DESIGN OF A SUSTAINABLE HIGH-RISE BUILDING
HoHo / TWIN CITY TOWER

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INTRODUCTION

Sustainability has become a trend for all areas of human life in recent years, so it is natural that this trend has been reflected in the construction industry, where building construction standards have continuously been raised in order to correspond to the new requirements of sustainable development. Architects and construction companies constantly face new challenges concerning improvement of their building projects in order to satisfy the latest regulations and certifications. The more restrictions and regulations emerge in the field of buildings construction, the more challenges the professionals have to face, which pushes them to look for innovative ideas and techniques. The design of high-rise buildings is even more challenging and complicated in the context of construction methods in correlation with sustainability principles and taking into account the recent extreme weather fluctuations caused by global warming. Unlike the buildings of regular height, high-rises do not offer such a wide range of possible materials to be used in construction and are more limited to the standard monolithic reinforced concrete skeleton type of the load-bearing structure. It gives them less flexibility and limits the opportunities to achieve the necessary sustainability level. These kinds of challenges during the design process of a high-rise building require more creativity from the architects and stimulate research towards of innovations.

Therefore, the aim of this paper is to analyse and compare two newly constructed high-rises: Twin City Tower Bratislava and HoHo Vienna (Holz-Hochhaus – "Wooden High-rise" in German). Both of them comply with the latest building standards and share a range of common characteristics:

- climate zone (located 46 km away from each other),
- situated in dense urban environment in a capital city,
- urbanism is based on a concept of a sustainable city,
- the buildings are used for commercial purposes (multi-purpose),
- modern construction (Twin City Tower completed in 2018; HoHo completed in summer 2019),
- high-rises (Twin City Tower Bratislava: 23 floors, 89 meters high ; HoHo Vienna: 24 floors, 84 meters high),
- floor area (Heated floor space 34,500 m^2 in Twin City Tower Bratislava; 25,000 m^2 in HoHo Vienna),
- both projects have received the green building certification (BREEAM Outstanding certificate for Twin City Tower Bratislava, which is also registered//has an application for WELL Core & Shell Certification; Gold Certificate by LEED for HoHo Vienna, Core & Shell Certification).

Despite many similar features, there are two major differences between the two structures, which are the use of materials and the construction methods. The structure of HoHo Vienna predominantly (about 75%) consists of local natural material – wood, while the Twin City Tower has a structure typical of high-rise buildings – a monolithic reinforced concrete skeleton with concrete ceiling slabs and a fully glazed facade. Twin City Tower uses proven building materials and procedures for its constructive solution, with the aim to improve and increase their useful life. In contrast, HoHo tower uses new experimental building solutions and combinations of materials. Nevertheless, both buildings

1 **Twin City Tower, new corner of Karadičova Street and Mlynské Nivy Street**
Source: Karolína Sásiková, 2019

comply with strict sustainability requirements as well as requirements for a healthy indoor environment. Therefore, the authors of this study compare these buildings, their constructional concepts, energy concepts and ecological solutions and analyse the differences and similarities, while keeping the focus on sustainability solutions.

"Sustainable development is a term that everyone likes but no one is sure what it means."
Herman Daly, 1996[1]

