A holistic approach for industrializing timber construction

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Abstract. Many strategies have been investigated seeking for efficiency in construction sector, since it has been pointed out as the largest consumer of raw materials worldwide and responsible of about 1/3 of the global CO₂ emissions. While operational carbon has been strongly reduced due to building regulations, embodied carbon is becoming dominating. Resources and processes involved from material extraction to building erection should be carefully optimized aiming to reduce the emissions from the cradle to service. New advancements in timber engineering have shown the capabilities of this renewable and CO₂ neutral material in multi-storey buildings. Since their erection is based on prefabrication, an accurate construction management is eased where variations and waste are sensible to be minimized. Through this paper, the factors constraining the use of wood as main material for multi-storey buildings will be explored and the potential benefits of using Lean Construction principles in the timber industry are highlighted aiming to achieve a standardized workflow from design to execution. Hence, a holistic approach towards industrialization is proposed from an integrated BIM model, through an optimized supply chain of off-site production, and to a precise aligned scheduled on-site assembly.

1. Introduction
For the first time in over 20 years of United Nations (UN) negotiations, a global agreement on climate dealing with the reduction of greenhouse-gas (GHG) was established in Paris in 2015 within the 21st Conference of the Parties (COP 21) of United Nations Framework Convention on Climate Change (UNFCCC) and the 11th session of the Meeting of the Parties (CMP) to the 1997 Kyoto Protocol.

The main long-term goal of the so-called Paris Agreement is to maintain the global temperature increase bellow 2°C related to pre-industrial levels through reducing GHG emissions [1], what would substantially help to mitigate the irreversible effects of a climate change. However, a report from the United Nations Environment Programme (UNEP) has concluded that such a goal is not achievable under current circumstances. According to the report from the UNEP, the energy intensity per square meter of the global buildings sector needs to improve on average by 30% by 2030 compared to 2015 to meet the ambitions from the Paris Agreement [2].

Building sector has here a decisive role since accounts for 36% of global final energy use and 39% of energy-related carbon dioxide CO₂ emissions [2]. Obviously there is an environmental need to reformulate construction implementing a better use of resources and avoiding wasteful practices.

2. Why timber?
Since building regulations have become more restrictive in terms of energy consumption in use stage, operational carbon has been considerably reduced. Consequently, the CO₂ emissions produced by building product manufacturing and construction phases (A1-A5), called embodied carbon, have
assumed a main role when reducing global emissions. By using low-carbon materials and employing more-efficient design and construction processes, the CO₂ emissions could be reduced up to 30% [3].

Lifecycle Assessment (LCA) is a standardized method to quantify environmental impacts of buildings throughout the whole life cycle stages, from material extraction and product manufacturing (A1-A3) through construction (A4-A5), use and maintenance (B1-B7), and end of life (C1-C4). Even supplementary information beyond the building life cycle can be quantified meaning the benefits and loads beyond the system boundary (D) [4]. Following this discourse, for the life cycle assessment of two variations of concrete and two types of construction timber, the Global Warning Potential GWP [kg CO₂–eq] over a time horizon of 100 years was analyzed (s. Table 1) according to the European standard EN 15978 [5]. The system boundaries for the calculation is based on the general LCA framework [5] and following stages are included:

|  | Product stage: Raw material supply – transport – manufacturing |
|---|---|
| A1-A2-A3 | End-of-life stage: Transport |
| C2 | Benefits and loads beyond the system boundary stage: Reuse, recovery, and recycling potential |

Table 1. LCA indicators of building materials Global warming potential GWP [kg CO₂–eq] per m³

|                | A1-A3 | C2 | D   |
|----------------|-------|----|-----|
| Concrete C25/30| 211.1 | 12 | -21.4 |
| Concrete C35/45| 265.1 | 12 | -21.4 |
| Glued laminated timber | -652.6 | 0.46 | -372.6 |
| Cross Laminated Timber | -633.4 | 0.44 | -357.6 |

The life cycle assessment (LCA) is based on the data coming from EPD (Environmental Product Declarations), containing transportation, set to truck, during extraction/production (module A2) which is included in the EPD module A1-A3 and transportation to waste disposal (C2).

