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Building More with Less Through Urban Mining

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Stefanie Weidner studied architecture and urban planning at the University of Stuttgart and the University of Melbourne. She graduated from the University of Stuttgart in 2014 and became a research assistant at the Institute for Lightweight Structures and Conceptual Design. While initially realizing a variety of projects for the institute, her work now focuses on high-rise structures, resource efficiency and adaptive structures, which are also part of her doctoral thesis. Currently, Weidner is in charge of the implementation of an adaptive high-rise structure on the University Campus in Stuttgart, which requires a high amount of interdisciplinary work and understanding.

Abstract

Due to increasing urbanization, the next 50 years will see a shortage of resources, which will be a key challenge for the construction industry. Architects and engineers must develop methods to alleviate the pressure on natural resources, while simultaneously generating high-quality habitats. Design concepts, such as flexible usage, urban refurbishment and adaptability are explored in the context of their applicability towards reducing material usage by highlighting the use of innovative products such as recycled concrete and graded building materials. One case study of a refurbishment project in Frankfurt, Germany demonstrates how an office tower built in the 1970s can be transformed into a modern residential building instead of demolished. The experimental unit UMAR in Switzerland exemplifies how cities can be transformed into urban mines, transforming demolition waste into raw materials for new products. These urban mines can not only deliver new building materials—they also provide other precious resources: space and quality of life.

Keywords: Adaptability, Construction, Demolition, Prefabrication, Retrofit, Sustainability

Introduction

We live in an age marked by an increasing world population and an ever-dwindling supply of resources. The built environment generates over a third of greenhouse gas emissions and accounts for more than a third of the total energy used. The built environment is also responsible for over half of the resource consumption and over half of the mass of waste produced. All of this raises the question: how can cities of the future be constructed, and of what materials, if society wishes to alleviate the onerous burden imposed by mankind on our natural environment. Faced with these complex challenges, the construction industry must show greater commitment and take on more responsibility than ever before.

The scarcity of natural resources combined with the increasing demand for building materials calls for a drastic change in the way buildings are envisioned and constructed. Some concepts and existing examples demonstrate how a more sustainable built environment can be achieved using technologies and materials readily available on the market. Portions of the concepts and ideas presented have been studied by various institutions extensively, and this research builds upon this precursory work. It presents the results of research undertaken in recent years as well as the practical experience gained from various projects, thus demonstrating the significant steps forward the field has taken in recent years. Overall, the twin concepts of urban mining and refurbishment lie at the heart of this strategic outline for the next 50 years.

Research Case 1: Graded Concrete

In 2010, 70.1 billion tons of material were extracted globally, out of which 44 percent were non-metallic minerals (UNEP 2016) like gravel and sand, the main substances used to produce concrete. This incredible quantity underlines the importance of the built environment in global resource consumption. By the 1940s, German engineer Fritz Leonhard stated that lightweight construction was "a demand of our time" (Leonhardt 1940). In the postwar era, resources were scarce and expensive, and numerous buildings had to be (re-)built quickly. The current era's motivations might be different, but the key message is still relevant.

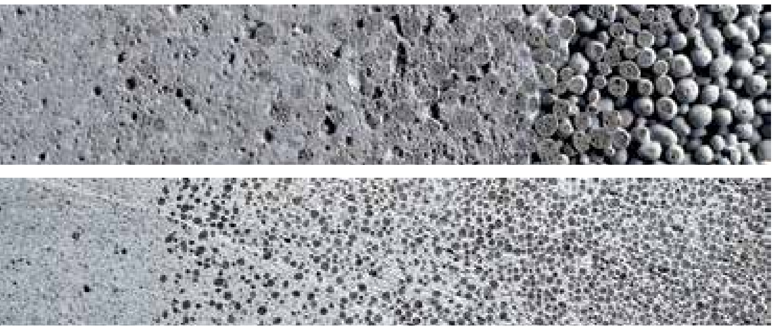

Figure 1. Concrete gradation by layered casting (top) and graded spraying (bottom). © Institute for Lightweight Structures and Conceptual Design (ILEK)