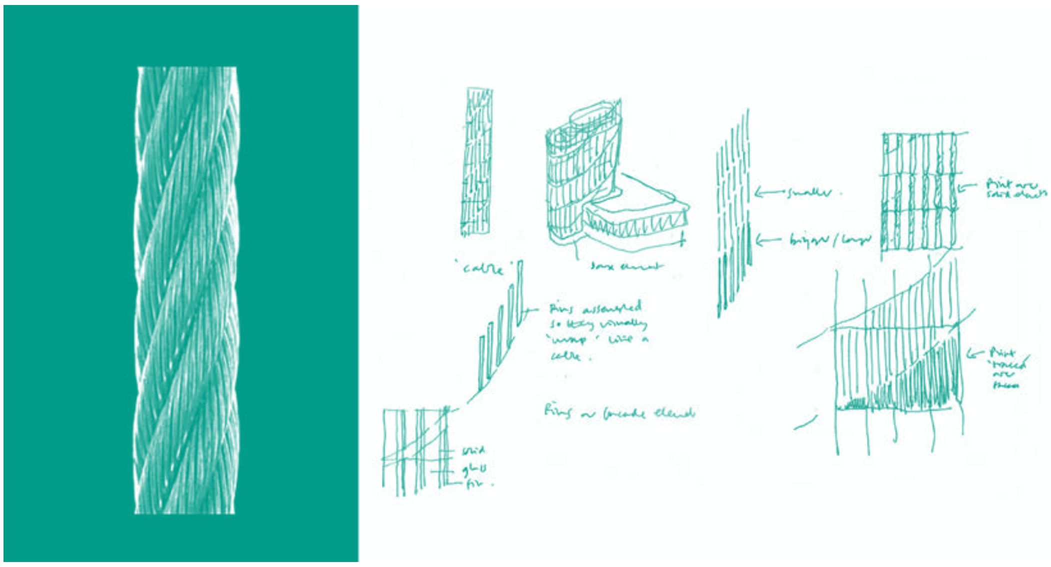
1. TWIN CITY TOWER BRATISLAVA

1.1. GENERAL DATA

Name: Twin City Tower
Proprietor/Contracting Authority: Investor HB Reavis Management s.r.o
Architecture and planning: John Robertson Architects, SIEBERTTALAŠ s.r.o, CEPM
Certification: aspirations to the certificates BREEAM - Outstanding and WELL – Gold
Gross floor area: 35,000 m^3
Rental area: 34,500 m^3
Building type: skyscraper with monolithic reinforced concrete construction
Floors: 3 underground floors + 23 floors
Height: 89 m
Use: commercial (offices, retail operations, a restaurant, etc.)
Years of construction: 2016 – 2018
Investment volume: about 75 million euro
Location: it is part of the Twin City complex and it is situated in the wider context of the newly emerging zone of Nové Nivy, which is located near the city centre and was previously an industrial zone of Bratislava (factory Kablo). Nowadays, there is a new business district with administrative buildings, a new international bus station, a shopping centre and public leisure areas with perfect accessibility by bus, trolleybus or car.

1.2. HISTORY AND MAIN CONCEPT

Nivy and the surrounding areas have always been an epicentre of work. Water mills on the Small Novozámocky branch of the Danube river have been replaced by factories at the end of the 19th century, and later also residences of architects and craftsmen were added.[2] Today the district is on its way to become the busiest business centre of Bratislava, comprising technology companies, start-ups, retail brands and leisure opportunities. It is, therefore, no surprise that Twin City architects have also built up on this strong legacy of the past. The design of Twin City Tower itself is a reminiscence of a former cable factory, particularly the facade design which was inspired by a copper cable. Another reference to the industrial past can be found in the



2 **Twin City Tower, facade concept**
authors: HB Reavis Slovakia, a.s.
source:https://www.novenivy.sk/blog/2019/05/13/projekty-na-novych-nivach-ziskavaju-odborne-ocenenia/

3 **Twin City Tower, facade**
source: Karolína Sásiková, 2019

brick cladding of the project base, which connects the project effortlessly with lower buildings, Twin City blocks, and also with the original development of the older part of the city. In addition to the reflections on the past, the project also looks forward to the future, as evidenced by the high standard of the building and the sustainable concept of the entire emerging Nivy site.

"Now, a nice piece of the future of Prešporok is growing up in Mlynské Nivy.[3]"

1.3. ARCHITECTURE AND CONSTRUCTION

The overall architectural design of the newly emerging corner of Karadičova Street and Mlynské Nivy Street respects the natural compositional axes of the area, which follows and thus creates a space suitable for the placement of a dominant in the form of a high-rise with rootstock (→1). Dispositional, mass-spatial and artistic design is based on the functional use of the building. Considering the unknown users of the building, the layout had to be designed as flexible as possible with the possibility of adapting to tenants' requirements and at the same time with the idea of future extension of the building's service life.

The building consists of a mass line parallel to the facades of the lower Twin City buildings and a 23-storey tower perpendicular to the base, which accentuates not only the height but also the direction to the crossroads of Mlynské Nivy - Karadičova.[4] The oval volume of the tower is extended on the northwest side to the intersection of the streets, where the tower's parterre is recessed over two floors with the main entrances retracted, creating a spawn passage for smoother entry from the intersection. The mass of the base is bent on the upper floor, thus creating space for technological equipment/facilities.

The exterior design of the building comprises two different types of facades: the facade of the tower (glass / copper panels) and the facade of the base (brick). While the role of the tower facade is to evoke the memory of the Kablo factory by imitating the helical structure of the cable through the rotation rhythm and the colour of the panels (→2), the facade of the base refers to the industrial past of the territory and, at the same time, connects the project with the lower buildings, Twin City A, B and C blocks and the historical part of the city. (→3)

The building interior is fully flexible and provides exceptionally bright spaces, which are enriched in common areas by a natural material – stone, which is used as a counterpart to the all-glass facade. The stone used in the lobby and corridors is matt and was treated to provide the most natural surface texture.[5](→4)

The main load-bearing structure of the building is designed as a monolithic reinforced concrete skeleton consisting of

4 **Twin City Tower, entrance hall interior**
Authors: HB Reavis Slovakia, a.s.
Source: https://stavbaroka.zoznam.sk/portfolio/twin-city-tower

5 **Twin City Tower, construction**
Authors: HB Reavis Slovakia, a.s.
Source: https://issuu.com/archinfo.laura/docs/portfolio_twin_city_tower_zmensene

non-pressurized ceiling slabs, which are locally reinforced with heads and columns inside and around the perimeter of the layout. The structure is also reinforced with vertical reinforced concrete communication cores – two main and one secondary vertical communication core with elevators and staircases. There is a reinforced concrete sill along the perimeter of the ceiling slab, which eliminates the different deflections of the ceiling slab along the facade. The building, as well as its base, is designed as a three-wing structure with a basic growth of the 8.1 × 8.1m modular warp. The lower part is mounted on the base plate, below the high-rise object, is designed to eliminate the different settlement of the building parts with different floors designed as a plate-pile foundation, a combination of the base plate and deep foundations of drilled large diameter piles. The base plate will be part of the white tub. With respect to the placement of reinforcing cores and the concept of the load-bearing structure, the building is designed as one expansion unit without expansion joints.

