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A systematic approach to sustainable urban densification using prefabricated timber-based attic extension modules

Stefan Jaksch\textsuperscript{a}, Angelika Franke\textsuperscript{a,*}, Doris Österreicher\textsuperscript{b}, Martin Treberspurg\textsuperscript{b}

\textsuperscript{a}alpS GmbH, Grabenweg 68, 6020 Innsbruck, Austria
\textsuperscript{b}University of Natural Resources and Life Sciences, Gregor-Mendel-Straße 33, 1180 Wien, Austria

Abstract

Urban agglomerations are growing rapidly worldwide. Building additional living quarters has to be complemented by refurbishment and urban densification actions. In this context, attic extensions offer a high potential to increase urban density. At the same time, modern refurbishment projects have to improve the living comfort and energy efficiency of our buildings. The objective of the research project 'Attic Adapt 2050' is the development of a low cost, lightweight attic-extension-system, applicable to a great number of buildings of the same construction type. Its primary goal is the creation of a timber-based, industrially prefabricated system with integrated renewable energy components and a highly efficient thermal envelope. Vienna’s social housing buildings from the 1950s – 70s provide both an uniform building typology and low density – offering a high potential for ecological and economical urban development. Due to the typological design of post-war residential buildings, the described system can be adapted to many similar building types across Europe. It thus provides a suitable and low cost solution for highly efficient refurbishment and densification in Vienna – and elsewhere.

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* Corresponding author. Tel.: +431-47654-87532 ;
E-mail address: angelika.franke@boku.ac.at
1. Introduction

The growing population in our cities requires additional living space. Lots for new buildings are not always available or cannot cover the overall need – therefore new strategies for urban densification are essential as well. Attic extensions offer a great potential in this context: creating additional housing space while taking advantage of existing infrastructure. In many European capitals, attic extensions are particularly well established in refurbishments of late 19th century buildings in privileged city locations, where high real estate prices have made them attractive for investors. However, the densification potential of buildings from other construction periods has not yet been fully recognized. In Vienna, the city’s social housing buildings from the post-war era seem especially suited for a systematic densification approach, due to their low housing density and standardized layout schemes.

As refurbishments of social housing buildings are typically carried out under inhabited conditions, minimizing disturbances for residents is a key requirement for successful refurbishment actions. By using a high degree of prefabrication, highest standards of quality as well as the abbreviation of the construction process to a minimum can be ensured. The prefabricated modules also enable the pre-implementation of renewable energy systems such as PV or solar thermal collectors. Integrated planning methods enable the design of modular building components that are suitable for different use scenarios within a specific building of the identified building type. As an interdisciplinary research project, ‘Attic Adapt 2050’ provides an in-depth analysis of the structural and thermal behavior of the proposed attic extension system under different boundary conditions [1]. A showcase project will not only aid in understanding the technical issues, but shall serve the purpose of convincing authorities and inhabitants alike of the advantages of the planned measures. Due to the typological design of post-war residential buildings, the described system can be adapted to many similar building types across Europe. It thus provides a suitable and low cost solution for highly efficient refurbishment and densification in Vienna – and elsewhere.

Urban densification in the form of attic extensions in Vienna has largely been focused on the ‘Gründerzeit’ buildings, located mostly in central quarters of the city. Due to restricted rents for pre-1945 buildings, these attic extensions and their subsequent sale or lease initially made large-scale refurbishment actions in these buildings affordable. Added benefits such as terraces and views over the city skyline as well as a high demand for living space made these attic extensions attractive investments and triggered a wave of developments, mostly in the high price segment of the market. At the other end of the market, the densification of post-war social housing developments has so far been hardly exploited. Focusing on this building stock for large scale refurbishment and urban densification actions has however advantages: The post-war social housing sector represents a high share of building types, which are very similar in shape and construction. Through their similar layout, these building types are highly suitable for prefabrication, allowing economical and fast paced construction.