Figure 2. Material consumption could be reduced by 50 percent with the interior arrangement of hollow spheres in a prototype of a floor slab. © ILEK

Since concrete plays such a substantial role in the built environment, an increasing amount of research in recent years has focused on this material and on methods of decreasing the amount of material needed for a specific task. Researchers at the Stuttgart-based Institute for Lightweight Structures and Conceptual Design (ILEK) have been investigating the concept of graded concrete (Sobek 2016). Building elements, impacted by bending, e.g. beams or slabs are afflicted with an inhomogeneous stress distribution on the inside. Optimizing the external geometry of these elements usually does not lead to the lowest weight possible—and is often hardly feasible because of manufacturing or usability reasons (Schmeer & Sobek 2018). The approach developed by Werner Sobek therefore aims at designing the interior of these elements according to the distribution of internal stresses. The result is a fully-stressed design with a minimum of resource consumption. By positioning pores and cavities in the low-stress areas of such concrete elements, it becomes possible to forego a significant portion of the material that is needed in conventional structures. Material savings can reach up to 60 percent.

Referred to as graded concrete, this approach can be applied either as micro-gradation or meso-gradation, depending on the size chosen for the pores or cavities. To achieve a micro-gradation, lightweight mineral aggregates or pore foaming agents are mixed with regular concrete. Depending on the mixing ratio, concrete with different properties in density, strength and stiffness can thus be implemented and placed according to the stress fields inside the component To guarantee the correct material distribution in the concrete component, two different manufacturing methods—layered casting and graded spraying—were developed and automatized with a large-scale multi-nozzle spraying robot (see Figure 1).

Since for micro-gradation the minimal density is limited by the size of the pores, the second approach, meso-gradation, uses larger cavities to further increase the mass reduction of the component. To ensure full recyclability and to exclude impurities imposed by material mixes, only mineral components are used. For this purpose, researchers at ILEK developed mineral hollow bodies that are inserted into the concrete structure. A biaxial centrifuge automatically produces these hollow bodies with wall thicknesses ranging between one to four millimeters. The shape and size of these bodies is specifically adapted to the stress fields inside the component. The application of this concept allows for a considerable reduction of the material embedded in concrete elements by more than 60 percent—without reducing the load-bearing capacities. In comparison to existing concepts, this method offers several advantages. On the one hand, conventional biaxial hollow decks (commonly known as "bubble-deck slab") embed plastic spheres into concrete slabs; this creates a composite of the components that can only be separated at great expense (making recycling more difficult and expensive). On the other hand, the aforementioned conventional hollow decks use only one sphere diameter and always place the spheres at the same distance. This does not allow for an optimal minimization of the amount of concrete used. The graded concrete developed at ILEK addresses both these problems: There is no composite material (making recycling easier) and the spheres differ in size and density (allowing for substantial weight reductions that could otherwise not be achieved). The arrangement of hollow concrete spheres in a prototype of a floor slab spanning six meters has the capability to reduce material usage (see Figure 2). By choosing four different sizes of hollow spheres, it was possible to achieve a mass reduction of 50 percent. In addition, the height of the floor slab could be reduced by 10 percent.

In shell structures, meso-gradation can also be achieved by perforation—an exposed, two-dimensional porosity. By applying stress-based graded perforation, the mass of a shell can be minimized, at constant load-bearing capacities (Sobek, Kovaleva & Gericke 2019). This concept was validated with the filigree Rosenstein-Pavilion (see Figure 3).

