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A THEORETICAL APPROACH TOWARDS RESSOURCE EFFICIENCY IN MULTI-STORY TIMBER BUILDINGS THROUGH BIM AND LEAN

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ABSTRACT: The timber industry has experienced in the last decades a relevant increase in terms of high performance buildings. Despite these advancements and the favorable properties of building with wood, the traditional position of "choosing by costs" still finds wooden building as more expensive than concrete or steel ones. In order to be competitive in the market against these two main building materials and meet the expectations of modern and large-volume wood based constructions, new improvements based on standardization and prefabricated systems have to be implemented. At the same time a full collaborative work between all the participants on a project is needed to redefine and optimize the construction and design processes through sharing specific and detailed information and extended know-how at a very early project stage. Through this approach, the high potential of combining off-site construction, Building Information Modeling (BIM) as a work methodology and lean management practices will be investigated, involving architects, engineers, BIM users in the timber industry, timber manufactures, contractors and all the stakeholders with the aim of reaching the most effective and productive design and construction process in multi-story timber buildings.

KEYWORDS: Building Information Modeling BIM, Lean Construction, Multi-story timber buildings, Offsite construction, Collaborative work, Interdisciplinary process, Integrated Design

1 INTRODUCTION

The challenges of the 21th century are well known. Together with the challenge of housing all the people moving increasingly to cities, concerns about climate change, greenhouse gas emissions, resource shortage and economical recovery are fundamental factors to be taken into account when designing new buildings.

It is forecast that circa 3 billion of people will be in need of new buildings in the next 20 year. Aiming to develop healthier and more sustainable cities, the use of new building materials should be implemented trying to avoid those which have put the construction sector as the responsible of about 1/3 of the global CO_2 emissions, including both operational and embodied emissions [1]. Thanks to recent building regulations, operational carbon emissions have been strongly reduced, becoming the embodied carbon emissions the dominating factor to look at when trying to reduce the contribution of the building industry to the global greenhouse gas GHG emissions.

Taking a deeper look into the embodied emissions, concrete and steel, which are the main common materials to build with, have very high energy and GHG emissions in their process, contributing to 8% of the global CO_2 emissions.

Due to its remarkable ecological properties, wood appears to be a material highly demanded in the 21th century, since it can help remarkably by reducing the GHG emissions related to the building industry, while storing CO_2. For these reasons and its additional properties including comfort, acoustic and fire isolation, temperature regulator, high static performance with less material, the use of wood in large scale buildings is experimenting a huge increase, giving a remarkable moment to the timber industry, which seems to advance a new promising era where improvements on productivity and efficiency are needed.

2 TOWARDS RESSOURCE EFFICIENCY

The building industry is the largest consumer of raw materials in the EU, and the construction and demolition activities account for about one third of the wastes generated annually (EEA 2010) [2], estimating that 21 per cent of this waste ends up in landfill without any form of recovery or reuse. Clearly, there is also an environmental need to redirect the resource-intensive and wasteful construction sector, towards a more

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industrialized resource-efficient construction involving several aspects such as material performance, buildings design, construction technology, operation and maintenance, flexibility in building use, stakeholder participation, energy and resource efficiency and long-term monitoring among others [3].

Resource-efficiency basically means using less natural resources and energy to achieve the same or improved output. When referred to construction, the focus is not only building more efficiently and using resources more effectively, but also implementing less resource-intensive materials, new technologies and new approaches to design [4].

The best opportunities to improve the resource efficiency occur during the design stage where the impact of decisions are maximal and their costs minimal. Besides a proactive approach and an integrated design, it is desired a great level of industrialized construction process, combined with an innovative and coordinated supply chain. Such a procedure can be strongly supported by methodologies, processes or tools as BIM, Lean and off-site construction, which combined can provide not only the desired savings, but also reductions to business risks [5].

On one hand, the use of BIM presents large opportunities to achieve a more resource efficient process. Through a "Digital Twin", an accurate test approach to the resource use and impacts of different alternative design solutions is enabled.
Besides, and based on Lean Management strategies, the early identification of waste can be implemented and consequently minimized or eradicated through a work sequences plan, deliveries and materials leftovers.
Both BIM and Lean combined with off-site construction are able to reduce significantly not only waste, but embodied carbon emissions, by well over the half in most cases.

