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CALCULATIVE COST AND PROCESS ANALYSIS OF TIMBER-CONCRETE-COMPOSITE CEILINGS WITH FOCUS ON EFFORT AND PERFORMANCE VALUES FOR COST CALCULATIONS OF MULTI-STOREY TIMBER BUILDINGS

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ABSTRACT: Composite structures use the advantages of two materials – timber and concrete – and improve the efficiency of a material application. Especially the concept of timber-concrete-composite ceilings has synergetic effects to achieve an effective ratio of thickness to span with high cost effectiveness simultaneously. Following the systematic analysis of operation procedures, a research project was carried out on site to gain accurate data on effort and performance values for future cost calculations. Because of the high level of prefabrication of timber structures labour costs are the leading influencing parameters. The methodology in accordance with the technique of REFA and the specific circumstances of the timber installation process were implemented into the analysis to generate an appropriate system for the examination of these new building systems. To create a feasible and applicable database of values, performance factors and activity values have been examined on site, interpreted and edited for future cost calculation.

KEYWORDS: CLT timber building system, timber-concrete-composite ceilings (TCC), construction management, operation procedures, effort and performance values, cost calculation

1 INTRODUCTION

Modern timber construction systems are distinguished by a larger scale and significantly more complexity in comparison to the traditional work of carpenters known over centuries. Recently developed timber products, connection components and buildings systems as well as their application on general construction sites and within the postulation of an extensive prefabrication process of multi-storey timber buildings demand a high grade of standardisation and unmistakeable unification. Therefore, the processes of an agile trade require further analysis to ensure confidence and settlement within the building market over the next years. Although cross laminated timber (CLT) has experienced great success as an alternative building material also in conjunction with concrete composite applications this building system has hardly been examined to date, regarding most economic aspects and building management in general. The presented survey allows a cost calculation especially for prefabricated timber-concrete-composite-ceilings (TCC-ceiling) with substantial effort and performance values as input parameters with high reliability for timber construction companies to optimise the financial aspects in order to originate an appropriate building system.

Figure 1: Typical TCC-element in the investigated object [1]

By implementing TCC-ceilings in timber buildings the advantages of structural solid timber panels and concrete slabs offer a comprehensive use in construction by achieving the synergetic effects of these materials.

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2 ANALYSIS OF CONSTRUCTION SYSTEM AND SEQUENCES OF TCC-CEILINGS

The operation processes during the construction of a timber structure include complex procedures and coherent sequences, which need to be identified to achieve financial success. These processes contain an intensive planning phase with a high level of detail in an early planning stage [2].

The absence of verified data and specific literature on cost calculations of timber-concrete-composite applications lead to current evaluations based on in-house knowledge of timber companies resp. main contractors without cross company references and profound evidence [3]. In fact, the impact of differentiating circumstances regarding technical behaviour, production systems and site conditions cannot be considered adequately at the moment. Thus thorough data acquisition on labour costs and machinery expenses on site is of further interest in order to obtain the required input parameters and primary data for suitable cost calculations. Because of the high level of prefabrication possible within the timber construction industry and especially in conjunction with timber-concrete applications in which material costs arise mainly during the factory process, the labour costs are the leading influence parameters in an accurate cost calculation.

2.1 INTIAL SITUATION AND PRINCIPLES

For the construction of a building the contractor has the choice of different construction methods that lead to the same construction outcome, provided that no other method has been predefined by the client. Nevertheless, the methods differ from a technical, economical and organizational point of view [4]. Thus, this research seeks to compare two TCC-ceiling systems with different levels of prefabrication to clarify their potential, to clearly identify the differences and to provide an extensive basis for possible future use. The construction methods of a specific TCC-ceiling using in-situ concrete and alternatively the prefabricated variant were compared in order to determine the effective incurred costs caused by both methods [5]. After considering the determined production costs and numerous other monetary factors that are difficult to assess during the process, as well as the given situation on the construction site and the internal and external conditions one method has come out as the more economical. Over the course of research, the TCC-ceiling made from in-situ concrete and the TCC-ceiling made from prefabricated components were compared to each other. The actual costs incurred were chosen as the key criterion.

