction and track progress. Consequently, a tool that is BIM-based blends properly within existing practices and eases the information exchange among concerned stakeholders, so it "supports team collaboration" and "maintain efficient communication." Design is an iterative process that entails many changes, which makes conducting a thorough assessment of the potential hazards demanding. Automating the hazard assessment process by simulating the construction activities reduces the demand on time and resources. Therefore, incorporating a simulation model into the developed framework increases its efficiency, allows to address several hazards concurrently, and speeds up hazard assessments. Additionally, to further streamline the hazard assessment process, hazard visualization is presented to construction and design teams by integrating visual clues into existing visualization schemes, e.g., 3D virtual models and schedule diagrams.

Given the presented discussion, Figure 2 shows the proposed framework that uses BIM as a medium for information exchange, simulation model to assess potential hazards, and displays the results in two different styles. The details of the proposed framework are discussed in the following subsections.

<Insert Fig. 2 here>

Information layer

The ease of incorporating simulation models into the design process is relative to the rapid and smooth information exchange from and into the simulation model (Bu Hamdan et al. 2015; Bu Hamdan et al. 2015). The increase in the project's size and complexity renders the manual acquisition and feed of the required information unfeasible. Thus, the information necessary to simulate the construction process is stored in an intermediary databased that are connected directly to the simulation model. The simulation model, then, uses the information in the database to generate the simulation entities automatically.

In this context, it is possible to differentiate between two streams of information, depending on their nature and the way their corresponding databased is generated, which are design-related information and construction-related information.

Given the focus of the present reseeach on CLT panels, the design-related information is concerned with panels':

- type or function, to define the type of connection needed;
- length, to calculate the number of connections required based on pre-set rules; and,
- floor to determine the vertical location of the panel.

It is also important to assign each panel a unique identifier for tracking and checking purposes.

This information is readily available in buildings virtual models in the BIM environment, where BIM authoring tools support exporting building data to database management systems such as M.S. Access.

The construction-related information, on the other hand, defines the site conditions, and it applies to all entities in the simulation model, this information includes winds patterns in the construction region, production information and installation requirements. The database, in which construction-related information is stored, is updated at the lower frequency compared to the design database- as changes in the site conditions are less likely to change compared to design information.

Note that, in addition to the construction-related information mentioned previously, the HA&V framework requires the construction schedule prepared according to the Location-based management system techniques, which is used for visualization purposes. Further on this point is discussed in the Visualization layer.

Simulation layer

The HA&V framework uses the discrete event simulation model proposed by Duncheva et al. (2018), which is developed in the Simphony.Net environment, to model the construction operations related to CLT panels installation. The model consists of two modules: the weather conditions module and the construction process module.

Weather conditions module (WCM)

Craning operations are vital in offsite construction. These operations are sensitive to weather conditions, chiefly, wind speed and gusts that halt craning work when above safe working limits. The WCM generates discrete events that follow the wind patterns prevailing in the area where the construction takes place. In turn, wind speed is modelled as a statistical distribution that is obtained from fitting the meteorological data. Once the wind speed exceeds the maximum allowable limit for craning, it triggers the construction module to stop craning operations until the wind speed is back to the working limits.

Construction operations module (COM)

The construction operation module (COM) concentrates on the CLT panels installation tasks, considering that the purpose of developing the simulation model is to evaluate the health hazards associated with CLT installations.

The simulation process begins once panels arrive at the construction site. Panels usually arrive at the site following the installation sequence. Panels may be delivered in the wrong order. In such cases, the wrongly delivered panels are stored until their scheduled installation. The COM addresses this issue using a probabilistic composition that assesses the likelihood of the wrong delivery of the panels and incorporates it into the simulation model.

The next task for the COM is to simulate the lifting process, where it interacts with the WCM for safe-working conditions. Once the panels are in the designated place, workers fix them using nails, screws, or both. The model simulates both processes independently to allow for collecting more customized data. To simulate the installation process, the COM 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 and non-load bearing wall)
- wall connection design per the function and location of the wall;
- wall geometry; and,
- productivity information for installation tasks.

Using the described input, the COM produces information related to the project and tasks duration and equipment and machinery utilization rates.

Fig. 3 summarizes the information exchange with the simulation model and the simulation output.

<Insert Fig. 3 here>

Analysis layer

CLT connectors tend to be metal plates, for which nails or screws are used to connect the adjoining CLT panels using the metal plate (Mohammad et al., 2013). Engineers can specify whether all openings for nails or screws should be filled, or how many and to what pattern. Another option for CLT connectors are screws used directly within the CLT, without metal plates. These tend to be installed at an angle, and are larger in size than the small screws used with the metal plates. In both options, the worker needs to spend time using power tools to install the connectors, either an impact drill or a nailing gun.

The interface between CLT connectors and the probability of workers experiencing HAVS symptoms is based on the in-depth study by the Health, and Safety Executive referred to in the introduction section (Palmer et al., 1999). Palmer and colleagues identified that the use of these power tools represented the most substantial risk of developing HAVS symptoms in carpenters, and construction workers in general. For this reason, this study considers the time spent using hand-held power tools as the leading risk factor associated with CLT connectors installation (Palmer et al., 1999). According to their extensive survey, i.e., Palmer et al., (1999), among the carpenters who experienced HAVS, 20.4% had been exposed to vibration from using a nailing gun, and 16.5% had been exposed to vibrations from an impact screwdriver. Based on these results, the HAVS risk associated with using nail guns and impact screwdrivers, typical CLT installation tools, can be expressed as follows (Palmer et al., 1999):

$$R_1 = T_1 \times 0.204 \tag{1}$$

$$R_2 = T_2 \times 0.165 \tag{2}$$

Where:

- R_1 is Risk of HAVS from nailing gun (%)
- R_2 is Risk of HAVS from impact screwdriver (%)
- T_1 is time spent using nailing gun (hrs)
- T_2 is time spent using impact screwdriver (hrs)

T_1 and T_2 are obtained by simulating the construction process.