The consideration of these measures may involve extra initial costs, as they imply a new way of thinking from early stages of a project with a higher investment of time and effort, but they will lead to a long-term recurrent cost reduction and potential increase on asset valuations.

2.1 PREFABRICATION

Off-site construction based on industrialized manufacturing methods have remarkably pushed forward wood buildings because of its high level of performance and unlocked a new level of high quality timber solutions, flexible and adaptable enough to suit different needs and requirements in residential and commercial buildings [6].

Since prefabricated elements are produced in a controlled factory where tasks are well defined, it involves lower production time, as workers perform the same tasks under favorable labor conditions all over again becoming more efficient and proficient and minimizing throughout errors, reworks and delays. Besides, a great level of accuracy is achieved thanks to the possibility to work with minimal tolerances and thanks to permanent monitoring and extensive quality controls. Throughout, the highest passive standards in buildings could be achieved, allowing consequently a significant reduction on operational carbon emissions within the whole lifecycle of the building.

Besides, prefabrication has been pointed as a driver for waste minimization, since through a right and efficient material handling and management within the specialized manufacturing environment, waste can be reused as secondary raw material, in paper and board industry or lastly in energy production [7].
Through this procedure, these residues obtained due to cuttings or over ordering in the production phase actually cannot be considered as waste.

A shorter project schedule is the most common benefit in productivity when working with prefabrication. It enables a significant level of time saving through the possibility of working off-site parallel and simultaneously to ongoing job site processes, protected from detrimental weather conditions.

Overall on-site construction time is also reduced as the installation process is simplified into one of a fast assembly of parts. Furthermore, prefabricated wooden based elements are easy to handle thanks to their reduced weight. That allows less and lower-skilled workers on-site and consequently less site management and less site facilities what should be reflected in reduced prelims [8].
Through the reduction of the activities on site, fewer accidents occur and consequently the safety improves, what can be also traduced to less insurance costs.
Besides, lower site errors occur because of lower labor requirements since the most complex components are assembled in a controlled manufacture site.

2.2 BIM

The use of BIM is expanding very fast through the whole AECOO (Architecture, Engineering, Construction and Owner Operator) community and becoming a worldwide reference to optimize the efficiency and productivity of a project.
The term BIM refers to a collaborative work methodology which supplies documentary evidence, graphical and non-graphical, of the whole lifecycle of a building, from the design stage through its operation and to the end of life.

Within this procedure a 3D model is elaborated in a Common Date Environment (CDE) with a consistent and structured amount of information to access and share efficiently across the supply chain. It provides a "digital twin" where a reliable monitoring of different processes and performances can be simulated even before the construction has started, and throughout the whole entire lifecycle of the object.

As an emerging methodology, the high potential of BIM on timber construction has not been completely explored and an integrated design has not yet been achieved where all the disciplines and the off-production requirements are coordinated and integrated.

2.2.1 Integrated Project Delivery (IPD)

An Integrated Project Delivery (IPD) brings all the participants of a project early together in a collaborative workflow with common incentives, responsibilities and objectives where the end product is the main goal, looking for maximizing the value to the customer.

This innovative approach implies a multi-party agreement construction contract called Integrated Form of Agreement (IFOA) where owner, design professional, and constructor are included as signatories.

Such a procedure opposes to the traditional one where every project participant has an isolated competence knowledge and is focused to maximize its own profit share.
Instead, an interdisciplinary and integrated collaboration among designers, constructors and owners is enabled, and which success depends strongly on the Level of coordination and of BIM Maturity.

2.2.2 BIM Maturity Levels

The purpose of defining these “Levels” is to describe the different stages of approaches to BIM with their corresponding tools and techniques and to serve as a structured learning progression over a period of time or an industry roadmap.