The seventh and eighth floors are partially recessed to the lower floors. The perimeter wall of the underground floors is part of the white tub, providing protection from groundwater and underground moisture. The cross-sections of the pillars have a semi-circular ending, with regard to the premises serving as a common garage and they are oriented in the direction of parking spaces.

Roof constructions at individual levels are generally formed by a single-skin flat roof with the opposite layers order and the surface finish depending on the purpose surface serves. The roof of the lower part is designed as a green roof with extensive vegetation, which positively affects the urban climate with rainwater retention and cooling effect on the environment. The roof above the basement is divided into hard surfaces and greenery.

Both types of facades are designed as an aluminium facade system, the column part – as crossbeams, and in the tower part as an element facade with thermal insulation glazing and required thermal insulation, acoustic and light technical properties.

Other steel constructions of this project, in addition to the anchorage of the facade, also include a system for facades cleaning on the top floor, a construction for ad attachment, a construction under the technological equipment, a telecommunication mast stand and other elements.[6] (→ 5)

1.4. SUSTAINABILITY CONCEPT

Although we can classify this building as a traditional high-rise type with regard to the construction and materials used, the design, on the other hand, places a great emphasis on the quality of the interior space and sustainable architecture. It has the ambition to obtain the international sustainability BREEAM certificate and the WELL healthy environment certificate with the highest possible rating.

The main material of the supporting structure is reinforced concrete. This composite material is made of concrete and steel, materials with very different properties that complement each other. Due to this specific combination of properties, reinforced concrete is such a frequently preferred material.

Concrete, also called the "liquid stone", has become the most important building material in the world in recent decades and its global consumption is second after water consumption. Water is one of its main components (1/10 of industrial water consumption is in concrete) along with cement and aggregates. Cement, as another key concrete additive, has a huge carbon footprint of about 4-8% of the world's carbon dioxide emissions. Half of concrete's CO_2 emissions are created during the manufacture of clinker, the most-energy intensive part of the cement-making process. If the cement industry were a country, it would be the third largest carbon dioxide emitter in the world with up to 2.8 bn tons, surpassed only by China and the USA.[7] The last component is aggregate (sand, gravel, stones, larger pieces of crushed rock, etc.), where mining in ecologically sensitive areas is the biggest problem.

The iron and steel industry is one of the biggest industrial emitters of CO_2, accounting for 4% to 7% of anthropogenic CO_2 emissions globally.[8] For this reason, the production of the second basic component of reinforced concrete, steel, is also very environmentally demanding.

Despite the many negative environmental effects of this material, it needs to be evaluated throughout its life cycle from raw material extraction, through production, transport, construction and use of the building until the material is disposed of or reused. It is, therefore, important to mention the following benefits:

Long life: reinforced concrete durability ensures that the building will retain its structural quality and aesthetic features for decades, thus eliminating the need to supplement or replace the structure. The carbon footprint is minimized when the need to build a new structure is eliminated.[9]

Safety: reinforced concrete buildings can withstand natural disasters including hurricanes, tornadoes, earthquakes and floods. They are non-combustible, which ensures their longevity and protection of human lives and reduces the economic damage caused by fire.

Energy efficiency: inherent thermal mass of reinforced concrete absorbs heat during the day and releases it at night, thus reducing HVAC costs and enhancing energy efficiency. This is especially important in buildings containing heat-generating equipment.

Improved indoor air quality: concrete contains no volatile organic compounds (VOCs), which improves indoor air quality. Since it is inorganic, which means no mould growth.

Resistant: concrete retains its structural integrity in a flood, thereby reducing disruption to homeowners, businesses and the community and minimising repair costs. This reduces waste of materials and downtime of homes, businesses and essential community services.

Recyclable: at the end of a long life, concrete can be recycled, thereby reducing environmental impact and preserving raw materials for future generations.

Local: concrete and its raw materials – aggregates, cement and water are locally available, thereby reducing transport emissions and distances to the construction site, when compared to imported materials such as steel

6 **HoHo Vienna, the concrete core**
Source: Darya Haroshka, 2018

and timber. Concrete production is a local business, creating local jobs and pumping the wages back into the local economy.

Last but not least, one of the most popular features of reinforced concrete for architects is the flexibility of design.