Attending to the environmental impact of the selected materials, the ecological advantages of timber compared to conventional concrete is highlighted underlining the potential for further developments, since its production is less carbon intensive, it is renewable and stores carbon for the long term contributing positively to the global warming control. Its strength-to-weight ratio makes timber an attractive material to build with since transport emissions are reduced, as so is the size of the foundations, while the workability increases.

Besides material selection, a leaner approach needs to be implemented to avoid the wasteful practices, which have put construction sector as the largest consumer of raw materials and responsible for about 1/3 of the global waste annually. Since the focus of the so-called Lean Management relies on eliminating waste, minimizing material use, avoiding errors and increasing accuracy and efficiency, a low-emission building site is therefore achievable through its implementation.

3. Methodology of research

Off-site construction may be the most positive factor when building with timber. Though prefabrication exists since decades, it is at present when it is not anymore linked to mass production, where all elements look alike with no customization, but to a systematic working methodology where sub-pieces, when combined, form an end-product with bare constrictions. Implementing off-site timber construction, overall time can be reduced by 25% [6] since the erection on site is based on an assembly process within an in-time project delivery. Besides, the production of the elements takes place in a factory away from weather detriments while parallel work on-site is allowed. Hence, strategies focused on industrializing and professionalizing the sector, based on prefabricated elements, are needed to be investigated in order to take the lead in the market of urban multi-storey buildings, taking into account that already from the design phase, different procedures as in traditional planning are needed in order to achieve an Integrated Planning (IP) with a high definition grade, buildable and divided into aligned work packages.
With the purpose to explore the weaknesses and potential improvements of the timber industry towards industrialization, expert surveys and extended literature review was conducted, where two main topics were explored: the constraints and possibilities of implementing timber or timber-based materials in multi-story buildings and the potential benefits of using some Lean Construction principles and methods throughout the entire process from design to execution. Through a crossed information exchange and case studies, a holistic approach about how to efficiently behave when planning and constructing multi-story buildings with timber or timber-based materials is proposed. As an ongoing project, the conclusions drawn served as basis to develop running systematic semi-structured interviews with selected experts on both themes with the purpose to deep into the underperformance of timber in multi-story buildings.

3.1. Expert surveys and literature review on multi-storey timber buildings

In the field of this research, a round of workshops under the umbrella of the project Holz.System.Bau were conducted and organized by MAGK-Architektur together with Eco.Plus (Bau.Energie.Umwelt Cluster Niederösterreich) and accounting 41 professionals taking part. Within two months different stakeholders from the timber industry actively highlighted weaknesses, potential improvements and possible strategies to investigate aiming to implement the use of timber as main material for multi-storey buildings. Planners, researchers, contractors, constructors, timber specialists and timber engineers, among others, in a brainstorming oriented round table, discussed an amount of decisive factors regarding to use resources more efficiently along the whole process from design to erection.

The first workshop was focused on highlighting the main goals and the boundary conditions of the approach, and the second was established as a follow up to deep into the proposed strategies and precisely establish work packages for a tentative project. A third workshop is expected to be arranged in upcoming months. The results of the sessions are organized in the following table (s. Table 2) with the purpose of simplifying the objectives, goals and strategies discussed.

| Table 2. Summary of the main topics discussed within the workshops series |
|-------------------------------------------------|
| **Urgent value-adding goals**                     | **Strategies**                                           |
| Design                                          |                                                 |
| - Extended knowledge in architectural design     | - Define a reactive and adaptive modular system with standard components |
| - Know-how exchange platform                    |                                                 |
| - Specific academic training                     |                                                 |
| - Energy and material efficient concepts         |                                                 |
| - Less constructive elements, joints and details |                                                 |
| Production                                      |                                                 |
| - Optimized logistic and coordination            |                                                 |
| - Competent handcraft                            |                                                 |
| - Shorter production time in factory             |                                                 |
| Erection                                        |                                                 |
| - Faster assembly through higher prefabrication  |                                                 |
| grade (plug-and-play)                           | - Spread the solutions through a BIM library as an open source |
| - Use rainproof constructive elements            | - Advance a collective value-adding actions catalog throughout the whole process |
| - Optimized logistic and coordination            | - Implement a crossed specific training           |
| - Null-error performance                         | - Improve efficiency through Lean Management      |
| Cost-time                                       | - Promote reliable cost and time plans by implementing Lean Construction |
| - Refinement of planning costs                   |                                                 |
| - Reliable cost and time plans                   |                                                 |
| - Faster offers and lighter comparability        |                                                 |
| End-product                                     |                                                 |
| - Cradle-to-cradle                              |                                                 |
| - Improved end-product quality                   |                                                 |