2.2 RESEARCH OBJECTIVES

This research project gives an overview of the results of a study of a specific building project in Vienna, Austria. The Kirchdorfer Fertigteilholding GmbH (Kirchdorfer) based in Wöllersdorf in the state of Lower Austria and Mayr-Melnhof Holz Holding AG (MM) based in Leoben in the state of Styria have formed MMK as a mutual joint venture with respectively 50% share to prospectively accelerate the market cultivation of their newly developed factory-prefabricated timber-concrete-composite ceiling elements with the product name XC®. This stands for X-lam / concrete; the combination of CLT and concrete in a hybrid ceiling system. This recent development of a new product as well as lack of accessible, comparable references on the issue of timber-concrete composite ceilings calls for such a study to be done. The elements are composed of cross laminated timber (CLT) with a factory-incorporated reinforcement layer and grout topping depending on the static requirements. The fact that the XC-elements have a high level of prefabrication by using CLT in combination with simple notches resp. birth mouths concreted at the factory postulates an adjustment of the distribution of major activities from site to serial production by accompanying operations in order to generate a feasible and applicable data base of values.

Figure 2: *Section of typical XC-element in the investigated object in Vienna [1]*

Within the analysis performance factors and activity values have been examined in detail, interpreted and edited for future cost calculations of prefabricated CLT based on timber-concrete-composite ceiling elements and the required assembly works on site.

An overall calculative cost and process comparison between two building systems allows fundamental output and quintessence for future application. This shows that not only the time for installation is significantly shortened by up to 20 % but also the amount of construction workers involved is lowered by almost 50 % as less trades are involved on site. As the level of prefabrication forms the main constraint in this building system, the number of transports required to site is significantly lower than with all comparable conventional building systems. Consequently, this leads directly to a higher quality performance of the installed elements. Encompassing all influencing factors and assuming appropriate site conditions these factors incorporate outstanding savings by using the recently developed timber-concrete-composite ceiling elements.

2.3 COMPARATIVE OBSERVATION – SYSTEM COMPARISON

With the help of the analysis of a specific building project in Vienna, which was used as a basis in this investigation, specific and practice-oriented key figures for the production of TCC-ceilings were defined. This specific project used in-situ concrete TCC-ceilings as well as pre-cast ceilings in the form of XC-elements. The calculations of the input data, the so-called effort and performance values, for future projects were determined using the general scientifically accepted REFA-classification [8]. This is done to acquire certified input data for the calculation of similar ceiling systems. Furthermore, a calculative system comparison of both ceiling systems in connection with building time, the involved workforce and their productivity on the construction site was created [6]. The system comparison contained the amount of transports to the construction site, the final cost of producing both variants and possible interruptions and delays as well. In future a comparison of costs of both systems with varying levels of prefabrication will indicate the possibilities as well as potential savings in an optimised building process always referring to the analysed building project [6]. Apart from that the chances of reducing accruing and expected costs in future will convey. Due to the elimination of reinforcement and concreting works using the XC-prefabricated component will result in a substantial decrease in construction time needed for the construction of the ceiling. The reduction incurring and expected costs as well as the construction time are substantial arguments for the adoption of such elements. Hence, the XC-element offers an economic and competitive ceiling solution that contributes to entrenching timber as a building material in the hybrid construction industry market again.

3 DATA COLLECTION ON SITE

Following the systematic analysis of operation procedures and work flow analyses of general construction works, a widespread research project was carried out in 2015 for a typical multi-storey timber housing complex. This was done to gain accurate data on effort and performance values for future cost calculations of similar installation works. The examined timber building was realised in 2015 in a suburban typical living district in Vienna, the capital of Austria.

Figure 3: Architectural image of the investigated object in Vienna, Paulasgasse [7]

The monitoring process took place during the main construction phase on 8 days in total lasting from Mai until July 2015. The observation on site was carried out by one observer [1].

3.1 PRINCIPLES OF INVESTIGATED PROJECT

Within the building complex 4 apartment blocks were realised next to each other. All 4 buildings consisted of three levels with an additional loft level on top of the buildings. All 4 buildings were completely made out of timber with timber frame elements for the walls and solid timber elements for the ceilings. The staircases as well as the underground car park was done in concrete.

The investigated object provides three levels of timber ceilings above ground. In 3 out of the 4 buildings, particularly in block 2, 3 and 4, the ceilings were made with CLT and in-situ casted concrete. In block 1 the option of a XC-element was used. Within this research only specific ceiling elements were investigated into depth. The layout of the building as well as the investigated areas are shown in figure 3.