Since the main material of the structure has been controversial from the long term perspective, the sustainability concept of the building aims to focus on those solutions and strategies, which are based on the benefits of advanced technological equipment.

From energetic perspective, the building uses a lot of technologies, especially high performance facades, photovoltaic glazing (Onyx solar) set on the 8th, 23rd and 24th floors of the building,[10] automatic shading, energy efficient lighting, energy efficient lift installations, air source heat pumps, low NOx heating and cooling technologies, real-time monitoring of energy usage and rainwater use.

Other factors which help the building to contribute to the overall sustainability, but are no longer directly related to the construction of the building, are the following: waste management policies which have reduced the construction waste, recyclable waste storage facilities, revitalization of the brownfield, a green roof, planting of grown trees in the public space, heights up to 12m and 6 tons weight, usage of a spillable soil cells system to prevent soil compaction and create space for retaining excess rainwater, parking places for electric cars or a "car sharing" system, excellent access to public transport and a bicycle policy.[11]

Thanks to these sustainable solutions, Twin City Tower represents a new standard of quality and environmental performance in the newly emerging area of Mlynské Nivy and, last but not least, the building aspires not only to the BREEAM - Outstanding certificate, but also to WELL – Gold certificate.

2. THE HIGHEST WOODEN BUILDING IN AUSTRIA

2.1. GENERAL DATA

Name: Holz Hochhaus Wien (HoHo Vienna)
Proprietor/Contracting Authority: Investor Günter Kerbler cetus Baudevelopment GmbH, Baumeisterin. Ing. Caroline Palfy
Architecture and planning: RLP Rüdiger Lainer + Partner
Certification: LEED Gold Certificate (Shell and Core)
Gross floor area: 25,000 m^3
Rental area: 19,500 m^3
Building type: Skyscraper with hybrid timber construction
Floors: 2 underground floors + 24floors
Height: 84 m
Usage: Commercial (offices, a hotel, a fitness-centre, a restaurant, etc.)
Years of construction: 2016 - 2019
Investment volume: about EUR 65 million
Location: city quarter Seestadt, part of the 22nd district of Vienna, with residential building complexes, a vast park area with an artificial lake, innovative research centres, close connections to the U2 metro line and city railways.

2.2. CONSTRUCTION AND CONCEPT

The building is erected around the core of solid reinforced concrete, which gives the construction better structural stability and fire safety (→6). The core contains the elevator shafts, staircases and technological equipment. The composite ceiling panels are attached to the concrete core and are supported by the columns of glued laminated timber (GLT) from the side of the exterior walls. The ceiling panels are prefabricated composite elements produced in Gerasdorf, not far from Vienna; they consist of a concrete slab on the upper side and a panel of cross-laminated timber (CLT) on the interior ceiling side. This way, the communication wires, heating pipes, and such are installed on the floor concrete slabs (→7) (in contrast to conventional

7 **HoHo Vienna, technical installations on the floors**
Source: Darya Haroshka, 2018

8 **HoHo Vienna, floor plans**
Authors: RLP Rüdiger Lainer + Partner
Source: https://architizer.com/projects/hoho-wien/

9 **HoHo Vienna, facade**
Source: Darya Haroshka, 2019

buildings, where the technical communications are installed in the walls) and then covered with movable floor panels to ensure the access to the communication technology if any maintenance or repairs are needed. The exterior walls are made of prefabricated cross-laminated timber panels. All interior walls are moveable, so that the function of each floor can be changed and adapted to any new needs in the future, providing freedom in multifunctional use of the building (→ 8).

The fact that the majority of the building elements were prefabricated represents one of the successful strategies applied in the project. Firstly, a high level of prefabrication has shortened the on-site construction process and made it possible to build as fast as one floor a week. Secondly, it led to a shorter period of lease of heavy machinery and construction cranes, a smaller number of workers required on the site and, therefore, the reduction of construction costs. Finally, it provided a higher safety level on the construction site, reduced the possible impact of unfavourable weather conditions and, as a result, a significant reduction of possible on-site construction mistakes and accidents.

Despite the fact that the wooden parts of the building have high fire-resistant qualities, an extra measure has been taken for the facade protection in order to prevent fire from spreading to the nearby buildings in case of a

10 **HoHo Vienna, wood in the interior spaces**
Source: Darya Haroshka, 2018

fire emergency. Therefore, starting from the third floor, the facade has been covered with Eternit inflammable fibre cement panels produced in Austria (→9). These panels provide additional protection against weather conditions, better sound insulation and typically have a long life span.[12]

In total, the proportion of timber construction in the building is 75 percent, which can also be visible in the interior, where the ceilings, exterior walls and GLT columns are left uncovered (→10). Therefore, fire protection questions remain the most popular when talking about this kind of a wooden high-rise. According to the information provided by the RLP Rüdiger Lainer + Partner construction company, the fire protection measures are the following:[13]

- Short escape routes,
- Short fire brigade routes,
- Small fire lobbies,
- Technical protection against fire,
- No vertical shafts in the wooden construction,
- Composite ceiling panels made of concrete and cross-laminated timber,
- Inflammable cement panels on the facade,
- The wooden components dimensioning exceeds the required level of E90 fire resistance.

