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Digital-Parametric Planning Processes for a Resource-Saving Redensification in Timber Construction

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Abstract

In the last ten years, the demand for living space in Germany's conurbations has increased. In many places, the housing shortage has led to the construction of new residential quarters in the peripheral areas of urban centers, which resulted in an increase in land consumption and generated additional traffic congestion between the urban centers and their periphery. Simultaneously, the design and technical infrastructure of many existing buildings offer the potential for adding stories. Numerous current studies confirm the need for vertical densification, which creates living space without taking up additional land (Beckh et al. [1]).

The paper presents a strategy regarding the methodology for the study of efficient spatial structures and their corresponding tributary areas, composed of internal slab and wall plate structural systems. This methodology allows the comparison of different configurations in order to optimally align architectural requirements with structural efficiency. An otherwise necessary load transferring system on top of the existing building can be avoided by activating the internal structure and defining the support points. This reduces the overall material consumption. The proposed methodology is implemented in a fully parameterized algorithm within the Grasshopper environment in Rhino 3D [2]. This approach makes use of wall and plate elements in timber, either with massive construction or panel construction, whose internal rib structure is adapted to the force flow.

Keywords: Timber panel construction, Spatial configuration, Parameterized planning, Free-span load-bearing systems, Vertical densification

1. Introduction

Over the past years, the demand for housing has risen drastically due to the growing population in the urban regions in Germany. While metropolitan areas are growing, the population in rural areas is steadily declining, leading to a shortage of inner-city living space. According to a forecast by the Federal Statistical Office [3], the greatest demand for housing is for one- to two-person households, due to the demographic changes of recent decades, increased life expectancy, and the effects of internal migration. The trend shows that this demand will continue to rise, while three- to four-person households will continue to decline. This means that the need for living space per capita will continue to increase.

Furthermore, according to a study done in Germany from 2016 and 2019, 1.1 to 1.5 million apartments can be created via redensification (adding stories to residential and commercial buildings), taking into account the technical and building code requirements [4]. One organization working on tackling this problem is Münchner Wohnen GmbH [5]. This organization emerged from the fusion of GWG and GeWoFag, the two largest municipal housing associations of Munich. The Chair of Structural Design at

TU Dresden, funded by Deutsche Bundesstiftung Umwelt (DBU) [6], is supporting Münchner Wohnen GmbH to implement the ideas of our research in a real project, with adding two full stories to existing residential buildings from the 1950s, located in Munich. The loads from the added stories will be transferred through the apartments' timber wall panels, creating a spatial structural system and conveying the loads to the facade in a freely spanning manner to a new support grid [7]. This project is the starting point of this research.

2. Related works

The idea of load-bearing wall panels flexibly arranged on at least two levels to form a spatial structure, also presented in the research from Conzett [8], forms the basis for our research. This paper presents a method to find a configuration of flexible compositions of wall plates and slabs as a structural spatial system composed solely of planar elements, working as three-dimensional load bearing systems.

The topic of this research correlates the configuration of the structural system with the architectural layout of floor plans.

2.1. Floor Plan Generation

Methods for floor plan generation typically take the outline of a building as input and a set of user constraints, such as room size and adjacencies between rooms, and propose a room layout that satisfies the constraints, providing room locations and boundaries (walls). Earlier efforts to address this used procedural or optimization methods and manually-defined constraints [9].

In a study done by Arvin and House [10], the indoor layouts are generated with spring-systems whose equilibrium provides layouts close to the design objectives. Merrell *et al.* [11] generated residential building layouts from high-level constraints with stochastic optimization and a learned Bayesian network. Rosser *et al.* [12] followed up on this work by also considering the specification of a building outline and room characteristics. Rodrigues *et al.* [13] generated building layouts from constraints with an evolutionary method. A few approaches have also been proposed to generate other types of layouts related to floor plans. The method of Bao *et al.* [14] allows a user to explore exterior building layouts, while [15] optimize the layout of mid-scale spaces, such as malls and train stations, according to a crowd simulation.