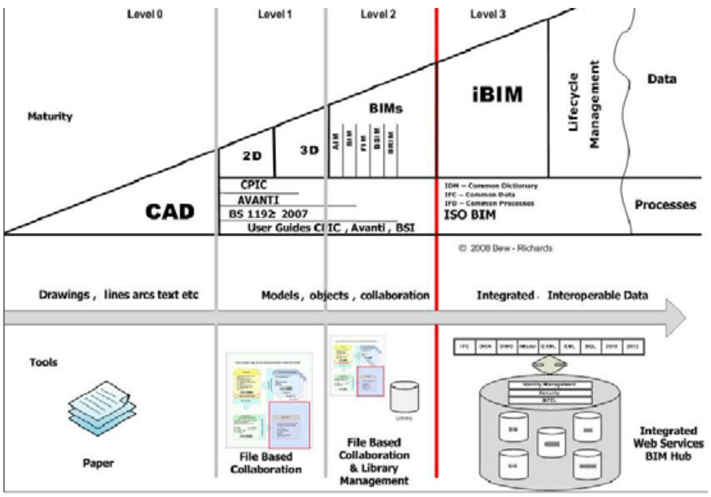


Figure 1: *The UK BIM Maturity Model (GCCG, 2011)[9]*

The sophistication of the use of BIM or its Maturity Levels are strongly related to the 7Dimensions of BIM.
While in Level 1, the data management occur within a closed BIM collaboration with no integration, in Level 2 commercial data is managed and integrated and in Level 3 a fully integrated collaborative process would be achieved through a web service.
These 2 more advanced levels allow the utilization of 4D-construction sequence, 5D –cost information and 6D –facilty management [10].

2.2.3 BIM Dimensions

The concepts of 4D, 5D, 6D and the recently added 7D-sustainability, are used to indicate the benefits of increasingly complex BIM models.
A 3D model provides an accurate project visualization and the possibility to detect clashes or incoherence early on the design stage, avoiding later on solving-problem-situations. Moving towards 4D construction planning and management is added enabling a schedule visualization where to identify key factors with favourable impact on the overall delivery of the project.
On this 4-Dimension is where the application of lean principles should be implemented, including site logistic, space utilisation, cranes, traffic and routes among others, aiming to reach a more efficient workflow.
Obviously such an implementation implies remarkable consequences on cost estimations 5D.
Advanced BIM models will be able to assume the changes occurred within the construction process and indicate the corresponding impact.
At the same time several hypothesis will be run and simulated as response to those changes.

2.3 LEAN CONSTRUCTION

Lean Construction is a new appellation of the concepts and principles of the Toyota Production System (TPS) but applied and adapted to construction. The focus of the system is to identify the wastes and reduce or avoid them, increasing the value to the customer and following continuous improvement [5].
Since Lean Management is a working philosophy based on the principles of null-errors and null-waste, it can be applied in every discipline and when talking about building industry in each project phase (design, production and erection).

2.3.1 Lean on Design Stage

The lean methodology is focused on the identification and minimization of wastes. When talking about the design stage of a project, those waste are referred to re-work, changes, lack of collaboration, lack of extended knowledge and problem solving among others.
Since the synergies between its application on the design phase and the BIM methodology above exposed are evident, in this chapter, will be just explored its application on the production and construction phases. However, a lean approach on the design phase implies also to model just what is needed on every stage of the project within its Level of Development (LOD), and not more.

2.3.2 Lean on Production Site

A Lean Management on the production site can bring favourable benefits to the end product as it has been developed in the automobile industry or manufacturing, which have both achieved a remarkable level of productivity along their production processes.
Following the same principles of null-error and null-waste, the conventional *Push Planning* based on the mass-production methodology turns to a *Pull Planning,* where is produced just what needed, and just when the

requirements to produce them are previously accomplished.
Throughout, the productivity arises while waste decreases, being the most common ones, overproduction, waiting-time, stocks and inventory.

Besides, based on the continuous improvement, also known as *Kaizen*, new methodologies or strategies from all stages should be explored and implemented aiming to reach a more industrialised process through the identification and minimization of the “7+1 Wastes in Construction” or so-called *Mudas*.

2.3.3 Lean on Construction Site

Already on the design phase, the development of a strategy to on-site-performance, implies a huge impact on the whole process and brings many benefits to the overall costs and building schedule. Although it may imply much more time on planning, the efficiency of the work on site is sensible to improve exponentially.