As a result, due to a combination of innovative engineering solutions and a high level of prefabrication, HoHo Vienna, as the tallest timber building in Austria, represents a successful showcase project that demonstrates a high potential of wood for the future of the construction industry.[14] The project has won a range of certifications and awards. Firstly, it was built according to the requirements of the new TQB (Total Quality Building) assessment system developed by the Austrian Sustainable Building Council (ÖGNB). Secondly, it has won the 2019 State Award for Architecture and Sustainability. Furthermore, on 1 October 2019, the Federal Ministry of Sustainability and Tourism of Austria (BMNT), which grants awards for projects that combine innovative and sustainable architecture with sustainable construction methods, as part of its climate protection initiative *klimaaktiv*, has named the neighbourhood around the Hannah Arendt Park, where HoHo is situated, the best project in the "Ensembles/Urban Space Development and Networking" category.[15] Finally, it has received the LEED Core and Shell Certificate in Gold. However, the LEED Core and Shell certificate only takes into consideration the buildings design and construction, but totally excludes the interior installations and cannot predict the user behaviour. Therefore, there is a concern regarding the future use and performance of the building during its utilization period, which is not covered by the certificate, which provides no guarantees and may lead to unpredictable outcomes.

2.3. WOOD AS THE CENTRAL ELEMENT OF THE SHOWCASE PROJECT

Building with wood is traditional not only in Austria, but also many other regions and climate zones on the continent, from the Atlantic Ocean to Siberia. Timber not only has excellent qualities as a building material, but is also extremely environmentally friendly. In contrast to reinforced concrete, for instance, which has been used as the main construction material in conventional mass building for about a century, timber is much less energy-intensive to produce. Furthermore, due to intensive extraction and use of sand, which is the major ingredient in concrete production, its resources are decreasing faster than they can regenerate.[16] This critical situation is one of the reasons forcing architects and building engineers to look for innovative building solutions and use other construction materials, rather than concrete. In addition, since the emergence of such problems as the greenhouse effect, ozone layer depletion and climate change, progressive societies have become more and more concerned about the responsible use of natural resources and the reduction of harmful impact people have on the environmental.

Advantages of wood as a construction material:

1. Wood is a naturally renewable source, which, when used responsibly, regenerates and provides more material.
2. Wood is a carbon-negative material, because it absorbs and stores CO_2 instead of producing it, which is a natural phenomenon called carbon sequestration. As a result, timber buildings contain significantly less embodied carbon (carbon produced during the manufacture, materials transportation and construction), than concrete ones.
3. When it is used in interior spaces, wood positively affects the room climate due to its ability to absorb large amounts of moisture and release it back into the environment.
4. Good insulation and acoustic properties.

In case of HoHo Vienna, in order to make the building even more sustainable, it was a matter of principle to use such wood for construction elements that comes from sustainably managed forests in Austria and is certified for sustainability.[17] In Austria, there is a clear aim to develop all aspects of the forest management in a sustainable way. The concept is not static, but is constantly enhanced and developed. The European Criteria and Indicators for Sustainable Forest Management adopted by the FOREST EUROPE provide guidance for shaping of the forest policies in Austria and also content for surveys and reporting. However, sustainable forest management in Austria is not secured solely by the state. Above all, private forest owners are actually responsible for the condition of 80% of the Austrian forests. These are mostly family farms, where the land is passed from generation to generation. The resolve of the forest owners to promote sustainability is the key factor of success in the field of forest management[18]. Two companies in particular, Mayr-Melnhof Holz and Hasslacher Norica Timber, that provided wooden elements for HoHo Vienna, can aspire to a certificate from the Program for the Endorsement of Forest Certification (PEFC). This certification for sustainable forest management and processing guarantees that wood comes from such a forest, which "follows the reforestation standards and respects the environment by planting new trees whenever others are cut."[19]

The key material used for the building - cross-laminated timber (CLT) - represents an excellent example of a combination of tradition and innovation. CLT was invented and first came to use in Austria in 1996. After about two decades of research, experimenting and building, in recent years the product has earned a name as the "concrete of the future" or "super-material" because of its outstanding properties.[20] CLT is made of perpendicularly connected layers of wood, the number of which may vary from 3 to 7, glued together under pressure.[21] This concept significantly enhances the original qualities of wood and strengthens the final product, making it more stable, less susceptible to deformations and more fire-resistant.

Advantages of CLT as a construction material:

1. Lightweight (it is approximately 5 times lighter than concrete), therefore, a building made with CLT would require a smaller basement.
2. High load-bearing capacity makes it possible to use CLT in higher structures.
3. It is flexible and, therefore, more difficult to break in comparison to concrete.
4. High airtightness.
5. When used for exterior walls, it also serves as an insulation material.