In more recent publications there have been different approaches in generating floor-plans. Egor *et al.* [16] have done a study where the main outcome of the research is the working floor plan generator, also known as Magnetizing FPG (Magnetizing Floor Plan Generator), that is currently in a development phase. The main inputs of the generator include the space allocation plan with all areas, all required room connections, entrance point and the boundary of the site. It works on a square grid, where the size of a cell can be altered to get more precise or faster results. This method is created in the Grasshopper environment as part of the Rhinoceros 3D software [2].

Another useful approach in automated parametric design can be found in the study done by Koenig *et al.* [17]. This study is also carried out in the Grasshopper environment as part of the Rhinoceros 3D software. Although this paper is not focused on the creation of a floor plan design, a methodology for the efficient semi-automatic generation of multi-family-residential building designs is presented. The generation method is based on the replication of the common residential typologies: block, slab, and solitary. Through the use of these principal typologies in modular grasshopper components, a series of actions, each performing a specific manipulation over the current block form, can be applied. This results in the creation of a sequence of actions whose outcome is different generated alternatives for the design of a residential building complex.

2.2. Structural Models

An example of computational design of parametric structural models was presented by Bollinger *et al.* [18] at a competition for a new architecture faculty building in Stuttgart in 2009. They used Octopus, a multi-objective evolutionary algorithm to optimize the proposed structure, not only in regards to the structural system but also to architectural criteria. In this competition three different objectives were used: vertical bending moments in the floor slabs under dead load; horizontal bending moments in the shear walls under lateral loads; and the placement of shear walls in relation to the cell property. The configurations with the smallest bending moments and the best composition of shear walls according to the cell properties were used to generate offspring.

3. Background

The origins of this project start with the above-mentioned research in collaboration with Münchner Wohnen GmbH. The project on the topic of vertical extensions of buildings is being carried out on four apartment buildings. The buildings were built in the 1950s, and have three to four full stories plus a pitched roof. The location of the project is Gotteszeller Strasse in Berg am Laim, Munich, Germany. The final outcome of this project is for the existing building complex to be redensified with two additional full stories as part of an energy-efficient refurbishment [7].

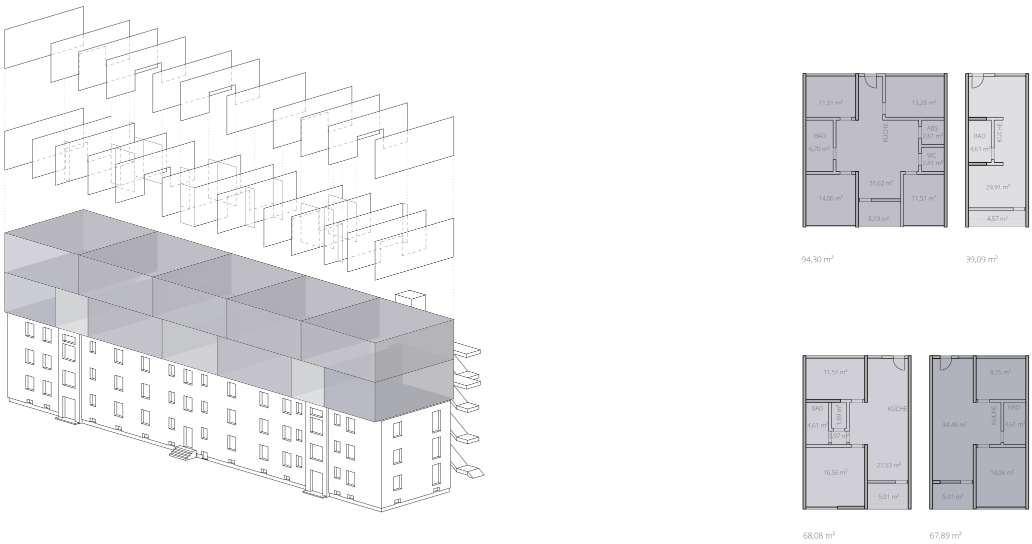


Figure 1: Variant for flexible floor plan layouts [7].