In the Austrian Climate Strategy 2007 as well as in the Austrian Energy Strategy, a refurbishment rate of at least 3% has been defined, so far it has still not passed the 1% mark though [2]. Utilizing the building stock of the post-war years within the yet largely untapped social housing sector by improving its quality and thus energy efficiency combined with urban densification, will significantly support the climate goals. Based on their year of construction, external shape and urban setting, the post-war social housing building types can be split into different typologies (cf. section 2.1 & Fig.1). Many of these buildings have been refurbished at some point; however some as far back as the 1980s with building standards adequate only for that time. Some of these buildings have so far never been refurbished. Assessing exemplarily the most common building typologies for their potential of attic extensions, the largest building type 1950.1 would allow roughly 150.000m² of available attic extensions, while the 1960.1 type would allow for approximately 190.000m². Assuming that the total floor area of the attic would be 10% smaller than a typical floor, there is still a substantial potential for the creation of additional living space.

Based on the fact that even with different building types, the overall layout, standard-dimensions and use of materials were fairly similar throughout the post-war construction era, modular lightweight and prefabricated timber-based elements can provide a sound and highly replicable solution for attic extensions of this building stock. Following this assumption, the research questions that have been assessed in the ‘Attic Adapt 2050’ project can thus be summarized as follows:
What are the impacts on the structural elements of the building and which structural measures have to be undertaken? Which construction elements can be pre-fabricated and how can both costs and time on site be minimized? How does the envelope and mass detailing need to be constructed to reduce energy consumption to a logical minimum whilst ensuring high thermal comfort?

The paper summarizes the main theoretical findings from the design development as well as structural simulations to date. The methodology as outlined in Section 2 describes the assessment of the status quo in terms of building characteristics, layout and structural elements. In Section 3 the prototype, which has been developed based on the assessment is summarized. The actual construction of the designed prototype as ‘proof of concept’ of the developed detailed construction design is planned for 2017 and therefore not yet covered in this paper.

2. Methodology

2.1. Assessment of Status Quo: general characteristics of the Viennese municipal building stock from 1950-1970

Attic extensions in Vienna are primarily carried out on top of late 19th century buildings, so called “Gründerzeithäuser”. They are mainly situated in central city locations, where real estate prices are comparably high and roof extensions have proven to be a lucrative business for investors. Affordable living space on the other hand is rare but desperately needed due to Vienna’s growing population numbers. With the traditional approach to attic extensions, a low cost housing system cannot be realized. In common practice, each roof extension represents an individual project-development due to a lack of standardization and a high variation of individual layouts and characteristics of the above mentioned building stock. This results in high planning as well as construction costs. The current standard roof-extension structure consists of steel-frames with timber infill, assembled on site, typically involving many different companies. Clearly, the interplay of numerous participating companies represents a major challenge for an error-free realization of projects. The possibility of prefabricating building elements is commonly not considered.

Special requirements for modification works of municipality buildings

The municipal housing administration in Vienna commonly carries out refurbishments under inhabited conditions, therefore a key requirement for construction works is to keep the disturbance of residents down to a minimum. The realization of conventional attic extensions is highly time consuming and can therefore not fulfill this demand. A prefabricated system on the other hand can be realized in a very short period of time, depending on local and technical pre-conditions. Due to the easy workability, relatively low weight and ease of transport, timber constructions are particularly suitable for prefabrication. During the past decades, timber construction enterprises have continuously enhanced their prefabrication techniques and have thus reached a very high standard. The use of pre-fabricated elements, manufactured in a single entity, not only speeds up the construction process, but also guarantees high standards of quality thanks to stable indoor assembly conditions and the use of CNC milling machines for manufacturing. The degree of prefabrication can be chosen depending on the requirements set by building owners and local preconditions. Prefabrication does require relatively high planning efforts at an early stage of the project development, but facilitates an exact cost- and process planning, leading to high financial security for developers. Especially in urban environments, short on-site assembly times, minimal emissions and noise pollution are striking arguments for the use of prefabricated structures. Logistical aspects on the other hand, such as accessibility of properties in dense living quarters, temporary roadblocks and the like must be planned ahead precisely.