2.4. SUSTAINABILITY CONCEPT

The energy concept of HoHo Vienna, according to its developers, includes a range of solutions, such as lifts equipped with energy recovery technology, photovoltaic systems, air/water collectors, fundament absorbers and a decentralized ventilation system with air-conditioning.[22] As a result of all of these measures combined with the innovative construction approach, the building has achieved impressive economy in primary energy (300,000 megawatt hours)[23] and significant reduction of CO_2 emissions (2,800 tons)[24] compared to the same design in reinforced concrete.

Moreover, numerous studies demonstrate the benefits of wooden and particularly CLT structures in comparison to conventional concrete buildings regarding the greenhouse gas emissions, embodied carbon of construction materials, ecological footprint and economical profits from a long-term perspective.[25] CLT has many advantages, but as a relatively new product on the construction market, it does not provide enough sufficient data on the life cycle assessment of CLT buildings, their possible life span and end-of-life scenarios, which causes great concerns. Moreover, studies say that "no records were found showing an actual case study where a CLT building was dismantled and its panels recovered for reuse, recycling or energy recovery."[26] Since the majority of sustainability parameters have already been evaluated in multiple certifications and awards won by the project, the authors will focus on these two parameters – the building's life span and its end-of-life scenarios – which lack sufficient information and remain questionable.

End-of-life scenarios for CLT structures provide several options:

1. CLT has a high potential for reuse of the building elements, which can lead to significant savings of the raw material, because CLT panels are easy to dissemble. However, reuse of the material is possible when the whole panel is in good condition. In such case, it can be removed and placed in a new construction. Otherwise, if the panels required additional manufacturing, the process would produce waste, which can also be considered to be a recycling//recyclable material.
2. The recycling of CLT panels is questionable so far, because CLT is a composite of wood and glue, which ideally should be separated for recycling purposes. However, scientists argue that "there are no technologies that could carry out the process on a large scale."[27] If we assume that a CLT panel is to be recycled without the separation of timber and glue, there is a question how the glue would behave during the recycling process. There are different kinds of adhesives used in CLT production; some of them are natural and some are synthetic. Natural ones are more ecological, but their adhesive properties are not always satisfactory. Synthetic glues are stronger, but provide fewer options for recycling due to possible noxious gas emissions, depending on the glue content. Finally, if a CLT panel can actually be recycled, the optimum product would be wooden chips, which would further be manufactured into substitutes of non-renewable materials or construction materials of lower quality and value, such as wood fibre insulation, chipboards and wood bonded panels.[28] This option would give a second life to the material, but it is necessary to consider that the recycling products will be "relatively short-lived and constitute the final use of the material before its incineration or disposal."[29]
3. Incineration of CLT panels is a questionable option for several reasons. Firstly, burning the adhesives can be a problem depending on their content and possible noxious gas emissions. Secondly, incineration will cause carbon production, the reduction of which was one of the reasons to use CLT in the first place. Lastly, it is a waste of elaborately produced material of a high quality and, therefore, is not recommended if reuse or recycling is still feasible.
4. Landfill is a questionable option, because while rotting, the wood releases methane[30], so it should not be considered if reuse or recycling is feasible.

Criteria	Twin City Tower	HoHo
Price	EUR 75 mil.	EUR 65 mil.
Load-bearing structure	reinforced concrete core	reinforced concrete core
Construction time	2 years	3 years
Exterior solutions	easily detachable exterior elements	exterior elements connected to the load-bearing elements during prefabrication
Natural material use	interior decoration	75% wooden structure
Floor plans	flexible	flexible
Ventilation system	mechanical with heat recuperation	mechanical with heat recuperation
Well-being concept	WELL certificate	buildings' multi-functional design
Life span and end-of-life scenarios	solutions secured by the BREEAM waste protocol	not enough sufficient information

Tabuľka 1 **Summary of the comparison of the two buildings**

Questionable methods of reuse and disposal of the composite building elements, especially the floor slabs, which partially consist of concrete and partially of cross-laminated timber, give rise to concerns when evaluating their sustainability. "The Building Research Establishment in the UK has certified the CLT product for a life span of 60 years and there are occupied timber buildings in Europe that are over 700 years old"[31] – ensures one of Australian CLT production companies. However, this is an innovative building approach; therefore, it will only be possible to discover its actual performance and ecological impact and also develop a convincing life cycle assessment in no less than 50-60 years, when the CLT buildings constructed now will come closer to their end of life and the professionals will have more practical experience with using CLT.