Visualization layer

The graphical representation of numerical results allows for an intuitive understanding of the consequences of decision without a thorough explanation (Bu Hamdan 2018; BuHamdan et al. 2017). Showing the result of hazard assessment is no exception to that. The present research employs a visualization mechanism that reproduces the numerical information resulting from the analysis of the simulation's output in an easy-to-relate graphical form. As such, decision-makers can better comprehend the consequences of their design decisions on the H&S of construction crews. As could be seen in Fig. 2, the proposed research offers two levels of hazard visualization; element-based and task-based. In the element-based visualization, the appearance of elements in the BIM environment is changed to reflect their contribution to the evaluated hazards. The task-based visualization shows the magnitude of risks associated with a given task over time and, therefore, conveys a multi-dimensional representation of the risk.

Element-based visualization

the concept of element-based visualization can be explained as follows. Assuming the magnitude of contributions for two elements toward one or more studied hazards is C_i and C_j, and the appearance of these elements is A_i and A_j, then the following argument applies (BuHamdan et al. 2020):

$$if\ C_i = C_j\ then\ A_i = A_j\ otherwise\ A_i \neq A_j$$

In other words, the visualization model assigns a unique appearance for the building's elements based on their collective contribution toward the hazards under assessment. In this context, BIM models are the visualization medium for the element-based level visualization. The present research follows a modified approach from the value visualization framework proposed by BuHamdan et al. (2019) to visualize the hazardous potential of a given design. It should be noted that, as part of the modification to the original value visualization framework, the change in the appearance will be limited to the elements' colour. The system calculates the new appearance of elements based on their hazardous contribution as per the following steps.

1. Assess the elements' hazardous contribution

The hazardous contribution of an element is its weighted normalized potential hazard. Where R_{ij} is the amount of the expected risk *i* caused by element *j*, and W_i is the weight assigned to risk *i*, element *j* hazardous contribution or H_{ij} is assessed using Equation 3.

$$H_{ij} = \frac{R_{ij}}{\sum_j R_{ij}} \times W_i \qquad (3)$$

Note that, $\sum_j R_{ij}$ represents the total hazard expected from the entire building, and W_i represents the weight assigned to the studied risk (Ri),e.g., the risk of HAVS from nailing gun, by the user to indicate its importance compared to other risks, where $0 < Wi \leq 1$ and $\sum_i W_i = 1$.

2. Calculate the appearance

The visualization modified the appearance (i.e., the new colour) of elements in the BIM model using their assessed hazardous contribution.

The colour vector of an element i or $\overrightarrow{C_i}$ in a Hue, Saturation, and Luminance (HSL) system is defined by the following components (h, 0.5, l). Note that, setting the saturation to a constant value of 0.5 serves two purposes (BuHamdan et al. 2020):

- to reduce the dimensionality of the colour definition problem from 3 (define the hue, saturation, and lamination) to 2 (define hue and lamination, only); and,
- to produce colours that are more familiar to people.

The other two components of the colour vector, i.e., the hue and luminance, are determined based on the number of hazards in question, where we can distinguish between two scenarios: a single hazard and multiple hazards.

In the case of a single hazard, the evaluation begins with choosing a colour that represents the studied hazard j or $\overrightarrow{C_j}(h_j, 0.5, 0.5)$. The element's colour vector's (or $\overrightarrow{C_i}\,(h_i, 0.5, l_i)$) components are calculated as per Equations 4-a and 4-b.

$$h_i = h_j \qquad (4\text{-a})$$

$$l_j = 1 - 0.5 \times H_{ij} \tag{4-b}$$

Note that H_{ij} is the hazardous contribution of element *i* to hazard *j* as per Equation 3.

Where there is more than one hazard, we follow these steps to define the colour vector of each element:

1. assign a colour for each hazard and find its corresponding hue; the colour vector of a hazard *j* is $\overrightarrow{C_j}(h_j, 0.5)$;
2. create a colour vector $\overrightarrow{G_{ij}}$ for each element i and hazard *j* that has two components, h_j and H_{ij} where h_j is the hue of the hazard *j* as per the previous step, and H_{ij} is the hazardous contribution of element *i* to hazard *j* as per Equation 3.
3. calculate the intermediate colour vector for element *i* or $\overrightarrow{C^{inter}_i}(h_i^{inter}, l_i^{inter})$, as per Equation 5.

$$\overrightarrow{C^{inter}_i}(h_i^{inter}, l_i^{inter}) = \sum_{j=1}^{n} \overrightarrow{G_{ij}}(h_j, H_{ij}) \tag{5}$$

4. Calculate the final colour vector components for element *i* in the colour space are calculated as per Equation 6.

$$h_i = h_i^{inter} \tag{6-a}$$

$$l_i = 1 - 0.5 \times l_i^{inter} \tag{6-b}$$

Task-based visualization

Unlike the element-based visualization, visualizing the hazards on the task level is dedicated to demonstrating the changes in the hazardous intensity over time and location. It links location, time, hazards, and hazard intensities in a multi-dimensional visual plot to allow for a better understanding of hazards over space. Figure 5 shows an example of a two-dimensional task-based visualization diagram, which will be called the Location-based hazard distribution diagram (LBHDD). Note that LBHDD is a modified version of the flow line to accommodate the presentation of the hazards and their intensities.

<Insert Fig. 4 here>

In Fig. 4, each task is represented by two parallel lines that move in a space that is defined by two axes, time and location. The start and end of each doubled line determine the start and finish time and location of the corresponding task, the distance between the parallel lines determines the intensity of the studied hazard. Consider D_{lk} is the distance between the lines representing task l in location k, then D_{ij} is calculated as per Equation 7.

$$D_{lk} = roundup(\frac{\sum_i^m \sum_j^n H_{ij}}{m}, 0.0) \tag{7}$$

Where,

- m is the number of considered hazards;
- n is the number of building elements involved in task l
- H_{ij} is the contribution of element j to the hazard i, calculated as per Equation 3.

The next section provides a case study through which usefulness of the proposed framework is tested.

Phase III- Testing the usefulness

An innovative CLT urban residential building was the case study selected to demonstrate the functionality of the proposed framework. The chosen building is shown in Fig. 5. The case study will use the developed framework to assess the H&S hazards associated with installing CLT panels from screwing and nailing tasks and visualize the intensity of the hazard on the element and task level.