Planning a contemporary timber building implies more expertise, since factors such as support structure, fire resistance, sound isolation, energy concepts and prefabrication need to be taken into account in an early stage of the project. Hence, important decisions must be taken sooner than in conventional constructions such as element size, joints, timber system and degree of prefabrication. Also technical building equipment must be integrated and their interfaces identified and defined [7]. According to the specialists, around 80% of the projects are already defined when the decision to build
it with timber comes, implying a re-design process wasting time, effort and resources. If the decision of building with timber were earlier taken and therefore, specific know-how from timber specialists or timber engineers were implemented in an early stage of the project, a significant amount of unneeded rework could be avoided. This lack of explicit knowledge in the design phase was highlighted by the specialists as one of the main factors constraining a fluent workflow. A collaborative design approach is needed to be implemented within an IP where all disciplines and aspects above mentioned are coordinated avoiding collisions, misunderstandings and errors among others. Some strategies regarding this procedure and cooperation models for planning and execution were proposed at the Technical University of Munich through the research project LeanWOOD showing how far is this ideal picture of a fluent workflow to reality [8].

Beside the lack of expertise in early stages, the overwhelming variety of materials and elements available on the market was also underlined as constraint, since the wide range of construction options eased often varies between construction companies. To simplify planning and construction, a standardization of available timber solutions should be implemented and construction sets should be implemented, which allows not only flexible solutions with fixed price, but technical details, work packages and coordinated production and erection. Within the research project Bauen mit WEITBLICK, a system building set was proposed based on parametric building blocks and a building assembly systematic to enable industrialized social housing in a high quality. All elements were digital defined in a BIM model including every relevant data to produce the building assemblies and the production planning. This optimization in planning and production shown a significant saving potential within a number of process analysis and optimization cycles [9].

According to the experts, an optimized construction management based on industrialized building methods using system components is still missing in the sector and should be implemented, for timber to take the lead as main material on multi-storey buildings. Main topics to be considered to reach such a goal are modularity and high prefabrication grade with standards elements and joints, and implementing reliable and transparent planning including work scheduling, tasks, logistics and construction techniques, what implies close collaboration within regular meetings, and fluent communication between architects, structural engineer and construction companies to coordinate the assembly sequence and connections. As a promising suitable work methodology, Lean Construction was proposed since the implementation of Lean Management in other industries such as automobile and manufacturing has brought relevant benefits in terms of productivity and resource and flow efficiency.

3.2. Literature review on Lean construction

Lean Construction (LC) is an adaptation of the Toyota Production System (TPS) applied to construction sector. The so-called Lean Management is a work philosophy whereas waste and errors (called muda in Japanese) are seen as opportunities to improvement, as quoted by his initiator Taiichi Ohno, “having no problems is the biggest problem of all” [10]. Its goal is to track and eliminate every task with no value to the end product. One of its main basis is the pull planning, instead of push planning, common on mass production like in the Ford Production System, where a large quantity of similar products are pushed forward along the production line. Contrary, pull planning delivers only the specific products and components asked, wherein a tight involvement and trust-based relationship between producers and sub-producers are needed. Throughout a Just in Time (JIT) delivery is allowed, coming the elements and products directly on site with no unnecessary stock space, no waiting time nor movements, also considered as muda. Another key concept related to lean is the so-called Kaizen or continuous improvement, where workers at every stage are able to stop the production process if a mistake is detected, being involved more actively in the process, assuming more responsibilities and avoiding unnecessary hierarchal climbing. Their implication is decisive since they know exactly how the tasks should be done. Such a statement was sentenced by Taiichi Ohno saying: “Standards should not be forced down from above but rather set by the production workers themselves” [10]. The source of the problem is then tracked and removed, becoming the process more efficient.