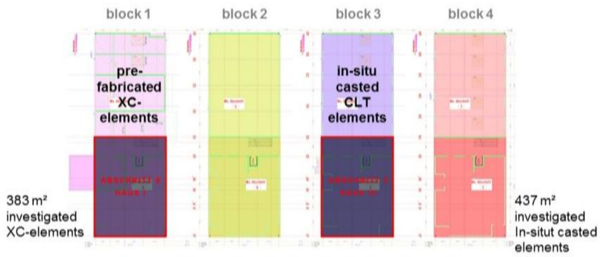

Figure 4: Set out plan with areas for comparison in the investigated object in Vienna, Paulasgasse [1]

The connections between the ceiling elements and the ceiling and wall elements -- all timber to timber connections -- could be achieved with standardised special accredited timber screws. Within the investigated areas 870 m² of CLT with approx. 6,600 special timber screws and 5,500 special perforated nails guarantee stability.

used material	in-situ casted CLT-elements
CLT (area of ceiling elements)	437 m² / 61 m³
CLT (gross area)	465 m² / 65 m³
Special timber srews	~ 3,500 pcs
nails (connection board)	~ 5,500 pcs
Special screws for reincorcement	~ 1,100 pcs
reinforcement AQS 60	2,30 to
concrete C25/30, d=8cm	38.5 m³
Filling with grit	-
used material	**XC-elements**
CLT (area of ceiling elements)	383 m² / 54 m³
CLT (gross area)	405 m² / 57 m³
Special timber srews	~ 3,100 pcs
nails (connection board)	-
Special screws for reincorcement	-
reinforcement AQS 60	1.45 to
concrete C25/30, d=8cm	24.1 m³
Filling with grit	1.12 t

Figure 5: List of materials used in the investigated object in Vienna [1]

3.2 AIM AND METHODOLOGY

The collection of appropriate data for future cost calculations as well as arguments for this system in the decision phase for architects and clients is a necessity before a new product can be placed on the market. The adapted methodology used for this analysis follows the technique according to REFA [8, 9] which is widely used for conventional building systems such as brick and concrete. Specific circumstances and characteristics of the timber installation process referring to the unique particular characteristics were implemented consequently into the analysis to generate an appropriate system for the examination of this new building system.

Therefore a system was implemented, which had already been used on similar timber projects, using the evaluation methodology to create effort and performance values using an adapted methodology of REFA which was reapplied in the investigation of this object [8, 10]. This included data worksheets as hardcopy issues for manual data collection on site. Before the construction started on site these recording sheets listed both building systems in detail by differentiating between the expected operating processes and the daily construction progress, separated for each worker on site on each day [9, 10]. By using this methodology it can be assured that suitable effort and performance values are generated through the analysis of all influencing factors by including all site parameters that accompany the works on site.

3.3 DATA RECORDING

Following the methodology of REFA, especially the multi-moment-recording-system with a five-minute observation interval formed the data survey for this building. Thus the acquisition on each day with eight working hours results in 102 control samples per worker. Therefore 510 records per day resp. 2.550 values during the installation were generated for the working crew consisting of five workers incl. foreman [1].

4 EVALUATION OF COLLECTED DATA

In the analysed building two TCC-ceiling systems were inspected. One was made from in-situ concrete poured on a prefabricated CLT-ceiling and the other was a completely prefabricated XC-element including timber and concrete. To assist the calculation of future projects the required input data and the effort and performance values were determined. This was done to acquire verified and comprehensible input data for the calculation of similar ceiling systems in future projects and to receive comparable data for existing systems. Furthermore, a calculative process comparison for both ceiling systems, concerning the building time, the workers involved and their productivity on-site as well as the amount of transports to the construction site and the final expected costs was conducted.
An extensive evaluation of the generated information after the data collection on site and an elaborately analysis using a proven scientific methodology ensures accurate values for future calculations. The aim was to gain realistic insight on actual effort and performance values following the executed work in a timber building [1].

4.1 ANALYSIS OF THE STUDY

The analysis of the progress on site followed two major courses: the evaluation on the first level included the time types required for work. The evaluation on the second level assesses the work following the activities carried out and the interruptions that occurred on site [1]. When using the first level within an application the analysis differentiated into the types of times and splits them into basic time, additional time and recreation time. These three types can also be combined into a proportion of the total time. Times which were not identifiable for the observer are not included in these percentages.