Analyses of the municipal building stock from the 1950-1970

Based on an analysis conducted within the research project ‘Attic Adapt 2050’, the main characteristics of the most commonly identified building typologies can be summarized as follows (see Fig. 1 below for schematic representation):
• 1950.1: hipped roof can include small dormers, uniform window formats, 1-2 window-axes on narrow side, 2-7 storeys, external elevators (added subsequently)
• 1950.2: steep saddle roof can include small dormers, 2 window axes on gable side, 2-5 regular storeys + 1 attic storey, relatively small-scale building blocks
• 1950.3: saddle roof, 2 straight window axes on gable side, sometimes (recessed) balconies on long side, 2-6 storeys, position of staircases clearly distinguishable by formally differentiated facades
• 1960.1: flat saddle roof, main façade often structured by alternation of (recessed) balconies and window axis, sometimes balconies on narrow building sides, 1-2 window axes on narrow side, 2-8 storeys

General common characteristics Vienna’s post-war municipal buildings:

• Functionalistic facades without stylistic elements
• Main façade with common rooms mostly facing south, entrances with staircases on the backside of building, facing north
• Division of apartment blocks into several units with separate staircases and typically 2-3 residential units per storey
• Relatively small building depth of 10.5m-11 m
• Compact floor plan in accordance with the functionalistic spirit and limited resources of the time
• Simple structural system consisting of load bearing exterior walls and central chimney wall with non-load bearing interior walls (see also 2.3 below)
• Economic dimensioning of all building elements due to a shortage of building materials after the war
• Recycling of construction material from destroyed buildings for new building projects, especially during the early reconstruction period and the 1950s (see also 2.3 below)
• Generous green spaces in between individual building blocks according to the dispersed type of settlement (ribbon development)
• Accessibility: The building entrance is typically located at an intermediate level, 1/2 storey below the first living floor and 1/2 storey above the basement level, resulting in stair landings on intermediate levels. A barrier free access to the flats does therefore usually not exist and is very difficult to implement even in the course of refurbishments. Additional lifts can be placed in front of staircases, connecting the entrance level with stair landings on intermediate floors. (Fig. 2 left) It is common practice, that an additional stair-lift is installed for disabled people, if needed. A complete refurbishment of the existing staircases is not common since reconstruction works are typically carried out under inhabited conditions. (Fig. 2 right)

Fig. 1. Schematic representation of the most commonly constructed building types among social housing buildings in Vienna of the post-war era: 1950.1, 1950.2, 1950.3 and 1960.1 (from left to right) [1]
2.2. Existing Floor plan layouts

Following the extensive devastation of buildings in Vienna during the Second World War, the demand for new residential spaces was extremely high - a challenge similar to the time after the First World War, when the first municipal housing programme was introduced by the former social democratic administration of Vienna (“Red Vienna”). During this time a total of 25,000 new apartments were constructed from 1923 to 1927 with an average size of just about 40m², providing desperately needed additional living space. Based on the floor plan patterns of this time period, an updated building-typology was developed for the municipal housing programme of the post-war years. It consisted of a small entrance hall with access to a private toilet, a living room with kitchenette, a separate bathroom and additional bedrooms (see Fig.3). The average apartment size was increased to 45m². In contrast to the Viennese building structures from the interwar-period, which are often described as “superblocks” (e.g. the famous Viennese Karl-Marx-Hof), much more small scale and dispersed structures are characteristic for the post-war building typologies. These are based on the goal of the acting socialist government, not to rebuild Vienna’s city after the war as it once was, but to rethink and change urban structures for the better.

As in many other European cities at this time, the guiding principles for reconstruction were based on modernist concepts, propagated by urban planners such as architect Le Corbusier, who demanded an “organized and loosened city”[4]. This concept was put into practice by dispersing formerly dense housing structures and introducing a new settlement type - the ribbon development. The separation of residential complexes into relatively small apartment blocks not only supported the establishment of housing communities, but also provided better lighting and ventilation conditions for every individual living unit as well as generous open spaces in between the respective buildings. In contrast to typical block perimeter developments from the late 19th century, the houses were intentionally moved back from roads and traffic, creating more quiet and private living situations within the city. Guidelines for new building projects suggested a north-south orientation of the building rows, aligning living spaces at the south façade and moving staircases and side rooms to the north side. After the immediate reconstruction phase from 1945 to the early 1950s, the focus of the municipal building program was shifted from generating the highest quantity of residential units as possible, to ensuring higher standards of quality. This development is indicated by increasing apartment sizes, but did not affect the fundamental layout configurations, which stayed almost identical throughout the entire post-war period.