The aim is to develop adaptive timber support systems that react to the different requirements of the existing buildings. For the added stories, the forces and loads are transferred by wall panels to the facade in a freely spanning manner and then to newly added support points. The wall panels themselves can alternate between the two levels to allow for more individual and flexible floor plans. The new support axes are integrated into the new facade, which is necessary due to the energy-efficient refurbishment of the existing buildings. The inner rib structure of the timber panel elements is optimized for the force flow.

The variants shown in Figure 1 are examples of the more flexible floor plan options compared to simply stacking the same apartment configurations. All variants are based on the module size of $62.5\,\mathrm{cm}$, standardized timber grid in EU. The wall-like load-bearing elements can be designed in mass timber or timber panel construction, in which the planking is designed according to the structural requirements for the slab load-bearing effect; the slab elements in mass timber construction or as timber box elements.

During the feasibility study for this research, it was found that the development of automated floor plan generation is a separate field of research that has not yet been completed as stated in section 2. The current developments cannot yet be used for a sophisticated floor plan design, as the division of room areas only takes place via rectangles, and the interlocking of orthogonal polygons cannot yet be mapped. Simplified assumptions were therefore made within the initial steps of this study. The division of the layouts and wall positions were generated manually for several examples and examined using Grasshopper programming. Furthermore, the floor plan generation is subject to the structure of the existing building. The wall positions are subject to two parameters when dividing across the stories. Firstly, the maximum and minimum wall distance on the grid must be defined. These values depend on the maximum span of the slab elements, and the minimum width of the rooms in the floor plan. The values for these parameters are: maximum span of $625.0\,\mathrm{cm}$ and minimum room width of $250.0\,\mathrm{cm}$. On the other hand, the wall element layout is subject to the condition that the elements intersect at least one point with the wall panels above or below them across the stories. Although the existing building structure and space allocation plan are predetermined for each particular scenario, the use of generative techniques allows for the creation of multiple floor plan variations, resulting in a diverse array of potential layouts.

Lastly, in the preliminary research it was found that free-span extensions with a spatial load-bearing effect for up to three full stories are possible with moderate cross-sections of the structure and are particularly material-efficient. Under simplified structural planning assumptions, a basic rectangular initial situation (existing gross floor area) and a variable room layout per floor, room structures could be generated using different wall positions. The framework generates a simplified spatial model from the initial parameters, inputs, presented in Section 5. With the help of the Grasshopper plug-in Karamba 3D [19], the load-bearing system was tested with different material cross-sections, as was the material utilization. In addition, these results were verified with the structural analysis software Dlubal RFEM [20].

4. Goals of the project

This research topic is part of a 3-year project scheduled to finish in September 2026. The goal is to develop a fully implemented algorithm in the Grasshopper environment that optimizes spatial timber structures based on varying input parameters. These input parameters may consist of: the existing surface of the building, grid dimension (construction grid), starting height of the extension, number of stories, story height, maximum and minimum wall spacing, and the specific load combinations applicable. The algorithm will output an optimized timber spatial structure considering force flow and layout, ensuring continuous force flow between stories.

The Grasshopper plug-in, depending on the variety of initial inputs mentioned above, is intended to obtain valid data on the force flow and component design in real time. A calculation algorithm is to be further developed that reacts simultaneously to changes in the structural geometry depending on the system stiffness and optimizes the structure in terms of design and force flow. In parallel to the use of timber panel elements, the use of mass timber elements is also to be investigated in the future. The aim is to minimize material consumption and optimize use of the material properties.

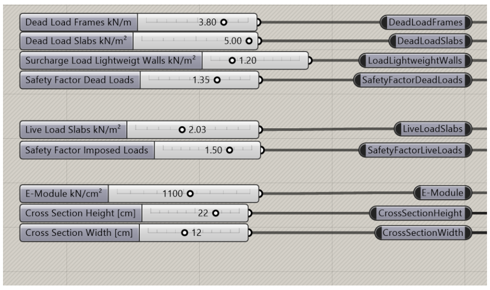
The load-bearing system should react to the different requirements of the existing building and transfer the additional loads to clearly defined support points, functioning as independently as possible from the existing building. The methodology for generating adaptive timber support systems, using a fully parameterized planning approach, depending on flexible floor plan design is to be expanded on the basis of specific case studies. Since the development of automated floor plan generation is a separate, not yet completed field of research, simplified assumptions will be made for the generation of the supporting structure.