<Insert Figure 5 here>

Previously in Scotland, CLT had not been implemented in tall buildings until the construction of the 7-storey building in Glasgow described in this case study. The building included 42 apartments, mainly 2-bedroom apartments with some 3- 1-bedroom, and some accessible. The building was designed to maximize the use of CLT in the superstructure and, therefore, the external walls, floors and internal partitions were all built-in CLT. Some steel elements were also necessary where apartment layouts changed, and these were outside the scope of this work. Two cladding systems were used: brick-slips and zinc panels and both included labour-intensive onsite activities. The overall construction started in October 2016 and ended in

March 2018. The connections specified varied between the different levels and were of three main types: concrete brackets, CLT brackets and screws. The brackets used different combinations of nails and screws. Examples of connections and typical layouts are shown in Fig. 6. The hazard assessment of CLT connections is displayed through the lines of the diagram in Fig. 6 a) that represent the main walls of the case study floor plan, and the different colors of the lines show the different types of connectors used on those walls. For example, the stability walls are marked in red and are present mostly at the extreme left, right, top and bottom walls of the floor plan as shown in the diagram. In these walls on the ground floor, there are metal plates located at 300mm centres, with 2 screws, 30 nails and 1 washer per plate. This type of connector is shown in Fig. 6 b). The typical connector plates for the upper floors, specified at various mm centres are shown in Fig. 6 c).

<Inser Fig. 6 here>

The BIM model of the building that contains the design-related information was prepared by the architects and was used to overlay the engineers' CLT model with the architectural model. The model underwent some modifications to allow for the information to be exported to the designated database.

Tasks durations are modelled as triangular distribution to account for the stochastic nature of the construction activity. 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 need to stop, concentrated between November and March (5 months), with much fewer high-wind days in the spring and summer months.

Analysis results

The total installation duration, as per the simulation model output, is 52,711 min with a 95% confidence interval of [52471,52951]. Table 1 demonstrates the time spent on screwing and nailing of panels as a percentage of the total installation duration, where R1 and R2 are the risks of using nail guns and impact screwdrivers, respectively and they are assessed using Equations 1 and 2. Note that, panels and their connections in floors 1,2, and 3 have an identical structural design, so do the panels and connections in floors 4,5, and 6. For that reason, we grouped the floors in Table 1 according to their structural design.

< Insert Table 1 here>

Visualizing the results

The following two sections detail the calculations of the visualization endeavours.

Element-based visualization

The case study evaluates hazards associated with the usage of nail guns and screwdriver. Following the steps explained earlier, the element-based hazard visualization begins with calculating the elements (in this case study, the elements are the CLT panels) hazardous contribution as per Equation 3. Table 2 shows the collective contribution of each floor elements to each hazard. Note that in Table 2, *i* denotes the floor number.

<Insert Table 2 here>

The next step is to assign a colour for each hazard, where we select red (has a hue of 0) and yellow (has a hue of 60) to represent *R1* and *R2*, respectively. Based on the hazards representing colours and Equation 5, Table 3 shows the $\overrightarrow{G_{ij}}(h_j, G_{ij})$ components and the intermediate colour vector for the elements' groups.

<Insert Table 3 here>

Based on Table 3 and Equation 6, Table 4 shows the components of the new appearance of the element group based on their contribution to the hazards. It also shows the equivalent values in the Red-Blue-Green (RBG) colouring system.

<Insert Table 4 here>

Fig. 7 shows the calculated appearance of the exterior panels based on Table 4.

<Insert Fig. 7 here>

Interpreting the colourized results depends on understanding the location of the colours. The colour of the panels on the ground floor (floor 0) is closer to red compared to yellow, which indicates that working on these panels involves a higher risk from nail guns compared to the risk from the impact screwdrivers. The panels on floors 4,5, and 6 have a yellowish colour that indicates a larger hazard from the impact screwdrivers. As such, if the decision-makers willing to reduce the hazard associated with nail gun usage, then they need to reconsider the design of the connections on the ground floor.

Task-based visualization

As the purpose of this case study is to demonstrate the functionality of the proposed framework, task-based visualization will be limited to two tasks only; panel screwing and panel nailing. Table 5 shows the duration of the tasks on each floor, the task risk contribution, and the distance between the representing parallel lines.

<Insert Table 5 here>

Note that, for the application of Equation 7, *m* equals 1, as each of the considered tasks involves only one type of hazard. The information shown in Table 5 is visualized using the LBHDD concept in Fig. 8, where both tasks are executed concurrently.

<Insert Fig. 8 here>

Validation

Face validation was used with the same structural engineers interview participants as in the PI-CD. The constructability results were reviewed by the construction manager during the interview, and overall they were considered to be an accurate and relevant representation of the CLT installation process (see Appendix C). Some changes were suggested by the construction manager in the definition of the CLT installation process to highlight how the buildability observed at the CLT case study related to typical CLT projects. For example, in a comparative CLT project, with the assumption of ideal weather and site conditions, the CLT construction manager would typically specify a target of between 15 and 20 cranage components per 8-hour workday. The number of components lifted by day is influenced by two key factors, the distance between the logistics area and the site and the size and number of the components. The installation at the case study used in this research paper was on the conservative side of this benchmark, speculated to be a result of the high wind loads in the area which prevented the use of the crane for more days than is typical and perhaps also because of the high number of connectors which were also speculated to result from the high wind loads in the area. For this reason, the structural engineers and construction manager approved the way in which the simulation model dealt with time-efficiency risks due to high wind speeds. The construction manager also approved of how the BIM model could be integrated with the simulation engine to count the connectors and their associated time spent using power tools. They did comment that other CLT projects could use different types of connectors. Thus more site observations could be useful to help generalize the calculations for time spent using power tools. They were also curious how with further work, a HAVS or other hazard variable could be attached to BIM objects or components, similar to costing or carbon footprint data. Their opinion was that with further work, this could bypass the need for a simulation engine by integrating data directly into a BIM model.