Research Case 2: Adaptivity in the Built Environment

Decreasing the amount of built-in material may render a structure more vulnerable to external impacts. Researchers at ILEK therefore also investigate active measures as a further


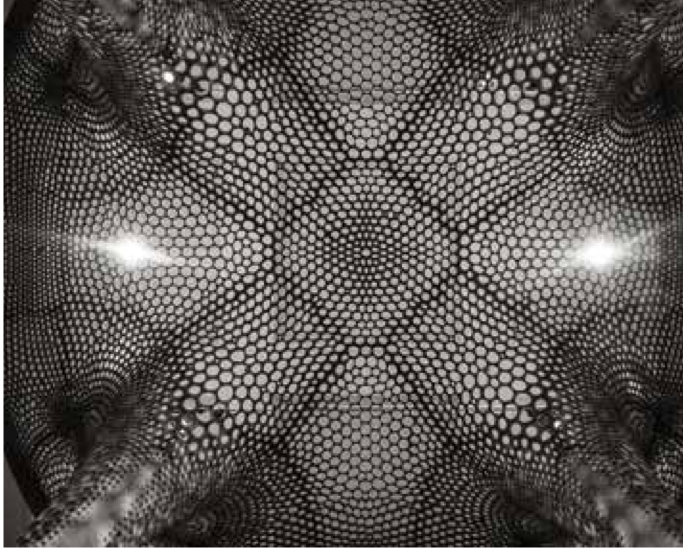

Figure 3. The Rosenstein Pavilion was designed and built for a special exhibition on construction bionics at the Rosenstein Museum in Stuttgart. © ILEK


Figure 4. The Stuttgart SmartShell demonstrates the potential of adaptivity in the built environment. The timber structure spans 10 by 10 meters, with a thickness of only 40 millimeters. © ILEK

step in their attempt to achieve ultra-lightweight structures. Enabling structures to react actively to extreme (but very rare) load-case scenarios such as storms or earthquake conditions is such a specific measure. Active structures can adapt their specific load-bearing capacities to changing external influences. They aim at manipulating the load transfer in a system by reducing deformations, vibrations and stresses via implemented active elements. Thereby, peak stresses can be avoided and material hitherto used to compensate these peaks becomes dispensable. This requires a permanent interaction between sensors, control units and actuators. Sensors (e.g. strain gauges) can detect even very slight changes in a structure and in its environment. The sensors send this information to control units. These register the changes and consequently send the respective commands to the actuators, which are attached to or integrated into the structure. This process happens in microseconds. The movement of the actuators thus initiates a secondary stress field that equalizes the overall stresses in the system. This approach is related to concepts introduced some decades ago, such as those by Reinhorn and Soong (1993), with active bracing elements being used to reduce earthquake-related oscillation. However, these concepts focus on dynamic regulation only, whereas research at the University of Stuttgart also allows for adaptation in the case of static load cases by an active redirecting of the load path.

This concept of adaptive structures allows for very significant reductions in the consumption of building materials. It has been successfully tested on various prototypes at the University of Stuttgart (see Figure 4). The latest of these prototypes is an adaptive twelve-story building to be completed in early 2020 (see Figure 5). After completion, it will be among the tallest adaptive structures worldwide. Twenty four hydraulic actuators are integrated into the load-bearing and bracing elements and ensure a homogeneous dissipation of occurring stresses, e.g. lateral forces due to wind (Weidner 2019). Thus, vibrations and deformations can be actively dampened by the structure itself, without the need for additional weight as is the case with passive damping systems.

Case Study 1: UMAR (Urban Mining and Recycling Unit)

Ideally, sustainable structures not only use as little building material as possible but should also store materials that can be used for future generations. In addition, sustainable structures should be constructed by recycling and repurposing existing resources that have been previously used elsewhere. Traditional sources of raw materials may slowly be running out, but cities can become the new mines of the future. The linear approach of excavation, exploration and disposal of materials currently applied in the construction industry needs to be changed to an approach according to the concept of the circular economy. This concept focuses on the preservation and reuse of resources in a circular model. In this system, materials are traded in closed biological and technical loops with the aim to retain the maximum value even in their second, third or further life usage. Thus, the built environment itself can be seen as a temporary storage for resources.

To prove this concept, the Urban Mining and Recycling Experimental Unit (UMAR), a laboratory for developing innovative solutions and dealing with the key questions at the heart of the construction industry, was installed in Dübendorf, near Zurich (see Figure 6). As such, its research goes far beyond the purely technical feasibility of material cycles. The design created by Werner Sobek with Dirk E. Hebel and Felix Heisel combines high-quality, sophisticated architecture with a responsible approach to our natural resources. It is based on the proposition that all of the elements required to create a building must be fully reusable, recyclable or compostable. This allows the experimental unit to serve both as temporary materials storage and a materials laboratory at the same time.