Many tools or procedures have been specifically defined under the working philosophy of Lean Construction. The most relevant is the Last Planner® System (LPS), which consists on regular meetings in which the focus is to identify the work that should be done to complete a successful project, what can be done and finally what will be done. The aim is to generate a reliable planning structure to move throughout and determinate alternative paths when failures or restrictions may occur.
The most commons tools in Lean Construction together with LPS, are the Takt Time Planning (TTP) and the Just In Time (JIT) Delivery. A TTP allows a structured and balanced schedule planning and through a JIT logistic, the elements are delivered on site a just-in-time.
Those strategies combined with a high level of prefabrication can reduce the time spent on site drastically up to 50%, in most of the cases, besides noise, dust and general disturbances.

Consequently the costs decrease since the on-site construction is turned to an assembly areal where the pieces are put together and as they come “Just in time”, the space required for stock elements is minimal.
Such a procedure is consequently the most suitable procedure in compacted cities with shortage of space.

3 PROBLEMATIC

Planning with timber requires a more detailed approach and knowledge concerning, among others, material properties and structural behaviour, since all the requirements regarding to fire, noise, humidity and heat isolation are integrated in the structural layer.
At the same time, all disciplines, architectural, structural, mechanical, electrical and plumbing (MEP), have to be also coordinated and integrated in the design phase since the openings for MEP should be created in the factory and modifications on site should be avoided.

It can be consequently stated that when planning a building with timber, the specific know-how transfer between timber specialists or contractors, and structural and architectural designers should occur earlier than with standard constructions, especially if those do not have previous and extended experience with timber constructions.

Ideally, on-site assembly strategies and off-site production systems are taken into account on the design phase, what later on enables an efficient workflow.

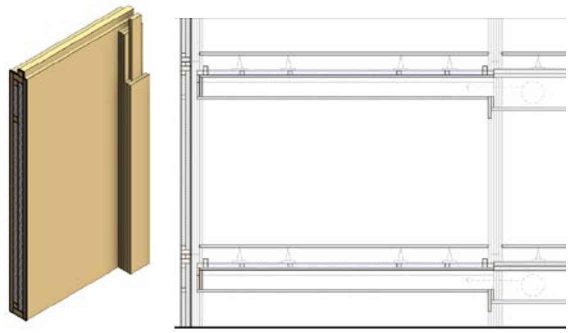


Figure 2: *Model of a timber-frame-wall with integrated column and first approach MEP*

Real-life experience of prefabricated timber constructions reveals that the specific knowledge on production planning and methods for off-site timber construction comes too late, usually after the building permit, what provokes re-works, changes, problem-solving, pressures and extra working hours which are commonly unpaid [11].
The further such a problems and changes come, the higher is the impact and the loss in terms of costs, reworks, time and resources.

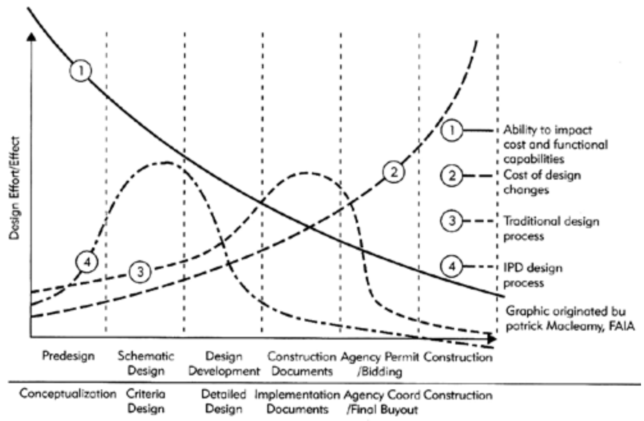


Figure 3: *MacLeamy Curve. Abilities progression to control the costs and the costs of change in the traditional and IPD approaches.* [12]

Since modern digital tools have been implemented in the off-site production of wooden elements through computerized numerical control (CNC) machines, timber manufacturers and planners are used to work within 3D models to solve joints and assembly between elements.
For this reason timber industry finds itself in a favorable position with a huge potential since the level of prefabrication is remarkable high, the use of CNC machines is widely extended throughout the industry and

the ability of manufacturers and planners to work with 3D models is also noticeable.