Fig. 3 below shows examples of floor plans of four typical post-war municipal buildings.
- B Type 1950.1 (1957-1959): Griegstraße 1-3, 1020 Wien
- C Type 1960 (1963-1966): Hackinger Straße 30-36, 1140 Wien
2.3. Existing Load Bearing Systems

The analysis of the building stock in regards to the structural design shows that a typical scheme for the load bearing system of post-war municipal buildings in Vienna can be clearly identified:

- A vertical load bearing system consisting of two external and one interior wall,
- Horizontal load bearing systems, commonly formed by ribbed concrete slabs (so called “Ast-Molin” system),
- A lightweight timber roof construction,
- Continuous concrete foundations beneath the main load bearing walls.

The shortage of building materials after the war led to very economic dimensioning of building components (see 2.2 above). A good illustration of this situation is the development and common use of so called “vibro” bricks, hollow concrete blocks made from construction rubble. Rubble was crushed in big milling machines in order to produce material with a certain grain size. Subsequently mixed with cement and water, the mixture was compacted using external vibrators – hence the name „vibro“-brick. This type of bricks is used in the walls of the topmost floors of the analysed building type. Given their comparatively low compressive strength, “vibro” bricks could not be used in the walls of lower floors, where the loads of the above floors sum up and lead to higher stresses. Resembling earlier building periods, solid clay bricks were used to build up the load bearing walls of lower floors. Basement walls, pillars and foundations were built of concrete with minimal reinforcement. Wall thicknesses range from 38cm for main load bearing walls and firewalls to 25cm for cross walls between apartments and 12cm for bracing walls.

The conducted analyses of the main characteristics, floor layout, materials as well as structural elements show, that the selected building stock offers a great potential for standardized refurbishment and densification approaches which have not yet been recognized to its full extent.

3. Results

Based on the preceding analysis of the building stock, a typical residential complex was selected to serve as the basis for planning a roof extension system within the project ‘Attic Adapt 2050’. The apartment complex in ‘Wagramer Straße 164-168’ is a typical ribbon development with east-west orientation, aligned along a well-developed road in the 22nd district of Vienna. It consists of four 3-storey objects of the building type “1950.1” (Fig. 14) constructed during the years 1959-1960.

Zoning regulations of this particular property allow for the building height to be raised by a total of 1,6 meters, therefore this object is ideally suited for both an one-storey attic extension as well as a two-storey extension. (In Vienna, the building height is defined as the point of intersection between roof and outer wall - from this point upwards the building outline must tilt back in a 45° angle. The roofline must stay within 4,5m above the maximum building height.). The selected apartment complex offers a high multiplication potential due to its size and typical 1950s layout, therefore planning results can be transferred to a large number of similar buildings in Vienna. Vienna’s municipal housing agency (“Wiener Wohnen”) pre-defines the housing standards for the new attic apartments. This encompasses
a certain standard for thermal insulation, cost-effective construction and usually no integrated heating, ventilation and air conditioning (HVAC) installations. As a matter of principle, however, the planned attic extension elements could include HVAC installation or provide higher thermal standards, e.g. on passive house level.

3.1. Development of the prototype

The dimensions of the designed system elements were chosen so that they can be loaded onto standard trucks for transportation to the building site. The possibility of prefabricating entire building modules (e.g. dormer or sanitary modules) was ruled out because of particular logistic considerations for urban areas with tighter roads and limited installation spaces.

Prefabricated wall and slab elements made of cross-laminated timber are equipped with appropriate connection details to facilitate fast assembly on a high quality level. Prefabrication of the building envelope includes the windproof layer. Windows, skylights and terrace doors are installed in the factory. Façade and roof claddings are mounted on site. To keep construction costs low, dry partition walls are built on site, however, they could also be prefabricated based on the client’s demand. In the case of two storey attic extensions, intermediate floor slabs (also made from cross-laminated timber) can be manufactured with millimetre precision and delivered to the construction site.