The future work is to be carried out in two phases. In the current ongoing phase, phase 1, a further in-depth analysis of the supporting structure, timber materials, and load distribution is required. Additionally, a more in depth study on the varying input parameters and boundary conditions is to be carried out. The findings must be integrated into the developing algorithm. The core task in phase 1 is to develop a generative algorithm for adaptive spatial configurations of timber panel and box elements or mass timber elements based on the system stiffness of different structural geometries.

In the second phase, the beta version of the Grasshopper plug-in developed in phase 1 is to be tested in a real construction design in order to verify the application. Finally, the application-ready Grasshopper plug-in, including documentation and the research results, will be made available to the public.

5. Current status

The research project is still in the first phase. The focus has been put on the development of the Grasshopper algorithm, with emphasis on the input parameters, and possible geometries of various layouts.



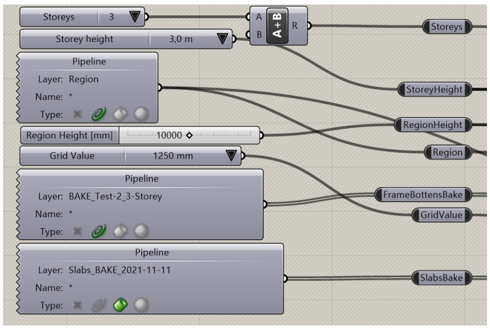


Figure 2: Initial input parameters in Grasshopper algorithm.

The initial parameters of the spatial structure are defined by existing structural conditions, as well as the loads from the environment, construction, and use. The assumptions regarding these factors in the current status are the following: existing surface as outline, grid dimension, starting height of the extension, number of additional stories, story height, and predefined wall lines. Regarding the design loads, the following is considered, all in units [kN/m] or [kN/m2] respectively: wall and slab elements, lightweight partition walls, and live loads. Other parameters taken into consideration are the material cross-section and maximum and minimum wall spacing.

The model is created in the Rhino 3D software in the Grasshopper environment. In Rhino, the base area onto which the grid is projected must be defined as a poly-line. This contour line also describes the base area of the existing building. However, the base area of the extension can also be created independently of the existing perimeter. The base area drawn can now be further processed in Grasshopper. It is manipulated using parameters, starting with the height of the extension, number of stories, and story height. These parameters can be seen in Figure 2. The story levels of the extension are created by generating a series of identical surfaces using the described parameters. The construction grid is based on usual panel dimensions and member axis dimensions in timber panel construction. When idealizing the timber panel elements as wall-like lattice girders, the axial dimension is adapted to the construction grid. The following geometrical restrictions apply: $125.0\,\mathrm{cm}$ x $125.0\,\mathrm{cm}$ grid, with internal struts placed every $62.5\,\mathrm{cm}$ and idealized axial dimension of $125.0\,\mathrm{cm}$