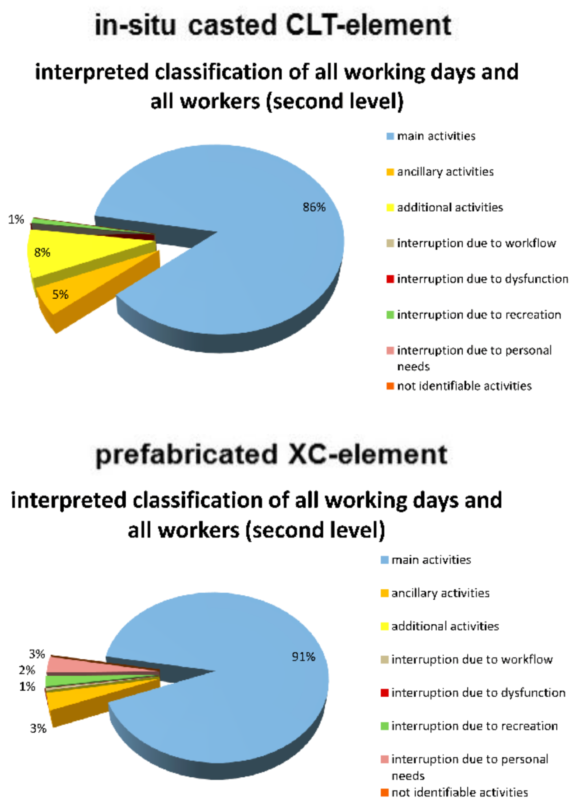

Figure 6: Breakdown of types of times for all workers on all working days (upper graph). Allotment of all working days into activity and interruptions (lower graph) [1]

The analysis of the ceilings considers results in subdivided activities and discontinuities based on the REFA-system, by splitting the collected data into occupation, interruptions and not identifiable tasks which can be seen in figure 6. Furthermore, the category occupation is split into main activities, ancillary activities and additional activities. All interruptions are classified as influences due to workflow, dysfunction, recreation and personal needs. The unidentifiable activities for the observer are included in this evaluation as well. The upper diagram showing the values for the in-situ concrete casting on the CLT-ceiling states that within the observed working days 86 % of the working time includes main activities, whereas 5 % can be classified as ancillary activities and 9 % formed interruption time of all workers observed, which indicates a high productivity. Following specific literature, a classification into good, medium and bad working behaviour states that all working days investigated reached the level good. Well organised circumstances on site and highly motivated labourers can be assumed.

The lower diagram of figure 6 states that within the observed working days of the installation of the XC element 91 % of the occurred working time includes main activities, whereas only 3 % can be classified as ancillary activities and only 6 % formed interruption time including the performance of all workers. This implies very high productivity. Once again following specific literature a classification into good, medium and bad working behaviour contains the level good for all working days. This classification assumes perfectly organized circumstances on site and highly motivated labourers.

The figure following only the evaluation on the second level elucidates that the percentage of main activities is even higher for prefabricated XC-elements than for elements using in-situ concrete. The prefabricated TCC-elements having more ancillary and complementary activities consequentially due to low level of prefabrication. This is based on the fact of the investigated floor areas shown in figure 4.

(Notice: To ensure comparability the term 'interpreted' does not contain determined times for occurrences like rain or CLT-cuttings.)

4.2 RESULTS – OBSERVED BUILDING TIME

The analysis of the building process tracked the required activities for cross laminated timber assembly, subsequent work, reinforcement works and concrete works for the in-situ concrete as well as prefab assembly and joint fill for the XC-element. Hence the construction sequence for this building can be split into the following areas for both applications:

Variant in-situ concreting:

Installation of CLT-elements, finishing works, reinforcement works, casting concrete

Variant XC-element:

Installation of prefabricated element, filling gaps with grit.