3. COMPARISON

PRICE

The construction price difference of the two buildings is almost 10 million euro, with Twin City Tower being more expensive. This is a result of several factors. First of all, in comparison to HoHo, Twin City Tower has a larger floor area and is significantly more equipped with sophisticated technical appliances, such as time-energy monitoring equipment, an intelligent facade, photovoltaic glazing, automated shading, etc. Secondly, high prefabrication level of HoHo construction made it possible to reduce the on-site construction work expenses, because of lower number of workers involved and because of shorter time for which heavy machinery and construction cranes need to be rented.

LOAD-BEARING STRUCTURE

The comparison indicates a similar design principle of the reinforced concrete structure, where the backbone of both buildings is a reinforced concrete core with shafts for elevators and stairways. The difference is that Twin City Tower is a classical monolithic reinforced concrete construction and thus forms one unit with other horizontal and vertical elements, while in HoHo, its prefabricated horizontal and vertical elements are attached to the reinforced concrete core separately.

CONSTRUCTION TIME

The overall construction period is similar in both buildings, which was roughly from 2016 to 2019. Both buildings were constructed around a monolithic reinforced concrete structure, whose preparation is highly time-consuming, as it requires more on-site work from mounting the frames, pouring the concrete to the waiting time of several weeks until it becomes solid. In the case of HoHo, the floor slabs could only be installed after the concrete core had been fully completed. This means that the high prefabrication level in HoHo, which is said to be one of the advantages of building with CLT panels did not actually result in the shortening of its on-site construction period, as it was supposed to.

EXTERIOR SOLUTIONS

Approaches to the attachment of exterior elements differ in the two examples. In HoHo, the exterior wall panels of CLT are prefabricated and attached to additional load-bearing columns made of glued laminated timber, which provide support to the floor slabs from the side of exterior walls. This approach makes the facade construction tighter, but also less flexible. In comparison, the facade elements of Twin City Tower were attached to the structure independently, after the skeleton and the floor slabs were mounted together. This approach allows for flexibility of the facade design in the future, adds possibilities to replace single elements and windows or even change the whole appearance of the facade in case it is needed, without affecting the concrete structure. As a result, it should extend the life-span of the whole construction, because the sophisticated intelligent facade elements will clearly have a shorter life span in comparison to the reinforced concrete skeleton and will require maintenance and replacement during the building's service life, which will be easily feasible.

USE OF NATURAL MATERIALS

Use of local resources contributes to the reduction of embodied carbon in the construction material due to shorter transportation routes and, therefore, is recommended as beneficial in terms of the whole building sustainability. In Twin City Tower, locally produced bricks and stones were used for decoration of the lower facade parts and common interior spaces, such as lobbies and corridors. In case of HoHo, it is the use of local wood from Austria for the CLT panels and glued laminated timber columns. Therefore, locally produced or local natural materials were used in both buildings, but it is obvious that the proportion of the use of local natural material is significantly higher in HoHo than in Twin City Tower.

FLOOR PLANS

Flexible floor planning, allowing for transformation possibilities, as well as multiple options for the building function, which can be adapted to the tenants' requirements is a similar design feature.

VENTILATION SYSTEM

In both structures, ventilation with heat recuperation is utilized, which provides good indoor thermal comfort and air quality. However, this choice of ventilation is questionable for the HoHo concept, because all the carbon negativity of the wooden construction, which made it so beneficial in terms of ecological footprint, can be negated during the building's lifetime simply by the use of mechanical ventilation.[32] Therefore, less energy-consuming solutions would be preferable in order to improve the whole sustainability level of the building.

WELL-BEING CONCEPT

One of the goals of HoHo architects was to create space that could provide healthy work-life balance for the building occupants. This was implemented with the multifunctional use of the building, which will combine offices, a hotel, restaurants, fitness and wellness centres in order to provide its occupants with a number of services, required for a healthy lifestyle. The same ambition is also inherent in Twin City Tower, which even aspires to the WELL certificate - a system designed to measure, certify and monitor built-in space properties that affect human health and fitness by improving air, water, food, lighting, but also mobility, comfort and the overall attitude to these topics.

BREEAM AND LEED CRITERIA

Both high-rise buildings have received the certificates, which are the most common and recognized on a global scale, because they have the largest range of parameters examined. Both BREEAM and LEED emphasize similar concepts of sustainable development, aimed at reducing energy consumption and environmental impact throughout the building's life cycle (construction, management, building operation, etc.). The BREEAM certificate is generally more complex and stricter than LEED, which is simpler and easier to modify. Despite these differences, it can be concluded that the match between the two certificates is 83%.[33]

We followed up on these findings with our comparison, for which the main criteria of both certificates were essential: energy, economy, indoor health and well-being, transport, water, materials, land use and ecology, waste, pollution and innovation. The comparison showed differences in particular in the areas of management, waste and pollution, where HoHo' LEED certification does not provide precisely defined procedures for dealing with these issues. Figure 11 demonstrates the connections between the above-mentioned certification criteria. The aspects of waste and pollution, which are included in BREEAM certification system, but are not covered by the LEED Core and Shell, are strongly connected with other criteria. Therefore, not taking them into consideration can significantly influence the results of final calculations in terms of sustainability and ecological footprint of the building.