3.2. Construction process

- Step 1: Demolition works, prolongation of existing chimney walls and staircases and installation of steel auxiliary construction as a base for intermediate ceiling and/or roof elements
- Step 2: Installation of prefabricated elements of the building envelope (outer walls, fire walls, intermediate ceiling, dormers, roof)
- Step 3: Roof covering and wall cladding (on site)
- Step 4: Interior works including installation of lightweight interior walls and placing into service of sanitary installations

Under ideal framework conditions the construction process from stage 1 to completion of stage 3 can be realized in just five weeks (one-story variant). See Fig. 5 for an axonometric view of the prefabricated construction elements.
3.3. Floor plan design prototype

The floor plan design of the attic extension system was partially influenced by the existing building structure, which predefined the position of sanitary blocks. In contrast to the existing highly functionalistic layout, the new design aimed at creating more open and generous space configurations. Despite the relatively narrow building depth, this could be achieved by opening up the middle wall between living rooms and kitchens, generating modern living areas with good natural lighting and the possibility of cross ventilation. The interior walls were pushed apart to create more spacious room configurations. All apartments received a private terrace to extend the living area outwards. Two different solutions were designed for terraces: they can either be formed through a setback from the existing outer wall structure, as illustrated in Fig.6-7, with the benefit of increased wall heights and the possibility to implement vertical glazing elements as well as terrace doors. The setback of the walls, though, results in slightly reduced room sizes and requires the introduction of a supplemental steel-beam-structure, as described in section 3.4. The second solution proposes the introduction of an independent balcony-structure in front of the building. This more economic approach requires the installation of dormers for terrace doors and results in lower ceiling heights and inclined walls. In Vienna, dormers are allowed to stand out of the permitted building outline to a maximum extent of 1/3 of the building length. This solution is especially suited if zoning regulations restrict the extension of the building height to a minimal amount. The 2-storey extension contains spacious maisonettes and generates a total of 600m² additional living space, which equals approximately 150% of the net floor area of the pilot building [1].

Fig. 6. Section (left) and Views of two-storey attic extension; East view with newly added elevator system (top image), west view with new balcony structure (bottom image) [1]
3.4. Structural Engineering Prototype

In the context of the verification of the overall load bearing capacity after refurbishment, the structural design of the attic extension is briefly described: Prefabricated wall and slab elements based on cross-laminated timber are linearly joined with wood screws. They are supported directly by the existing external walls and a system of steel profiles connecting to the central interior wall (chimney wall). For certain versions of the prototype’s architectural design, where terrace elements are planned with an offset, a grid of steel beams (hidden in the top slab construction) distributes roof loads to the external wall. Interior walls, with the exception of partition walls are designed as non-load bearing elements which can be placed freely, enabling a large variety of floor plan designs.

3.5. Prefabrication and economical effects

Results of a preliminary cost analysis of the proposed attic extension variants show that erection costs are approximately 10% lower compared to a conventional attic extension using a steel frame construction assembled on site. These savings result just from those calculation positions that differ between the on-site assembled and the prefabricated variant. A cost comparison of attic extensions with newly built apartment houses will be prepared later within our project’s schedule and is expected to show an even higher saving potential.
While there is obviously an economic advantage of prefabrication, there are some shortcomings that have to be kept in mind when planning a construction project with a high degree of prefabrication:

- Architectural planning should ideally be considering the modular structure and dimensions – resulting in higher planning efforts in early project stages.
- A high number of element junctions results in higher requirements on the quality of timber and other materials as well as the preparation of more detailed measurements of the existing building for the prefabrication.
- High logistic requirements in a short period of time and the requirement for a larger crane due to heavier elements.
- Modular construction methods are unsuited for building projects with complex geometries.

However, in the case of Vienna’s typological post-war-building stock, the advantages of prefabricated roof-extension elements outweigh these shortcomings and facilitate not only gains in terms of costs and execution time, but may also help to improve the building quality:

- Shorter on-site construction period and less nuisance to existing residents.
- Lower overall lead time for production and implementation of roof extension.
- Easier and faster window installation at the production site.
- Lower personnel costs due to the lower average wages of the employees in the factory.
- Shorter derivative time requirements of construction site equipment.
- No space requirements for temporary storage of construction materials.
- Achievement of a higher quality end product and dimensional accuracy.
- Lower risk of water damage to the underlying existing properties.
- No risk of water damage to the timber construction and thermal insulation material on site due to bad weather conditions.
- Process- and cost-optimization due to simultaneous multi trade construction at the facility.
- Overall high quality construction at a lower cost than conventional methods.