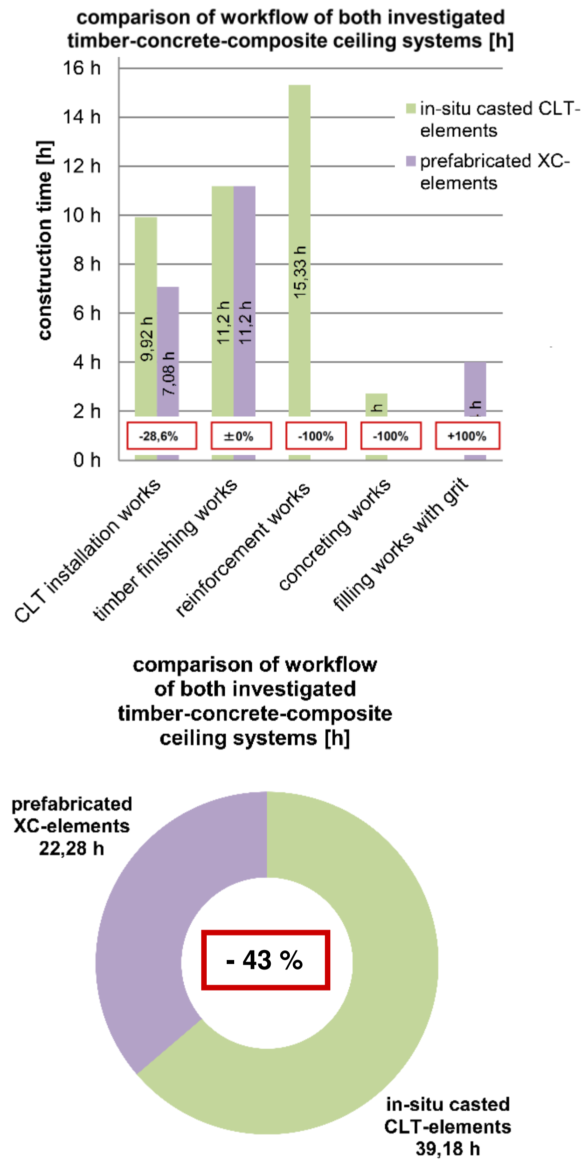

Figure 7: Comparison of building times for both variants – number of working time required for different activities (upper graph), summation of working time required (lower graph) [1]

Following figure 7 the total construction time of the in-situ concrete variant observed was 39 h and 12 min, that corresponds to 39.18 h for 437 m² in-situ casted CLT decking. In comparison to that the XC-prefabricated component investigated only took 22 h and 17 min, which corresponds to 22.28 h in construction time for 383 m² of prefabricated ceiling. The figure shows that the total construction time is reduced by 43 % when XC-components are used in comparison to the in-situ concrete variant. Within this range all values are based on the compared floor areas as shown in figure 4.

4.3 RESULTS – OBSERVED WORKFORCE

During the installation of the prefabricated variant 5 workers were involved in the building process whereas 4 ancillary workers undertook the finishing works. Additionally, 2 workers were required in this case for filling in the gaps with grit which makes a total of 11 workers involved. In the case of the in-situ casted CLT-ceiling 5 workers were involved in the installation of the prefabricated elements, 3 additional workers have installed the reinforcement and 7 workers were required for pouring the concrete inside the building. This makes a total of 19 workers for variant.

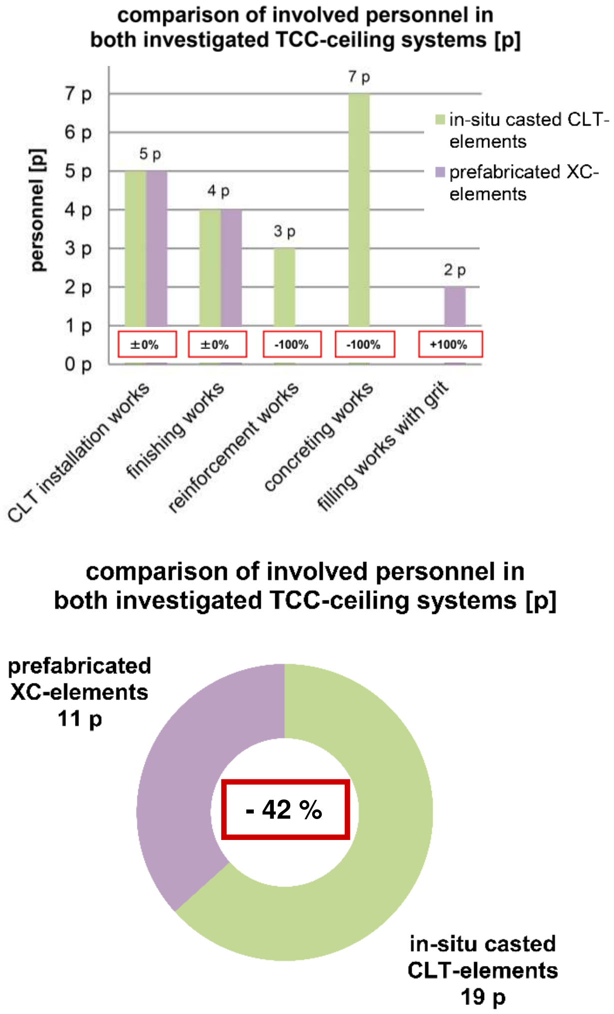

Figure 8: Comparison of workforce involved – number of workers required for different activities (upper graph), summation of all workers required (lower graph) [1]

Figure 8 shows that 19 workers were needed in total to produce the TCC-ceiling using in-situ concrete for CLT-assembly including all necessary edge and subsequent work as well as reinforcement and concrete works. It also states the number of workers required for each single task. For the construction of the TCC-ceiling using the prefabricated XC-components 11 workers were needed including all necessary edge and subsequent works.
The comparison correlates to a factor of 1.7 to 1 of involved personnel.
Thus, the amount of workers and the total required working hours when using the XC-variant were reduced by 42 when based on numbers of workers resp. 44 % when adapted from wage hours.