The term Lean Construction was first formulated by L. Koskela in 1992 [11] who highlighted the main and chronic problems of construction sector and suggested to learn from another industries which have managed to increase their productivity while in construction sector has stood still [12]. LC was
then defined as a production system to minimize material use, time, and effort in order to generate the highest value possible, as it is made in a factory. Its principles follow transparency, quality and stability based on collaborative and reliable plans, with no constraints nor deviations. Such an approach is under the umbrella of LC within three main methods that trigger a cooperative and efficient way of construction management. These methods are Integrated Planning (IP), following the line of Last Planner System® (LPS), and the Takt Time Planning (TTP).

LPS is a pull planning system developed by Glenn Ballard, whereas regular meetings are handled between workers, last planners, aligning the tasks of every trade in a trust-based collaboration achieving a reliable planning and a continuous workflow [13]. It consists of defining which tasks can be done, which should be done and which will be done in different periods of time, providing besides the order and the requirements and preconditions for the tasks to be performed. This work methodology can be applied during the design phase by integrating the different departments and stakeholders in one planning process, and throughout achieve an IP [14].

TTP is another significant strategy inherent from LC, which aims to increase productivity by fitting and optimizing work packages and workers to suit a balanced and desired frequency of production, so-called takt, where non value-adding time is reduced and a continuous flow of production at a steady rate is achieved [15]. TTP was developed by Porsche Consulting and its suitability to improve project-based production systems has been highlighted since a better use of available resources is achieved. Although theories have explained how to apply TTP and its potential benefits, there is a lack of documentation about practical approaches and analyzed empirical data [16].

3.3. Case Studies: Timber goes Lean

Both the utilization of timber on multi-storey buildings, and the application of lean construction strategies have been barely implemented together in the sector, even though it is expected to bring a lot of positive aspects. Through this paper two case studies were selected whereas IP, LPS and TTP were implemented in high-rise timber buildings and analyzed through extended literature review, being suitable examples of the implementation of some principles described within this paper.

3.3.1. Moholt 50|50

A complex system was developed specifically to build the five passive house tower blocks made from timber elements which comprehend the Moholt 50|50 in Trondheim. At the time of construction, the project designed by Masu planning and MDH Arkitekter SA, was the largest massive timber building in Norway, with 632 student apartments [17]. The erection of this nein stories high student housing was based on prefabricated Cross Laminated Timber (CLT) elements industrially produced coming on site JIT and scheduled through TTP and an adaptation of LPS and IP to “Nordic Model of Work”, named “Involved Planning”, what was especially developed for this project by the construction company Vaidekke AS and the researcher Lars Andersen [18].

Builders were strongly involved throughout the whole process within the Involved Planning holding multiple roles and employing actively their skills in planning and problem solving. Because of their implication in early stages, the project was buildable and the technical plans detailed with a description of the building process. Planning meetings were regularly conducted, where builders, leaders and engineers planed work packages in terms of “look ahead”, as in LPS, for different periods of time, two months, two weeks or one week. Thus, the information was always up to date and the tasks for next week accurately updated, adapted and planned. Consequently, a smooth building process with few errors was achieved. The work on site involved an intense participation through daily planning meetings between on-site crew leaders and office foremen about what was done and how, being the Key Performance Indicators of the running status of on-site work. Works on-site started in February 2016 and in November 2016 the first three towers were completely finished and students moved into, while the last two were under final inspection [19].

The interior building process was structured under the TTP principle, since the deadline was extremely close and no delay was possible. The TTP was developed and managed by the site manager from the main contractor, who had been trained in Porsche Takt. The right method to correctly define a TTP according to his experience, consists on identifying trade order while minimizing the times each...
Therefore the highest timber use in Switzerland is recognized in an 1, as highlighted also within the expert survey, 70x763 IOP Conf. Series: Earth and Environmental Science 323 (2019) 012015 doi:10.1088/1755-1315/323/1/012015

Based on this collaborative working model, builders were able to finish Moholt on time, below budget and without serious errors nor injuries. Furthermore, leaders stated they would continue to perform down this path [19]. However, an important factor to be mentioned is that the project was selected through an architectural competition, wherein its construction was planned within a conventional steel and concrete structure. It was after winning when the decision to build it with CLT came in order to meet better energy and climate standards [22]. Consequently, the whole process could have been optimized, as highlighted also within the expert survey, if the decision of using timber as main material would have been earlier taken, and thereafter specific know-how sooner implemented.