However, the desired integrated design procedure has not yet been completely achieved since design and production are still unconnected and isolated.
The weaknesses are then on processes, coordination and on data transfer throughout a BIM model, from computer-aided design (CAD) to computer-aided manufacturing (CAM) and exported to CNC.
In most of the cases, timber contractors and manufacturers build a completely new 3D digital model even though receiving a BIM model from designers. The main reason of this re-work is the need of re-designing details and structural content, or adapting to specifications of production.
This lack of coordination and standardization or a CDE constrict the remarkable potential offered by BIM on the whole workflow and leads to inefficiency through rework, overlapping tasks and overrun on time and costs, what also provokes lower levels of reliability.

4 METHODOLOGY AND CASE STUDY

Together with an integrated design process as above exposed, a proactive approach is desired in order to industrialize the whole design and construction processes and to optimize the resources used on a project in terms of material assessment, effort, time and costs.

With the purpose to optimize structural and ecological performance of wood based systems in multi-story buildings, several research projects were explored in the Department of Structural Design and Timber Engineering at the Vienna University of Technology.

Based on these previous and on-going research projects, a standard prototype building was developed in order to prove the applicability of those advancements and the suitability of the system proposed within this paper itself.
Throughout a 63 m. long and 14 m. width seven-story commercial building was proposed, where the basement and ground-floor are assumed on concrete.

According to its morphology, different approaches and strategies were investigated, detecting potential advancements and proposing few methods to achieve the highest level of efficiency on the design, where production and construction should be integrated.

One of the scopes of such a procedure was to upgrade the level of prefabrication in order to transfer the major amount of work to a controlled factory where the elements are industrially produced in a controlled environment with permanent monitoring and regular quality controls, being after their production delivered on site just in time with the only need to be assembled.

The first approach was to identify all the elements sensible to be produce off-site, and then few options were proposed based on on-going projects at the Department of Structural Design and Timber Engineering at the Vienna University of Technology.

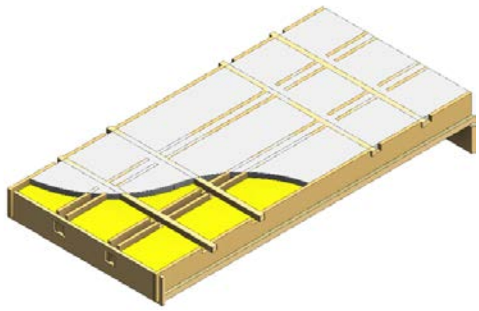


Figure 4: *Proposal for semi-prefabricated timber-concrete-ribbed decks*

According to the specific requirements of each element, including span and width, and considering also material combination and transport logistic, several low-energy innovative and modular systems were proposed for the slabs.

Three prototypes were explored for the slabs combining different materials such as laminated veneer lumber (LVL) with wood lightweight concrete (WLC) and with different grades of prefabrication (Figure 4, 5), aiming to optimize the structural and ecological performance of each material, while offering at the same time suitable acoustic and fire protection.

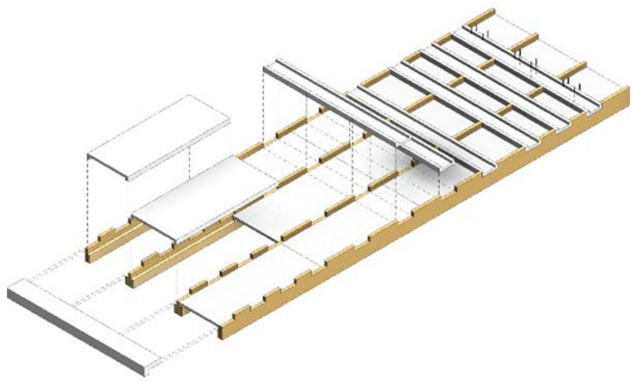


Figure 5: *Proposal for prefabricated timber-concrete-ribbed decks*

The use of industrially prefabricated WLC boards allows wide span widths with low material investment, what together with its lightness reduce significantly the weight of the construction, and consequently the resource intensity in the whole building and especially on the size of the foundation. Besides, they allow a more efficient transport logistic, being the load of the emissions related to transport lower.
When combined with a metallic shear connection between concrete and timber, its load-bearing capacity is increased (Figure 6).