Conclusion

Using CLT as a construction material is gaining increasing recognition from construction practitioners and researchers due to its low environmental impact and improved levels of constructability. With the increasing demand for CLT in construction projects, it is vital to assess the H&S aspects associated with CLT installation. This paper utilizes BIM with discrete event simulation to develop a decision support model that assists designers and project management teams to evaluate the potential H&S hazards during CLT installation that are associated with a particular design. The simulation layer mimics the onsite installation works starting with the delivery of the CLT panels onsite, then the lifting operations that are integrated with a weather-conditions sub-module to analyze possible H&S hazards due to gusts of wind. The nailing and screwing of the CLT panels are then simulated independently. The developed framework helps designers to test the compliance of their design with health and safety regulations and modify according to the findings. The potential increase in the H&S measures improves the appeal of CLT for a broader range of contractors and owners, and consequently, enhances the sustainable practice in the construction industry.

In the investigated case study, the connector designs on levels 4, 5, and 6 had a possible 67.74% probability of workers experiencing HAVS symptoms from using a drill, and the ground floor connectors were associated with a 45% probability of workers experiencing HAVS symptoms due to utilizing a nail-gun. Thus, the contribution of this research is a novel appreciation of the impact on installers' Health & Safety based on the specified type of CLT connectors. The research specific advancement in knowledge is the introduction of a novel measurement method that sheds new light on the social sustainability of innovative mass timber construction systems, using an innovative BIM-based approach to measure the H&S impact on labor productivity. When applied in engineering practices or scientific consultancies, this novel approach will help engineers specify the connectors that minimize the possibility of installers experiencing HAVS symptoms, while ensuring that those connectors will also be installed time-efficiently. This is important in light of the recent industry trends of higher responsibility placed upon designers for the health, safety and well-being of workers constructing their designs, as exemplified by the Construction Design & Management Regulations (CDM 2015) in the United Kingdom.

The usefulness test, described in this paper, shows the potentials of the proposed HA&V framework. There is, however, plenty of further research to be completed, and this should be approached considering the following points. The developed framework assesses risk concerning exposure time. While this approach works on the HAVS risks, it does not necessarily suit the analysis of other health-related risks. Additionally, while incorporating simulation into the design process can reduce the time and effort required to analyze risks, it entails adding new expertise, i.e., simulation experts, to the design team that is not otherwise needed. Finally, this research was concerned with reporting the development and functionality of the presented HA&S. Testing the efficiency of the developed framework was not within the present research scope, and that is why the reader doesn't see any efficiency assessment. These points are expected to be rectified in future endeavours.

Data availability statement

The BIM model and the weather database used during the study were provided by a third party.

All data generated during the study appear in the submitted article.

Acknowledgement

This research was enabled by funding from the Built Environment Exchange (beX) programme led by Prof Robert Hairstans. We are grateful to Fiona F. Bradley for her feedback during the onsite data collection. In this study, secondary data collected from a research project funded by the Construction Scotland Innovation Centre was used for connections constructability analysis. We especially thank the anonymised interview participants from the onsite CLT installation team, the architecture and engineering practices, and the main contractor company for providing guidance, data, validation and access to the case study site. This paper is an extended version of (Duncheva et al. 2018).

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Appendices

Appendix A

1. What are the responsibilities of the head-carpenter on a CLT project?
2. How do you distribute the roles on site?
3. How does this distribution change at the different construction phases?
    a. At the start
    b. Up to mid-floors
    c. Upper floors
    d. After the CLT has been installed on site?
4. What are the main activities to assemble a CLT building storey?
5. Which activities require fewer man-hours (are more time-efficient)? Why is this so?
6. Which of these require more man-hours (are more time-consuming)? Why is this so?
7. Are there any risks that people need to be aware of whilst working on a CLT project?
8. Have there been any challenges so far?
9. Do you think this project's installation and assembly could have been improved?
10. How has this project gone overall compared to other CLT constructions you have worked on?

Appendix B

1. Have you worked on many CLT projects?
2. To what level do you use BIM for CLT projects?
3. What design software do you typically use in a BIM workflow?
4. What functionality do you use when creating details?
5. In these details, how do you specify connectors?
6. How do you consider health and safety impacts in specifying connectors?
7. What could help you improve health and safety when specifying connectors?

Appendix C

Could you please review the attached spreadsheets and after the presentation on the day of the meeting, provide feedback on the methodology, the accuracy of results and functionality of the following?

1. Installation datasheet and videos
2. Connection count drawings and data
3. Simulation model – to be demonstrated and explained by Duncheva during the meeting using a Powepoint presentation showing the process and simuation results.

List of tables

Table 1 Simulation results and hazards calculations

Task	Average utilization	Standard Deviation for utilization	Maximum utilization	R1	R2
Screw Floor 0	2.10%	0.10%	2.30%	0	3.76
Screw Floors 1,2,3	9.21%	1.20%	95.10%	0	16.51
Screw Floors 4,5,6	37.80%	1.40%	41.20%	0	67.74
Nailing Floor 0	31.60%	1.20%	34.40%	45.81	0
Nailing Floors 1,2,3	23.10%	1.00%	26.40%	33.48	0
Nailing Floors 4,5,6	24.00%	1.10%	26.30%	34.79	0

Table 2 Panels' contribution to the hazards

Panels Location	R1	H_{R1-i}	R2	H_{R2-i}
0	45.81	0.401563	3.76	0.043
1	11.16	0.097827	5.501974	0.063
2	11.16	0.097827	5.501974	0.063
3	11.16	0.097827	5.501974	0.063
4	11.59642	0.101652	22.58139	0.257
5	11.59642	0.101652	22.58139	0.257
6	11.59642	0.101652	22.58139	0.257

Table 3 Elements' colours intermediate calculation

Panels Location	$\overrightarrow{C_{R1-i}}(h_{R1}, H_{R1-i})$		$\overrightarrow{C_{R2-i}}(h_{R2}, H_{R2-i})$		$\overrightarrow{C^{inter}_{i}}(h_i^{inter}, l_i^{inter})$	
	h_{R1}	H_{R1-i}	h_{R2}	H_{R2-i}	h_i^{inter}	l_i^{inter}
0	0	0.401	60	0.043	5.037	0.42
1	0	0.097	60	0.063	22.753	0.14
2	0	0.097	60	0.063	22.753	0.14
3	0	0.097	60	0.063	22.753	0.14
4	0	0.101	60	0.257	44.019	0.32
5	0	0.101	60	0.257	44.019	0.32
6	0	0.101	60	0.257	44.019	0.32