3.3.2. Suurstoffi 22, Baufeld A + Arbo, Baufeld 1 – Areal in Risch Rotkreuz
The first high-rise timber building in Switzerland, designed by Burkard Meyer Architekten, is a pioneer project where BIM and Lean Construction Management (LCM) were together successfully implemented. The ten stories high office building located in “Baufeld A”, in Risch Rotkreuz is part of a renowned innovative project with nine areal in Luzern promoted by Zug Estates Holding AG. The whole project, which has been widely praised because of its innovation and sustainability, was defined through a BIM model as a digital twin within all processes were defined and optimized through LCM in an iterative way linked to the architectural model. The 36 meters high building received the silver price from Prix Lignum, where the best accomplishment of timber use in Switzerland is recognized in an every three years event. The final CAM (Computer Aided Manufacturing) plans needed for the industrialized prefabrication of the timber elements within CNC (Computer Numeric Control) machines succeeded directly from the architectural BIM model by the company Erne AG Holzbau. The BIM model was based on a catalogue from the construction company where all building elements were defined and identified. Hence, a JIT delivery was allowed from ordering along production and delivery to on-site execution. LPS and TTP were implemented within the project, where one day was defined as the Takt Time and one floor was finished in ten days [23].

Following the discourse by S22, another 60 meters high timber building with 15 stories was designed by Manetsch Meyer Architekten and Büro Konstrukt AG in “Baufeld 1”. This new high timber-based building named Arbo (Tree in Latin) will host the Hochschule Luzern (HSLU) and is, since December 2018 [24], erected and therefore the highest timber-based building in Switzerland. Besides, two more buildings conform the area, whereas one is also a wood-based construction. The first phase is expected to be completely finished by August 2019 with two institutes from HSLU moving inside, and the second one by spring 2020 [25].

Drees&Sommer (DS Consulting Process & Organization GmbH), together with Schockguyan, are the responsible of the LCM of the project in “Baufeld 1”, which was praised with the Arc-Award BIM 2018 in the category “Innovation”. Besides, Kaulquappe AG and Archobau AG as BIM and LC
Managers, made possible the coordination of the information exchange between all stakeholder through an Open-BIM system, and the digital management of on-site performances through a permanent monitoring linked to the BIM model. For the development of the required IP, an Open-BIM system served for the coordination of around 260 stakeholders from 40 different companies using each office different software for their specific purpose. J. Amann from Kaulquappe AG assumed the role of BIM Manager together with M. Giera, and assisted, together with A. Eisenhardt, as BIM Support within architecture, engineer, building equipment and construction site management. Besides, there were BIM Coordinators also taking part from different offices [25].

Like in S22, the IP was conformed of construction elements from a catalogue what allowed a high definition and, as above exposed, the possibility of getting the CAM plans directly from the BIM model. Each activity was linked to its element on the model with an ID and subdivided into daily tasks [26].

The alignment of those tasks started with an overall process analysis with the definition of work areas and process steps enhancing transparency and identifying problems. Then the Takt and Takt zones were defined with the amount of work per area, size of crews and duration with the purpose to uncover optimization potentials. After that the TTP is leveled and visually draw with the identification of trades and workflows optimizing its duration and identifying parallel processes. Throughout, an overall schedule was planned with the milestones and checked upfront processes making sure all requirements are available and preconditions are solved, following the philosophy of LPS. At the end, a detailed planning board was developed with specific information for daily activities, where was possible to identify obstacles, increase the stability and reliability and consequently optimize the Takt [26]. Within the on-site daily meetings, the BIM model served as a basis to define the tasks to be done with information about work steps, resources needed and their ID’s. Those tasks, were printed on so-called Kanban cards, like in manufacturing, and posted on the planning wall on-site. At the end of the day, for the controlling, the cards whose tasks were accomplished were turned green and scanned through a bare code and updated into the BIM model [25].

Consequently within the digital twin it was possible to know what had been done, how, when and with which amount of resources in a short period of time. Thanks to the Open BIM approach, a steady up-to-date Single Source of Truth (SSOT) was achieved, and throughout the loss of information and possible misunderstandings were minimized, while the transparence increased. According to Brigitta Schock, from Schockguyan, the application of lean construction principles came after the development of the BIM Execution Plan (BEP), what brought re-adjustments and changes. Consequently the whole process could have been further optimized if those principles would had been earlier implemented [27].