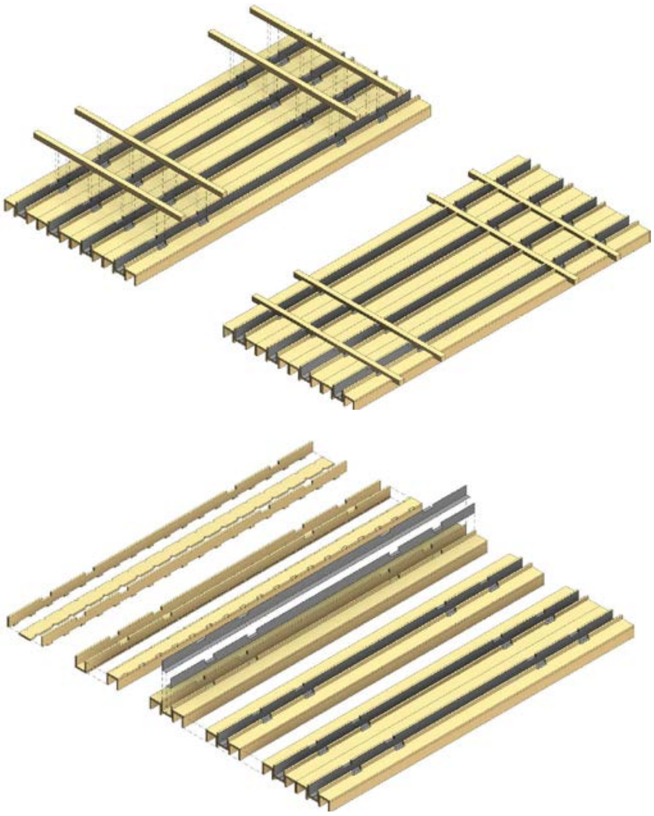


Figure 6: *Proposal for prefabricated timber-steel-concrete-ribbed decks*

Following a modular raster of 2,70m. throughout the whole morphology of the building, the path of action implied not only slabs but structural and non-structural elements like columns, beams, bracing and façade and wall elements.

Façade-elements are produced off-site 1-floor high with a maximal length of 8,80m. and come together with the load-columns which are every 2,70m..

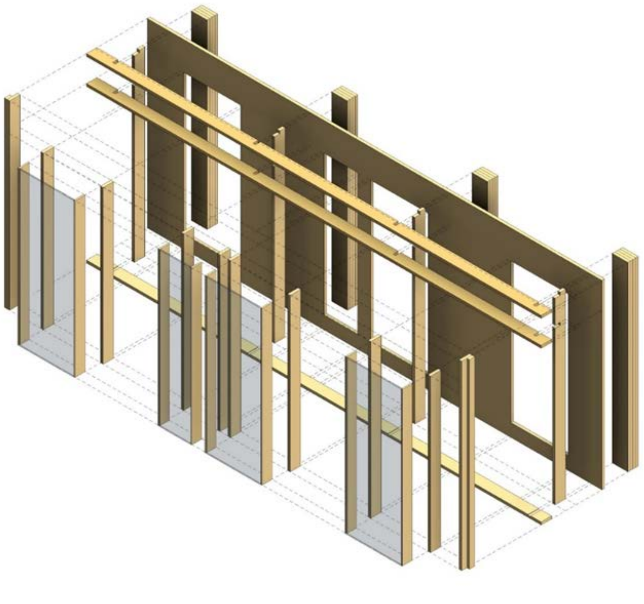


Figure 7: *Timber-Glass façade scheme.*

Through modularization and standardization, the whole building was divided into pieces or elements which were defined and designed from construction through production.