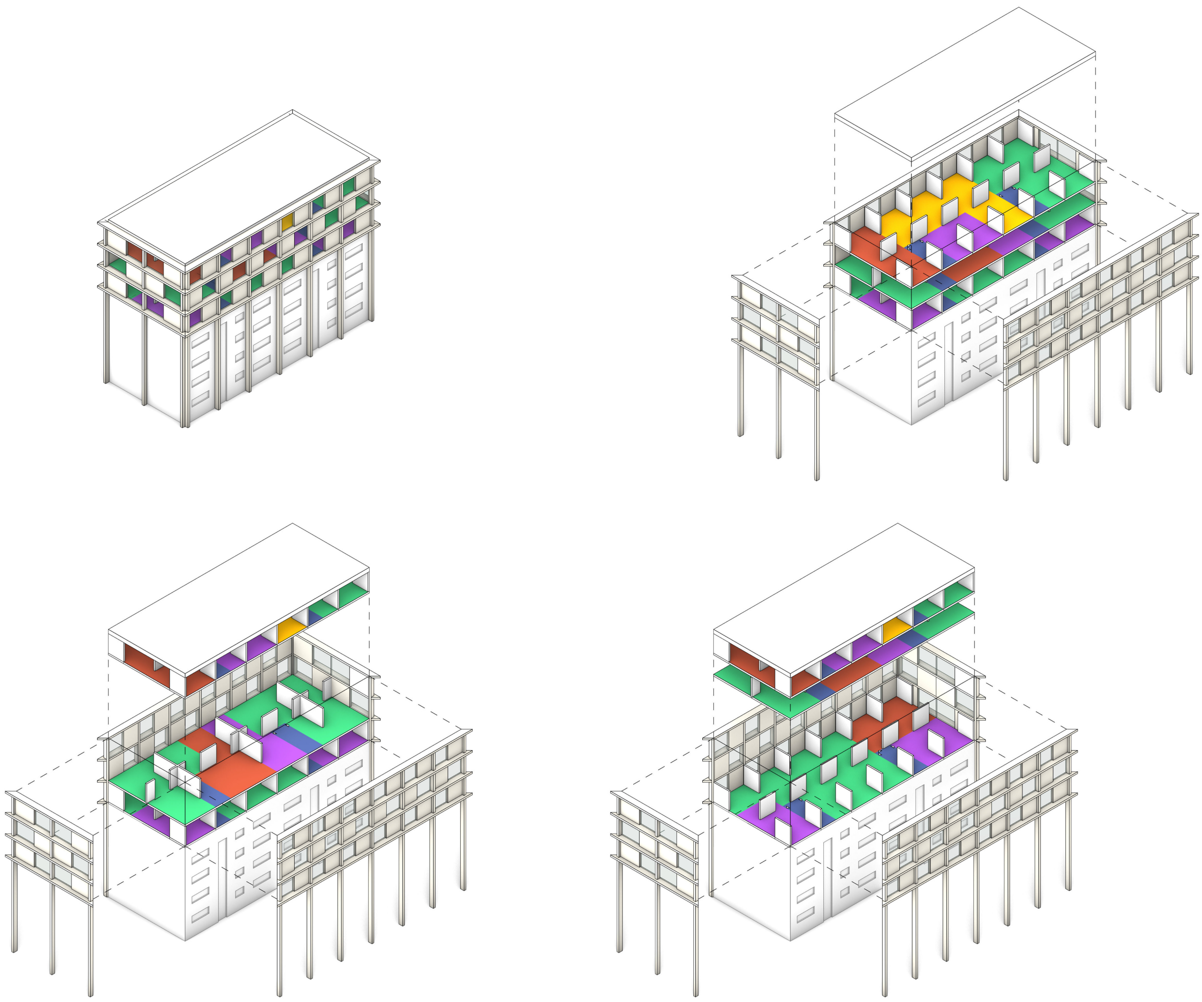


Figure 3: Manually designed flexible wall panel layout, forming a spatial structure across the stories.

The grid is created in Grasshopper depending on the series of base areas for the extension and the grid dimension parameter. Currently, the grid is limited to a rectangular base. To generate the grid, a frontal and a longitudinal edge are first selected. The extension of the surfaces in the X and Y directions is then determined and divided by the grid value. By rounding up the respective value, the number of grid lines required in the X and Y directions over the entire base area is obtained. Finally, the intersection points of all grid lines are generated in order to define the grid points. The grid lines and grid points are saved in separate lists for each story.

With the definition of the existing building structure, and the space allocation plan are defined for the respective case under consideration, floor plan variants can be created, resulting in a high variance of possible layouts. In this initial phase, the division of the layouts and wall positions were created manually for several examples and examined using Grasshopper programming. Furthermore, the floor plan generation is subject to the structure of the existing building. Access cores and media connections or shafts must be taken into account during parameterization. Due to the dependencies between the structural system and floor plan layout, the wall positions in this phase are also determined manually.