4. The holistic approach: potential of industrialized timber construction.
A systematic approach, where a project is subdivid in similar elements being produced in a factory, brings several positive aspects like higher productivity, speed of execution, fewer errors, higher quality and reliable cost and time plans. Since it is based on standardized elements and details, the planning and production of fewer elements is eased, while the errors are minimized. Timber appears to be predestined to success with such a systematic approach since solid timber products have been for decades made in industries and customized for specific projects, firstly being represented within 3D software with a high grade of detail and information, through CAM files, and then sent to CNC machines. Besides, collaboration and an engaged commitment with material use and resources are main pillars of the work systematic of the timber industry, what have been found as synergies between BIM and Lean philosophy.

Based on the research conducted throughout this paper, a holistic approach is proposed, where the whole process, from design to construction, is optimized and automated based on standardize products and processes with the purpose to highlight the potential of timber towards industrialization applied on multi-storey urban buildings.

Considering that on-site changes are not an adequate procedure when building with timber, the collaboration between all disciplines in the design phase is crucial. Technology, especially BIM, enables a continuous know-how exchange and a permanent up-to-date information access, and through the integration of detailed components, elements and systems in a BIM model, an IP is achieved, being fundamental for an off-site construction implementation. Based on the IP and within the Pull Planning,
the off-site production is allowed, being the elements produced after being called, in the right amount, in the right sequence and delivered to the right place in the right time. Thanks to this JIT delivery, no stock space is needed, nor waiting time, minimizing the time spent on-site and consequently costs, accidents, noise and dust, and achieving a pulled smooth production line from factory to field.

Within regular collaborative meetings under the framework of LPS and its backwards working philosophy, the milestones and “look ahead” plans are visually settled down, where work packages, areas and steps are defined and aligned, identifying restrictions and unlocking constraints. Combined with TTP [15], the amount of work is leveled, synchronized, stabilized and sensible to be optimized through the definition and analysis of daily activities. Although it has been proven that TTP can be applied in non-repetitive projects [28], its application in projects sensible to be divided into zones with similar work packages appears to be the most suitable scenario [29]. Consequently it can be stated that a systematic approach, such as the one proposed within this paper, seems to be the most suitable procedure for an efficient TTP. Through the construction phase and thanks to these detailed tasks planning and based on regular collaborative meetings, an earlier detection of deviations and constraints is allowed, providing a proactive approach which brings the possibility to modify and adapt the procedure and stay in plan, while potential improvements are uncovered and sensible to be implemented.

Supported with specific software, the daily planned activities, are digital defined and shared with all participants. Within an ID, those defined activities are linked to the particular construction elements in the BIM model, including valuable data such as location, work stage, resources needed and trades among others. Printing those activities on so-called Kanban cards, the daily tasks and their accomplishment are permanently monitored on-site and through the scan of their bare code, the real state of the construction site is up-to-date in its digital twin serving as a real SSOT.

5. Conclusions

BIM is the tool that allows a lean management along the whole process, from design along production to execution [30], starting with a Lean Design based on IP, following with a Lean Production on a factory within JIT and getting to LCM through LPS and TTP. All in a backwards planned smooth process which implements not only the resource efficiency, but the flow efficiency. Although their application is not specific for timber constructions and can and should be implemented also in massive construction, timber seems to be predestinated to optimally perform under such an approach, considering that the industry has been working since decades within 3D models with lots of information, off-site construction within a responsible material use and close collaboration. Nevertheless, there is a need of empirical applications regarding the use of lean principles linked to a BIM model in timber sector, in order to state and document some proven principles, strategies or methodologies and quantify benefits, deficits and potential improvements.

While traditional construction culture is strong based on the so-called “golden triangle” of “quality + schedule + budget”, both BIM as a supporting tool and Lean as a work methodology are strongly based on collaboration and communication seeking for efficiency, higher productivity and continuous improvement, so is the timber industry, being those more focused on “people + process + technology”. All in all, several synergies and enormous potential exist between Lean, BIM and timber, aiming to be explored and exploded, being the timber industry in an optimal position to take the lead in the multi-storey urban buildings market.

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