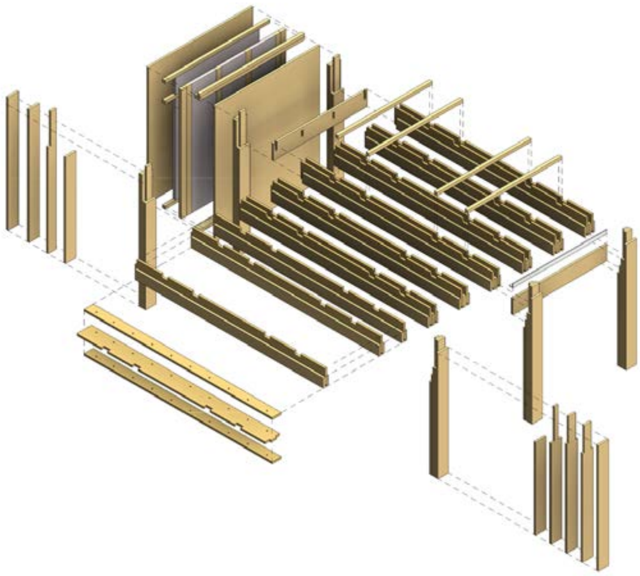
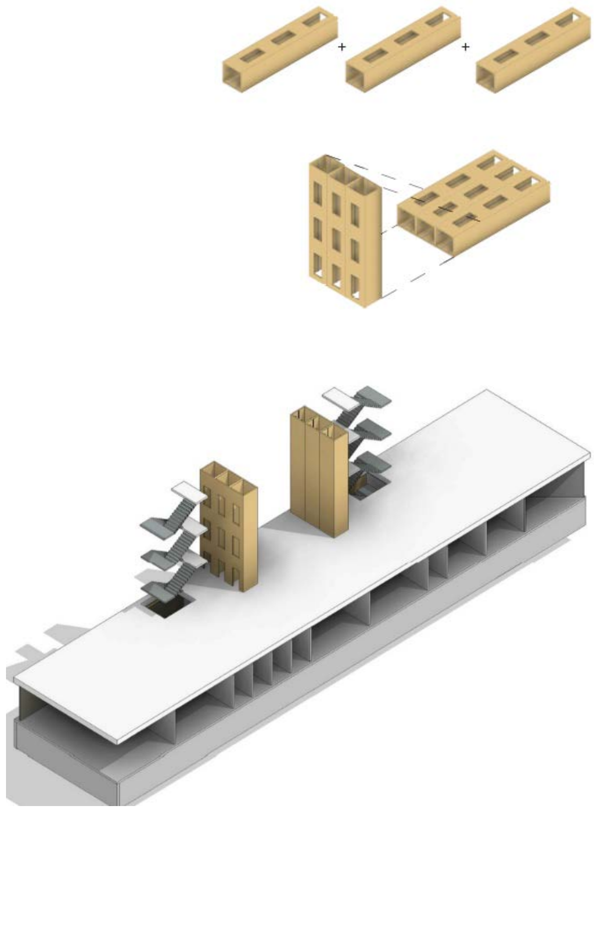


Figure 4: *Complete system scheme including columns, walls and ribbed decks.*

Once all the elements sensible to be prefabricated were identified and implemented, the off-site production and the on-site construction processes were also explored.
The main facts to put down study involve mainly building schedules and deliveries and transport logistic. Through specific literature review and different scenarios simulations, a construction process was proposed seeking for improvements on productivity and efficiency.