4.4 RESULTS – OBSERVED TRANSPORTS

The analysis of the number of transports required is based on a loading capacity of 45 m³ for CLT-elements and 8 m³ for a concrete mixer.
For the in-situ casted CLT-ceilings 5 trucks were required for the concrete, 2 trucks for transporting the CLT and 1 for the reinforcement. This gives a total number of 8 trucks for transporting the required material for 437 m² in-situ casted CLT-deckings on site.
In comparison to 4 trucks that were necessary for the transport of the 383 m² prefabricated elements from the factory on site as the loading capacity is lower and self-weight of the element is much higher. Additionally, 1 truck was required for the transport of the filling grit.

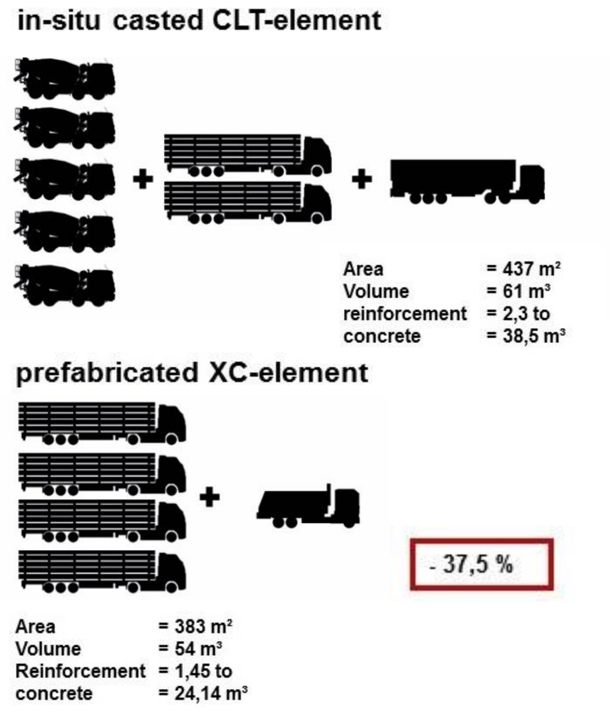

Figure 9: Comparison of required transports – number of trucks required for different materials for in-situ variant (upper graph), number of trucks required for prefabricated system (lower graph) (1]

The analysis of the amount of transports to the construction site required to produce both ceiling systems showed that the total number of transport vehicles is determined by a ratio of 1.6 to 1 as shown in figure 9.
Therefore, the XC-variant leads to a reduction of the number of transports to and from the construction site of around 37.5%. Due to the low comparative area and the missing filling capacity of some trucks involved a reduction of transports of some 25 % can be assumed.

4.5 RESULTS – EFFORT AND PERFORMANCE VALUES

Based on the evaluation following the assessment the effort and performance values could be calculated subsequently for the installation of both ceiling systems.
The generation of effort and performance values for the installation of ceiling elements was undertaken for every

single element in a first step to be summed up to an average value contributing all investigated decking elements. However first a single value was generated for every activity required on one element. This includes the fixing of lifting accessories, lifting and positioning, removal of the lifting accessories, final placement, connection between timber to timber and timber to concrete resp. decking to decking and decking to wall underneath, the inclusion of sealing strips, the attachment of the supporting structure as well as all works required within reinforcement and casting the concrete.
The graphs show the investigated values required for the installation of both systems. These effort and performance values were adjusted as mentioned under 4.1 subsequently for the occurrences of rain and CLT cuttings.

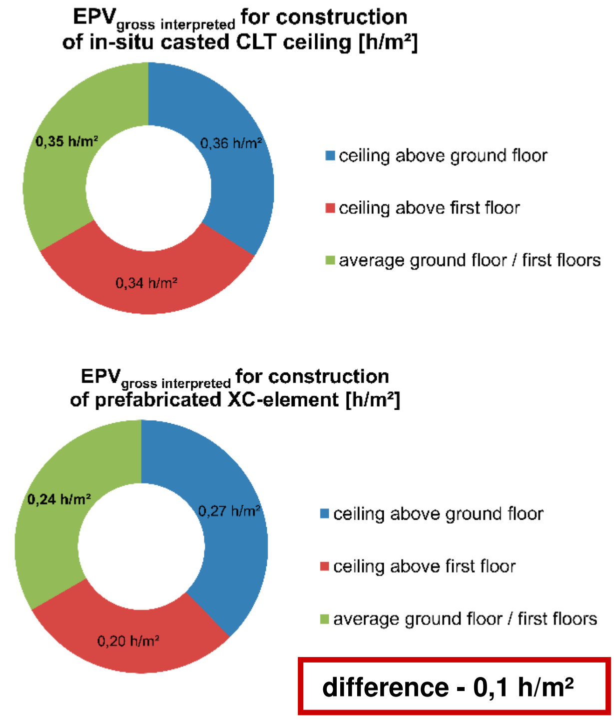

Figure 10: *Total EPV$_{gross\ interpreted}$ – EPV for different ceilings and on average of the in-situ variant (upper graph), and prefabricated XC-variant (lower graph) [1]*