The walls are modeled through the connection of corresponding nodes on the top and bottom grid belonging to the relevant floor. The initial geometry for generating the idealized wooden panel elements are flat lines aligned orthogonal to the grid. At the beginning, the lines are ordered and cataloged so that the position of the wall plates can be traced at any time. In the first step, the lines (L) are sorted and listed using the Z-coordinate of their starting points. This gives the wall lines for each extension level. The list paths numbered consecutively in Grasshopper define the levels (E). In the second step, the plane-sorted wall lines are sorted and listed according to their position in the X and Y direction (X-R, Y-R) within the stories. An extension of the list nomenclature enables a hierarchical structure of the model during this and subsequent programming. Each list sorted by level is thus subdivided. The lines are then re-sorted within the lists according to the X and Y coordinates of their starting points in order to catalog them in sequence. After these three steps, each wall line can be uniquely retrieved in Cartesian space for subsequent processing. By extruding the cataloged lines in the Z direction with the story height, surfaces are obtained by which the frames of the wooden panel elements can be described. This way the top and bottom plate, the frame, and the edge studs can be defined by selecting the respective surface edges. A graphic summary of this process is presented in Figure 4

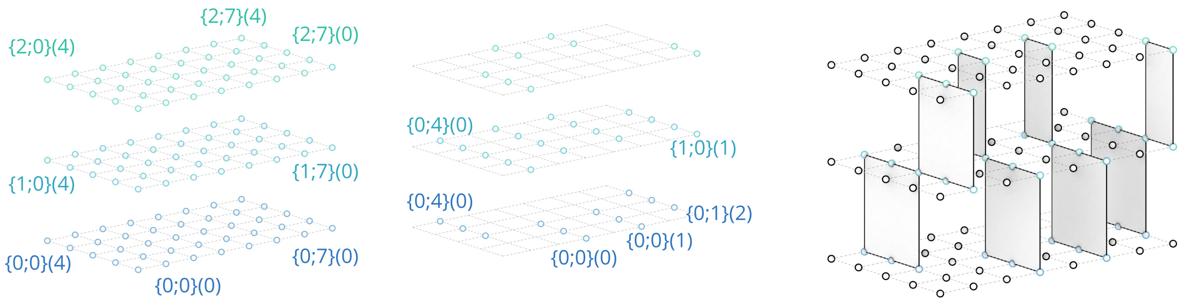


Figure 4: Graphical representation of geometry construction.

Finally, an integral part in this research is the flow of forces within the spatial structure and the overall stability of the construction. The spatial structures, apart from efficiently transferring the loads, allow a great variety in different apartment configurations and layouts. This provides the design with substantial architectural freedom, but also with varying corresponding tributary areas of the spatial structure. The topic of load transfer and tributary areas is being realized by employing mechanical routines within the Grasshopper environment mentioned earlier, while using an interface to the RFEM software from Dlubal as a cross-check reference. The study on the tributary areas has only been done on previously determined structural wall layouts.

6. Conclusion

Using a standardized method, individual structural solutions can be implemented in a cost-effective and material-friendly manner, depending on customer requirements and environmental conditions. The focus of the research is therefore on automated structural optimization depending on the existing building, and the desired space allocation plan.

This project has the potential to develop an important building block for the further development of the digital planning chain for timber engineering. During the design phase, it will be possible to define optimized structural design and component assembly of load-bearing timber walls and slabs with variable floor plan designs. This integrative method can save planning and material costs. In the process of design optimization and fabrication, it's essential to minimize the use of structural timber and wood-based materials, ensuring the conscious conservation and efficient utilization of this renewable resource. Individual planning solutions can be found for different initial situations, which take into account the wishes of planners and builders, but at the same time include the cost advantages of mass production through a high degree of prefabrication. It also improves the dialogue between structural engineers, architects and (timber) construction companies. The developed parametrics could also be applied to structural engineering planning in timber construction.

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