4. Discussion

The results of the analysis of building types showed the high potential for prefabricated attic extensions. The development of the floor plan design and architectural integration provides suitable as well as adaptable solutions for the considered building types. A critical point will be the thermal performance of the lightweight construction and in particular the indoor thermal comfort during the summer periods. Further thermal dynamic simulations have to be carried out during the course of the project to assess various envelope configurations (wall and roof build-up, thermal mass, glazed elements and shading elements) in regards to thermal behaviour and energy performance.

Another critical point will be the structural assessment: As in every major refurbishment project, the load bearing capacity of the adapted building has to be proven accordingly to effective building codes. For most attic extension projects carried out before Eurocode became effective, so called “light attic extensions” were common in Vienna and quite easy to achieve approval for. According to the now effective Eurocode the main verifications have to be made regarding the load bearing capacity of the top slab construction (due to additional loads from changed use case), the external and interior walls, the foundations and the earthquake stability. Earthquake security of the refurbished state might be hard to prove due to the additional loads and the increased number of inhabitants. The conditions found in a specific building strongly affect verifications of the load bearing capacity. This includes soil conditions of the specific construction site and various material properties (e.g. mortar and brick strengths in solid brick masonry) that would have to be evaluated using strength tests on original specimen in order to verify a specific material. As the municipal buildings are ideally refurbished while still inhabited, these destructive testing methods are not applicable for estimating the load bearing capacity of a great number of buildings. In order to overcome this problem, a generic verification scheme for the structural design was developed using parameter studies. Based on an existing building in Vienna, number of floors and material properties were varied in order to receive a set of fictional but not unrealistic example cases for structural calculations.
The structural analysis of these example cases show, that it is not possible to verify the refurbished building for all possible variants. Proving the load bearing capacity for any of the above mentioned verifications could be problematic for certain combinations of parameters. This means that it is hard to make a general statement, if a certain building type with a specific number of floors is likely to have sufficient load bearing capacity for an attic extension project (without any additional constructional measures concerning the specific building). Both in-depth analysis of the necessary verifications for a variety of parameters and investigation of suitable reinforcement constructions are still work in progress within the project context.

As there is a reasonable potential for saving costs, the proposed system still poses a great opportunity to create new attractive living space at comparatively low costs. Even when taking possible complications into account (like the necessity to reinforce the load bearing structure), modular attic extensions are likely to be a cost-effective alternative to newly built apartment houses.

5. Conclusion

The 1950s and 1960s social housing blocks of the city of Vienna can provide a significant – and yet largely untapped - potential to create additional living space and support urban densification. The identified building types are well suited for modular prefabricated attic elements, based on their layout configurations and settings in the urban context. Due to recurring characteristics of all post-war building and construction types, a timber-based lightweight prefabricated system offers a cost-efficient and fast construction method for this type of buildings. The prototypical development can be applied to a series of buildings of similar age and type in Vienna and other cities across Europe, where comparable building types were constructed as well.

A well-insulated and tight building shell ensures high energy efficiency standards, however due to the relatively lightweight construction, granting high indoor thermal comfort during hot summer periods can be challenging and may require additional adaptations of the building envelope.

Prefabrication processes allow for the integration of renewable energy systems into the building envelope (e.g. building integrated PV), promoting a decentralized and renewable energy production directly at the building. In the course of the project, simulations on the energy demand, summer overheating and energy balancing will be carried out to assess the overall energy efficiency of the developed system.

The structural analysis highlighted, that buildings would need to be assessed on a case-to-case basis. However the goal is to present a catalogue of structural measures for various situations:

- A quick check if a building (for which estimated material parameters are known) allows for a one-storey or even two-storey attic extension without major reinforcement constructions (“as is”).
- If in doubt, identify sensible building components and spots from where to take material samples for strength tests.
- When a building cannot be verified “as is”, present suitable reinforcement measures (favorably measures that allow the construction works while the inhabitants stay in their apartments).

In a next step the construction of the developed prototype is planned for the following year. The aim of the pilot project is to provide a proof of concept and detailed case study for further projects to follow.

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