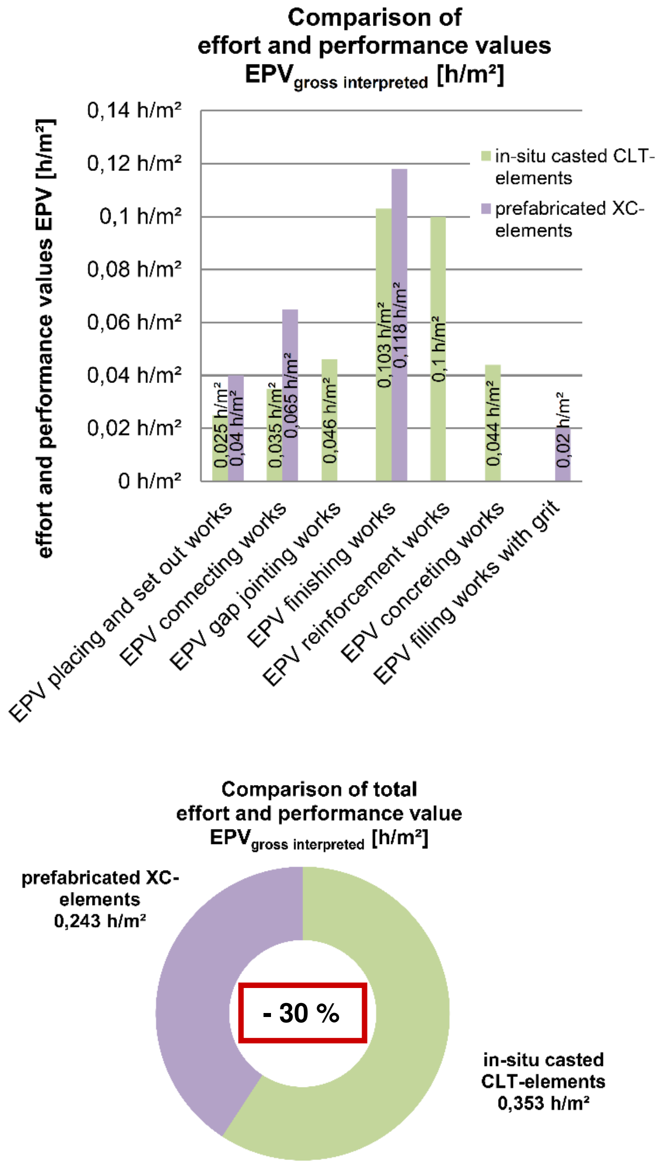

Figure 11: *Comparison of EPV – EPV for different tasks included in the in-situ variant (upper graph), total EPV for the installation of the systems (lower graph) [1]*

Following the analysis an effort and performance value EPV$_{gross\ interpreted}$ was determined for the in-situ concrete variant with a mean of 0.35 h/m² as shown in figure 11. Whereas the XC-variant's value is merely 0.24 h/m² and corresponds to a difference of 0.1 h/m² as shown in figure 10.
Hence, the total expense values of TCC-ceilings can be seen as 30% lower than the values for in-situ concrete.
These values can be taken into account in a future cost calculation by including all constraints that other building projects show and by assuming a similar workforce and level of prefabrication. However it is always required to prove and verify this data before applying these figures in a costing system.

5 SUMMARY AND OUTLOOK

Although cross laminated timber experienced great success as an alternative building material during the last few years it was hardly examined up to now regarding the economic aspects especially referring to cost evaluations. Additionally the application with prefabricated concrete-composite panels does not show accurate data and was not investigated to date to actually prove the system's input data for an appropriate cost calculation which decides on the success of the recently developed building system.

Interviews with experts as part of an investigation in 2014 [11] show that the application of prefabricated TCC-ceilings can be seen as a great opportunity for the construction industry. The modular design, the high level of prefabrication and the constructional simple execution are impressive arguments for the increased use of these ceiling systems.