Table 4 The calculated appearance of elements

Panels Location	$\overrightarrow{C_i}(h_i, l_i)$		Equivalent RBG		
	h_i	l_i	R	B	G
0	5.037	0.79	228	181	176
1	22.753	0.93	246	235	228
2	22.753	0.93	246	235	228
3	22.753	0.93	246	235	228
4	44.019	0.84	234	224	194
5	44.019	0.84	234	224	194
6	44.019	0.84	234	224	194

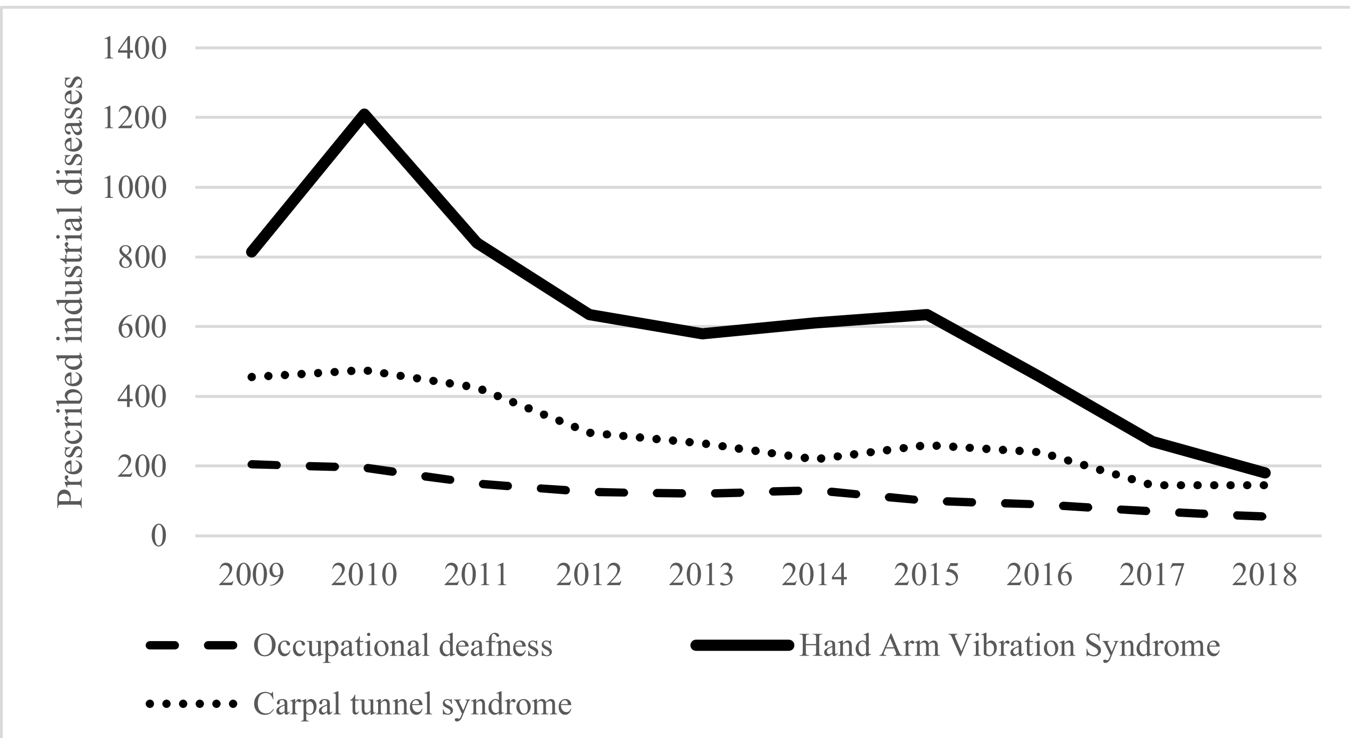
Table 5 Tasks contribution to hazards, duration, and thicknesses of lines in the LBDHH