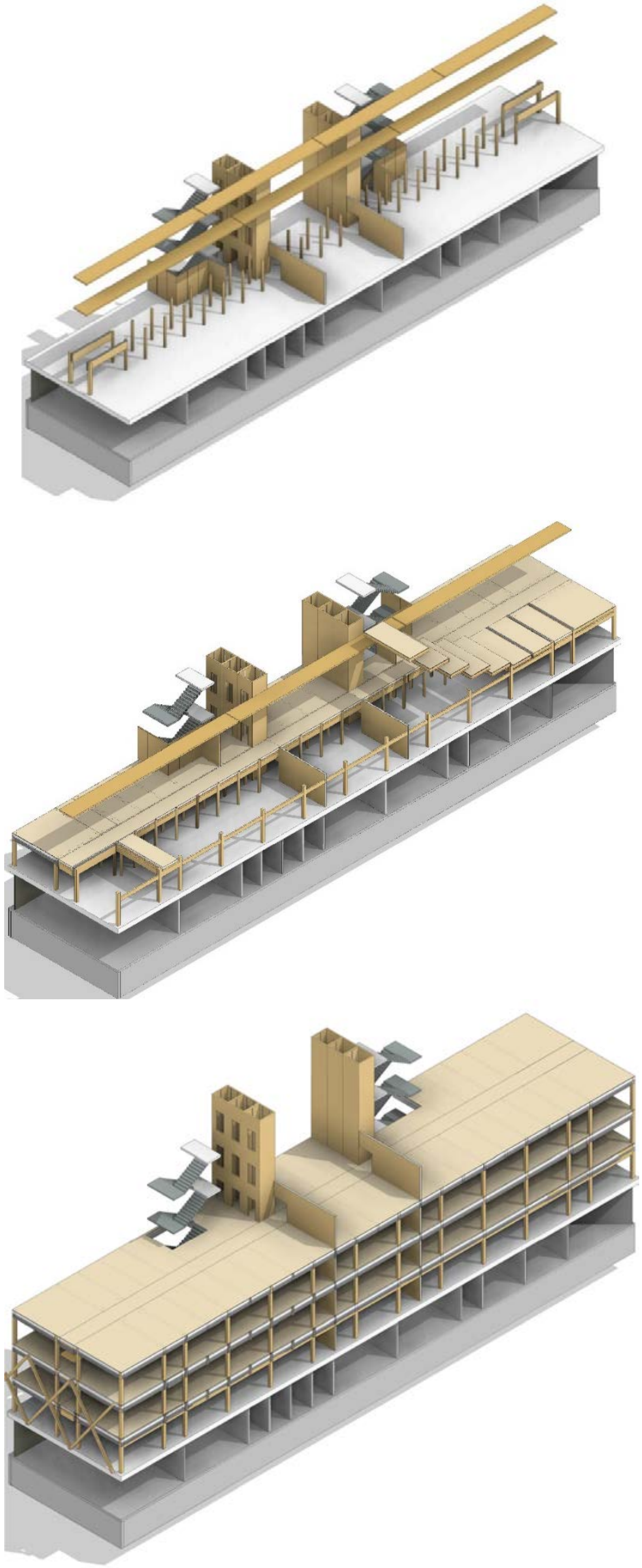


Figure 5: *Simulation of a proposed industrialized construction process*

Through a BIM model the erection of the timber building was simulated, where all the non-structural elements, and all the structural elements, such as like exterior walls, façade loading walls, lift core, beams, columns, slabs and bracing elements, were planned to be produced on a industrialized factory and are supposed to be delivered on-site Just In Time.

In order to better quantify the benefits of upgrading the level of prefabrication on a project, the energy used for factories will be taken into account when considering embodied carbon.

Additionally, factory location may be a factor since long transportation distances of prefabricated elements will add significant carbon emissions and additional costs. Besides transport distances, the mode of transport is an important factor to consider, since transport by road is circa 4 times more carbon intensive than transport by rail, and around 40 times more than by sea [13].

All in all, an effective off-site construction has to ensure that these additional costs and emissions caused by factories and transport, have lower load than the benefits of reducing waste.

5 CONCLUSIONS AND EXPECTED RESULTS

As it has been above exposed, each stage of a project is sensible to be improved. Besides, an appropriate and effective workflow from BIM to CNC in modern timber construction is still needed.

The objective of such an approach is to implement wood as a standard material to build within high levels of productivity despite its higher initial costs.

Regarding to the design phase and despite of recent developments and advancements on technologies, it may still suffer a lack of efficiency in management, since the specific know-how regarding to off-site construction and on-site assembly are not included.

The required extended know-how from timber specialists comes in real-life too late and implies remarkable amount of rework and extra investment of time and effort.

Specific libraries and Open BIM Standards for timber constructions should be implemented in the next years in order to facilitate design approaches and reach thoughout a more efficent workflow capable to go from design to production.

When talking about off-production processes, the timber industry may be the most advanced industry related to construction, since the productivity is an important issue which has been improved in the last decades. However and taking advance of what has been done in another industries such as mannufacaturing and automobile industry, new advacements will come.

On the on-site construction scenario, few improvements could be achieved through different lean construction procedures as above exposed (Section 2).

Further savings can be achieved on-site since the crane size can be reduced due to the component weights. Furthermore, because of its lightness, more components can be brought to site on each truck, meaning four times less deliveries than compared to concrete constructions. Throughout costs and emissions are reduced while the traffic load to the neighbors also decreases.

The proposals and systems proposed through this approach are still a work in progress and all the requirements needed for the construction of the project, such as acoustic, vibration, heat and fire isolation, have not been determined. More detailed definition is needed before being able to examine the suitability of the proposals and its consequent impacts.
Since the project has not been yet completed on the design phase, no strategies regarding to logistic on site have been investigated through this paper.

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