Nevertheless, it is important that both buildings are an example of a sustainable high-rise building design (environmental, social and economic) with different concepts. HoHo bases the sustainability concept on an experimental construction with wood as the main building material, which is complemented with another secondary material and technology level. In contrast, the Twin City Tower has a technology level sustainability concept, complemented with a material quality level and other points, which, however, are not directly related to the construction of the object.

These findings underline how important it is to think about certificates that aim to cover the widest possible range of sustainability criteria, more than half of which do not relate directly to the building as a structure, but give more consideration to additional points that may not be permanent. For this reason, the sustainability of a building is so greatly influenced by its user. Although building design is perfect, technology is man-driven and not vice versa, and this factor is very important because it requires the tenant's responsible approach to building design.

LIFE SPAN AND END-OF-LIFE SCENARIOS

Life span and end-of-life scenarios seemingly differ for the two buildings. In case of Twin City Tower, which has a typical construction concept common for high-rises and which has been used for many decades, the life span and end-of-life scenarios are much easier to estimate, since the professionals already have enough experience with this type of construction. In case of HoHo, the end-of-life scenarios do not appear to be so obvious. Firstly, because of its innovative type of construction, which includes not only cross-laminated timber panels, but also composite floor slabs of concrete and CLT panels. Secondly, because CLT is a relatively new product on the construction market and there is no record of examples of CLT that have already reached their end-of-life stage. There are several possible options of end-of-life scenarios, but architects and construction companies do not have enough practical experience with this type of buildings so far and can estimate their lifespan and end-of-life scenarios only in theory.

A summary of the comparison of the two buildings can be found in Table 1.

CONCLUSION

The aim of this research was to compare two different building examples and find out which solutions are more beneficial in the context of a sustainable high-rise building design from a long-term perspective. Three stages of the building life cycle are taken into consideration for the building comparison:

1. Stage of a ready-built construction before utilization, including the raw-material extraction and manufacturing of the building elements.
2. Utilization period.
3. End-of-life.

At the moment, it is only possible to evaluate the two chosen building examples at the stage of a ready-built construction before utilization, because both buildings are not yet fully occupied. At the current stage, the major difference between the two buildings which affects the buildings' ecological footprint and sustainability is the choice of materials. Due to the choice of materials and the innovative construction solution in HoHo Vienna, it became possible to reduce the construction costs, significantly reduce the embodied carbon and therefore improve the sustainability of the building. These solutions prove to be beneficial in the context of a sustainable high-rise design. Moreover, HoHo, as a showcase for timber architecture in Austria, demonstrates high potential of CLT as a constructional material of the future.

In the case of Twin City Tower, its lifespan and end-of-life scenarios are easier to estimate for a high-rise with a typical monolithic reinforced concrete skeleton structure, as the LCA and life cycle costs can be calculated and, therefore, the environmental impact of the building is known more precisely before the construction is started. Embodied carbon of the concrete buildings is high, but it has been proven that these constructions are long-lasting. However, due to the innovative approach applied in the HoHo example, it is problematic to estimate the end-of-life scenarios and the overall environmental impact of the building as yet.

Therefore, the article concludes that both buildings represent successful examples of modern sustainable architecture. However, it is recommended to conduct evaluations during the buildings utilization period and monitor both buildings performance and evaluate the possible end-of-life scenarios when it becomes relevant in order to make precise evaluation and define the differences between a typical concrete high-rise and a CLT high-rise building on the scale of the buildings whole life cycle.

There are examples of LEED and BREEAM certified buildings, where occupants misused the resources (e.g. water, electricity, etc.), did not use the appliances and available technical devices in a proper way or simply neglected them. In several cases this kind of user behaviour resulted in different situations: either the building as such lost the sustainability level below certification limit or it did not perform as it was supposed to. Therefore, it is recommended to promote social awareness and educate the occupants of the buildings about sustainable maintenance and operation of the building. Secondly, it is recommended to evaluate the energy demand and overall performance of both buildings in 5 years after the start of utilization in order to determine whether they are functioning as planned and whether their energy performance still corresponds to the certification demands.

A beneficial implementation of recertification is the WELL Building StandardTM certificate, which is a leading tool for improving health and well-being of building occupants and also the next step to designing functional, green and, above all, healthy buildings. It evaluates eight basic aspects and provides monitoring and recertification every three years in order to ensure the declared healthy indoor environment and to extend the certificate validity.[34]

This study has demonstrated how little we currently concentrate on the main load-bearing structure material when designing sustainable high-rise buildings. Reinforced concrete perhaps is not the optimum solution in conjunction with advanced technology, although it is the most successful worldwide concept so far. However, this is a reason to encourage and promote alternative experimental approaches to building design, which have a high potential to set the direction for future sustainability of the high-rise buildings, although there still might be a lot of outstanding questions and directions for further research.

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