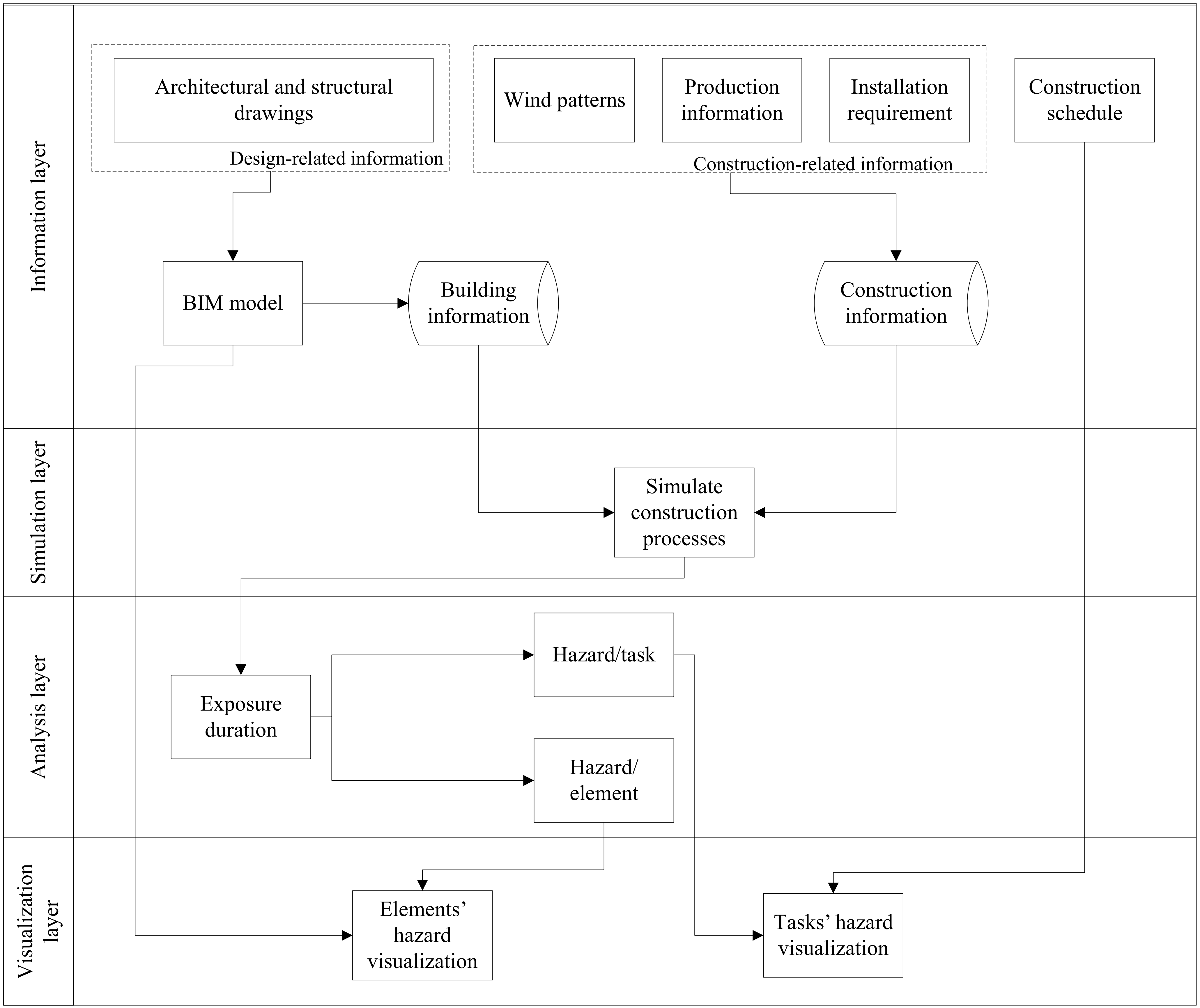
Panels Location Levels	Nailing Panels			Screwing Panels		
	H_{R1-i}	D_l	Duration (Day)	H_{R2-i}	D_l	Duration (Day)
0	0.401	0.5	11	0.043	0.1	3
1	0.097	0.1	8	0.063	0.1	4
2	0.097	0.1	8	0.063	0.1	4
3	0.097	0.1	8	0.063	0.1	4
4	0.101	0.2	9	0.257	0.3	13
5	0.101	0.2	9	0.257	0.3	13
6	0.101	0.2	9	0.257	0.3	13

List of figures

Figure

Click here to access/download;Figure;Fig. 1.pdf




Information layer
Simulation layer
Analysis layer
Visualization layer
Architectural and structural drawings
Design-related information
Wind patterns
Production information
Installation requirement
Construction-related information
Construction schedule
BIM model
Building information
Construction information
Simulate construction processes
Hazard/task
Exposure duration
Hazard/ element
Elements' hazard visualization
Tasks' hazard visualization

Figure

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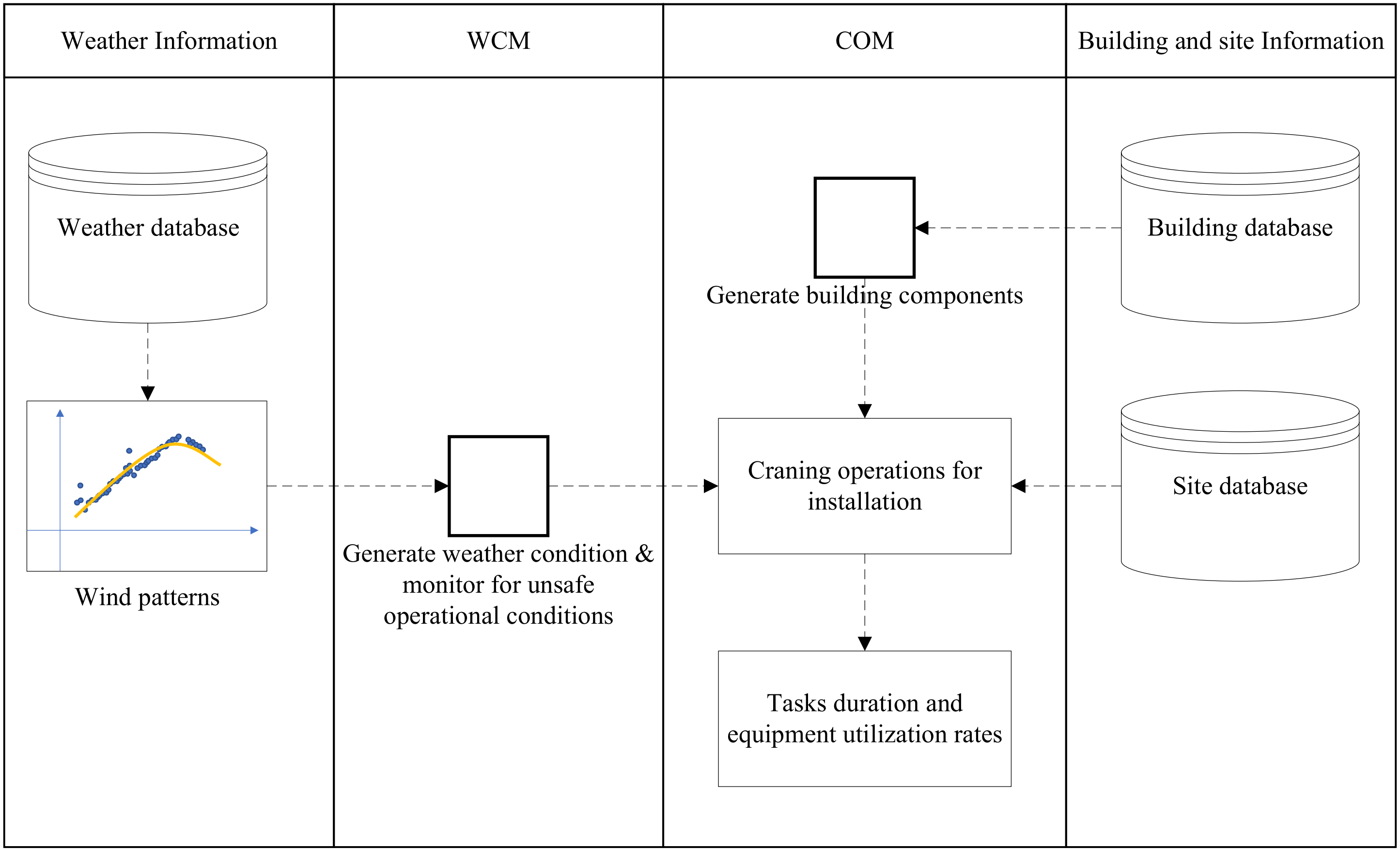