The survey on site contributes another module in the lack of knowledge on economic aspects to optimise the construction management within the construction process of large scale timber buildings in conjunction with conventional building materials. Therefore, the determination of effort and performance values as the most substantial input parameters within a cost calculation in construction as well as the arguments for reducing the building time, workers involved and transports required advances the improvement of multi-storey timber buildings by an accurate evaluation of critical financial aspects in order to generate an appropriate and cost-effective building system.

5.1 KEY MESSAGE FOR FUTURE USE

Derived from the study of the specific building project for future use of TCC-ceilings in combination with CLT the following key messages can be drawn:

Both variants take about the same time to produce and assemble, despite structural and prefabrication divergence.

The advantages of the XC-variant in comparison to the in-situ concrete-variant are clearly the lower construction time, which takes about one third less time to produce the raw ceiling.

Further advantages are the amount of workers needed is about one third lower, the reduction of wage hours on site of around one third as well, a significantly lower expense value for the production of the prefabricated raw ceilings on site and decreased local traffic inconvenience though fewer transports.

__Figure 12:__ Finished building – investigated object in Vienna, Paulasgasse [1]

The expected higher production cost of the XC-variant compared to the in-situ concrete-variant are compensated by the aforementioned advantages as well as the reduction of building time and interfaces.

5.2 POTENTIALS OF PREFABRICATED TCC-CEILINGS

A crucial advantage of prefabricated components is the low space requirement on site. The elements are usually delivered just in time, placed directly from the trailer to its final destination using a crane and assembled quickly. On site the connections are formed and the joints are closed. In contrast to the in-situ concrete variant, the prefabricated TCC-elements require no assembly or storage area for formwork elements, reinforcement steel, concrete mixer or concrete pump on site. The biggest advantage compared to other building methods, like the production of TCC-ceilings with in-situ concrete for example, is the noticeably shorter construction period. Concrete as a building material requires a sufficient and standard drying time after pouring before continuing with further extension works. Ceilings made with prefabricated components do not require reinforcements before applying the concrete. Therefore, the XC-variant, which is classified as a dry building method, has a substantial economic advantage due to shorter assembly times during the shell construction phase. Because of this costs for wages relating to uncertainties due to weather and the like can be significantly reduced. Compared to ordinary construction methods like the common reinforced-concrete method, timber engineering requires less staff for planking, reinforcing and concreting. The production of prefabricated TCC-ceilings on site rather has the character of an assembly operation than classic crafting techniques, which bears more potential for the ceiling system. Although, the system requires trained technicians and workforce, they can be provided on the part of classic mineral concrete construction as well as constructional steelwork. Crew sizes between five and eight fitters are enough for most construction sites to implement such construction systems.

The low amount of craftsmen needed for the XC-element compared to the in-situ concrete ceiling nevertheless has potential that has not been recognised sufficiently to date. Due to the high prefabrication depth of the initial product XC® with fewer layers in the overall design, more and more complex building projects will result in solution approaches that are uncomplicated and carried out in a timely manner. These will not only focus on the shell construction but also on the building technology aspect of facilities. The smaller number of those involved will contribute to the reduction of lost effects due to faulty and insufficient coordination and communication with one another. An important step for improvement and optimisation may involve increasing the level of prefabrication, whereby the XC-element displays high performance ability.

5.3 SUMMARY AND INTERPRETATION

In conclusion it can be noted that both variants require about the same amount of time for both assembly and production-assembly of each raw element component without concreting work, despite constructional and prefabrication-related divergence. The benefits of the XC-variant are the notably shorter building time of around one third less for the production of the raw ceiling, approximately one third fewer workers needed on site, the reduction of the total amount of wage hours by more than one third as well, the remarkably lower amount of effort needed to produce the prefabricated raw ceilings, and much less local traffic inconvenience due to less transport being needed.

The biggest potential of timber construction methods is found in the short time of installation required on site in comparison to brick and concrete works. The amount of site installation equipment is much less corresponding with smaller areas for temporary storage as the delivery happens just in time. Additionally, the installation time is affected by the lifting facilities and mobile cranes as well as the erection performance of the team on site.

All these arguments as well as the evident values shown in the figures give high potentials for timber construction. However, in many cases the investigated values but even more the obvious arguments are not commonly used as they are hardly quantifiable and rateable. Time influencing circumstances as well as cost facts are difficult to separate between the cooperating companies on site as many activities cannot be clearly assigned to special trades.

Timber construction and timber as a leading building material has a high potential for pioneering tasks. Especially when turnkey strategies are implemented and the advantages of the material are integrated into a building system the successful way over the last years of this building material can to be extended further. More effort is required not only in the technical and material sector but even more in the building economic domains in order to allow the eco-friendly material to become a widely used building system.

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