Figure

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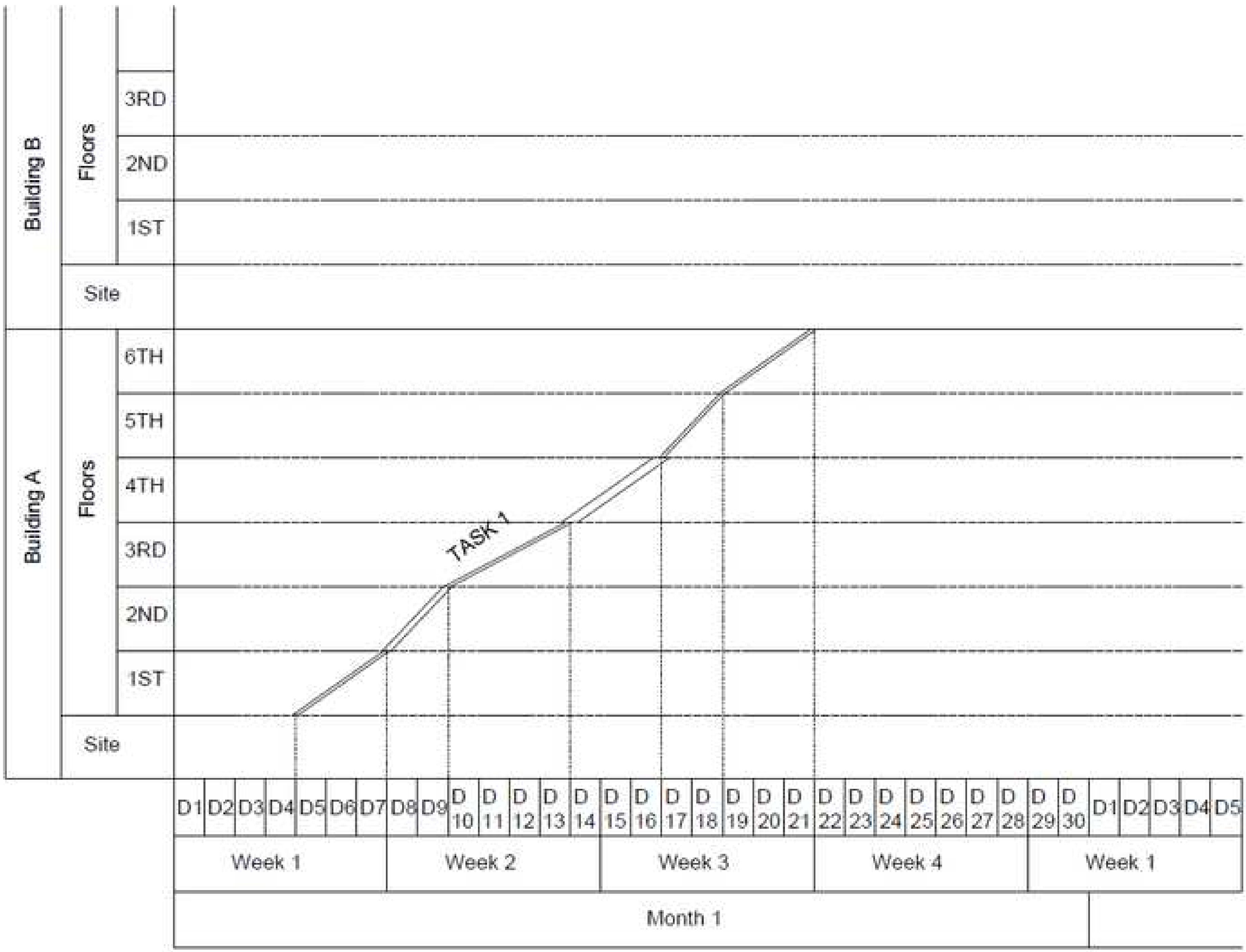

Figure

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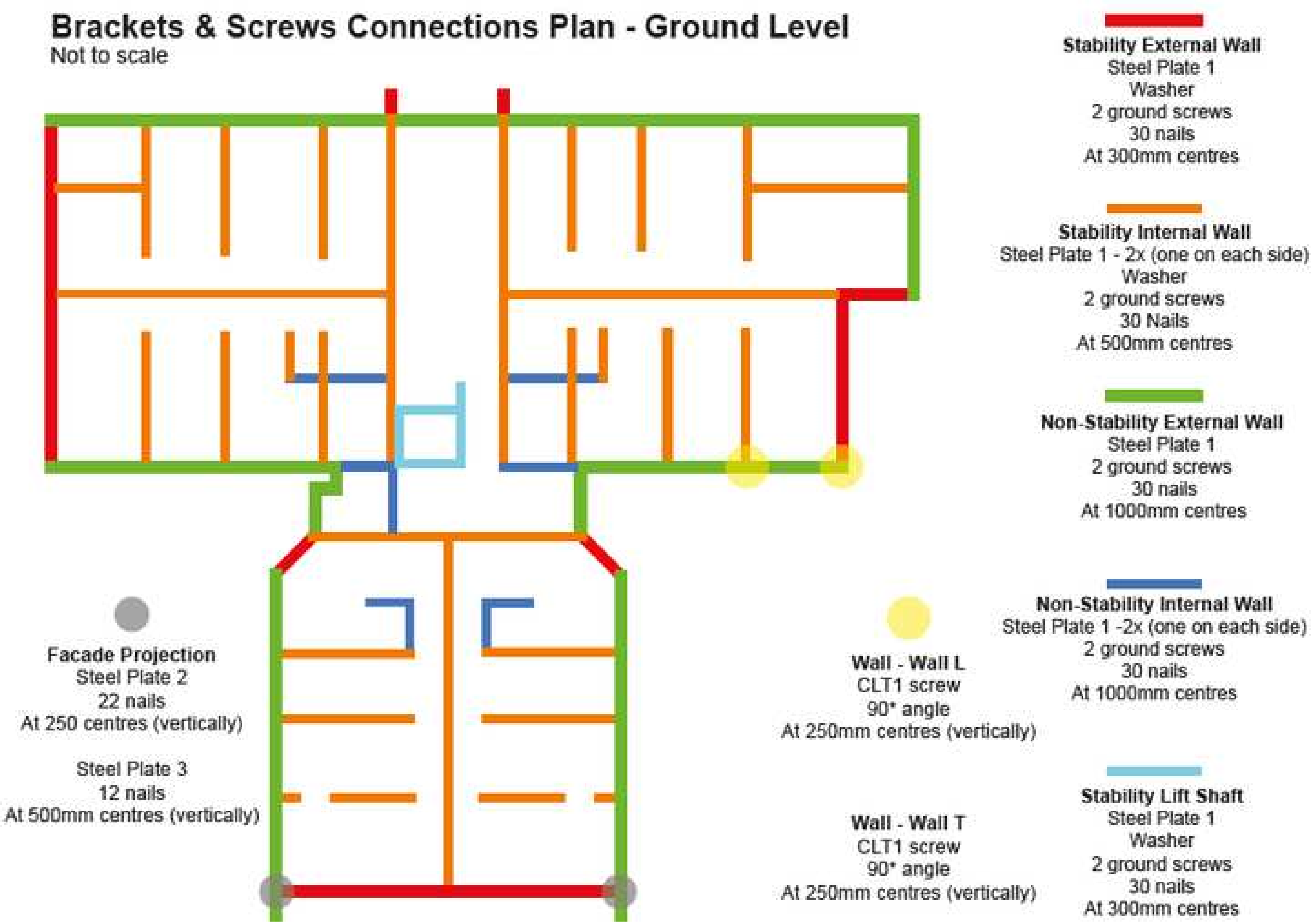
Brackets & Screws Connections Plan - Ground Level
Not to scale
Stability External Wall
Steel Plate 1
Washer
2 ground screws
30 nails
At 300mm centres
Stability Internal Wall
Steel Plate 1 - 2x (one on each side)
Washer
2 ground screws
30 Nails
At 500mm centres
Non-Stability External Wall
Steel Plate 1
2 ground screws
30 nails
At 1000mm centres
Non-Stability Internal Wall
Steel Plate 1 -2x (one on each side)
2 ground screws
30 nails
At 1000mm centres
Stability Lift Shaft
Steel Plate 1
Washer
2 ground screws
30 nails
At 300mm centres
Wall - Wall L
CLT1 screw
90* angle
At 250mm centres (vertically)
Wall - Wall T
CLT1 screw
90* angle
At 250mm centres (vertically)
Facade Projection
Steel Plate 2
22 nails
At 250 centres (vertically)
Steel Plate 3
12 nails
At 500mm centres (vertically)

Figure

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Figure

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Figure

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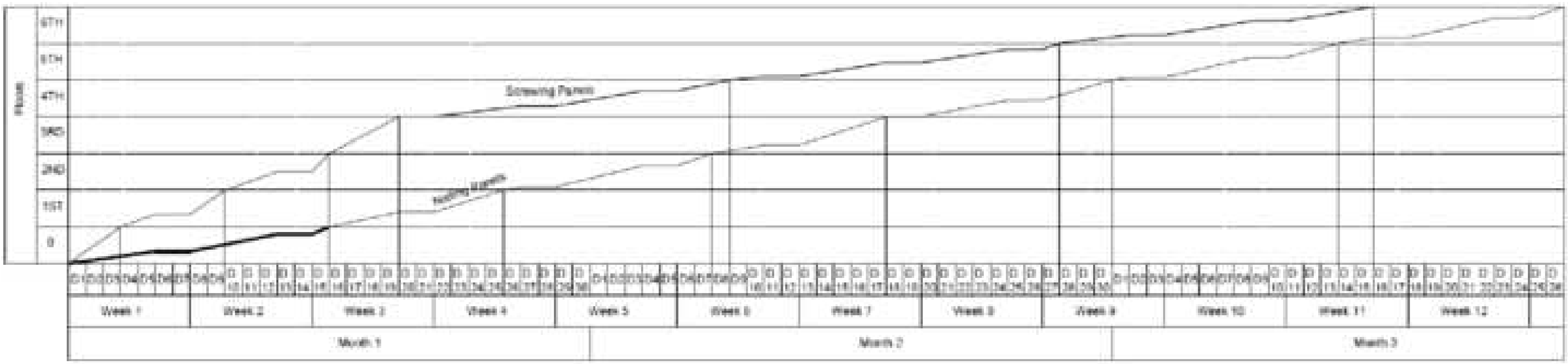

List of figures

RESPONSE

Manuscript: COENG-9963R1

Manuscript title: Developing a BIM and simulation-based hazard assessment and visualization framework for CLT construction design.

As requested, we removed the shading from Table 4 and replaced the shades with their correspondet colour coding values in the RBG system. Table 4 look as follows:

Panels Location	$\overrightarrow{C_i}(h_i, l_i)$		Equivalent RBG		
	h_i	l_i	R	B	G
0	5.037	0.79	228	181	176
1	22.753	0.93	246	235	228
2	22.753	0.93	246	235	228
3	22.753	0.93	246	235	228
4	44.019	0.84	234	224	194
5	44.019	0.84	234	224	194
6	44.019	0.84	234	224	194

Lines in the submitted manuscript were changed to reflect that which they read now:

“Based on Table 3 and Equation 6, Table 4 shows the components of the new appearance of the element group based on their contribution to the hazards. It also shows the equivalent values in the Red-Blue-Green (RBG) colouring system.”