In order to bring such objectives to fruition, it must be possible to separate all materials and products out cleanly into their constituent parts after use. As a consequence, it is essential to scrutinise every single detail, every product and every structure involved in a project with a critical eye. In addition, it is vital that all of the sorted materials can be reintroduced into their relevant biological or technical cycles as required (they must not be irreversibly bonded together).

A cycle has no beginning and no end. Accordingly, the products and materials used in the UMAR project occupy a wide range of different positions in their respective cycles (see Figure 7). Some are new or as good as new, while others have already been reused or recycled once, or several times, before. The only thing that matters, however, is that they can be returned to their cycles when the Unit is dismantled. This is not just for the sake of the building's occupants, but also for the benefit of the planet as a whole—today, tomorrow, and for many centuries to come.

Case Study 2: Aktivhaus Units

The German town of Winnenden was looking for a quick way to accommodate around 200 people on a plot of land at the edge of an existing residential area. The proposed housing estate needed to include a number of individual residential units, each with its own private bathroom and kitchen. As well as being economically viable and suitable for conversion in the future, it was important that the structures also comply

Figure 5. Rendering of the adaptive high-rise structure currently being built on the university campus in Stuttgart. © Institute for Lightweight Structures and Conceptual Design (ILEK) / Institute for Engineering Design and Industrial Design (IKTD)

Figure 6. Urban Mining and Recycling (UMAR) is part of the Swiss experimental building campus in Dübendorf near Zurich. © Zooey Braun

Figure 7. Selection of the recycled materials used for UMAR. © René Müller

with sustainability standards regarding energy consumption and their potential for dismantling after use. Thus, a modular approach was one obvious solution. Modular construction methods have been researched and used in Europe and the United States for several decades; however, in Germany and other countries they are often still seen as a solution providing less quality than regular construction. Moreover, they are rarely used for multi-occupancies. This is now slowly changing, not least because of exemplary projects as the Aktivhaus Estate built near Stuttgart in Germany. A total of 38 modules were deployed (see Figure 8). The units typically feature a gross floor area of 45 square meters or 60 square meters. They offer enough space for one or two bedrooms respectively—a kitchen and a bathroom.

All Aktivhaus units were made of ecological building materials—primarily wood and other renewable resources. Their elaborate design enables a clean and thorough separation of the constituent raw materials at a later date. Each Aktivhaus module was prefabricated, tested and checked before it left the plant. The modules were delivered with all their interior fittings completely installed—including kitchens, bathrooms and lighting—so they were ready to be lived in straight away.

The Aktivhaus modules were built in a lightweight timber frame construction and were stacked to a height of two stories on a gently rising plot of land that enjoys views of the neighboring vineyards. In addition to adapting the arrangement of the buildings to the topography of the site and the urban setting, it was also vital to design the exterior spaces in such a way that the surroundings would be just as pleasant for the residents to spend time in as the interiors of the structures themselves. The modules are intended to be used for approximately three years as longer-term accommodation for refugees fleeing the Syrian civil war. They can easily be converted into social housing units at the end of this period by carrying out a handful of internal modifications. Next to the residential units, the project also includes a technology module, two community rooms and a multifunctional space that contains equipment such as washing machines and dryers.

The modular design is not only beneficial to the building process, but, by extension, the dismantling process as well. A wasteful and destructive demolition process can be replaced by a non-destructive process of dismantling and sorting of the different materials used in the building. This suitability for deconstruction was considered right at the beginning of the planning phase and is an integral part of a conscious understanding of the built environment as an ephemera, comparable to a guest staying temporarily in his present environment.

Case Study 3: Recycled Concrete

The usage of recycled concrete is not completely new—recycled concrete aggregate (RCA) is already used as granular fill, base and sub-base material, or as aggregate in new concrete pavement or airport runways. However, for load-bearing elements, recycled concrete (RC concrete) has so far only been used to a limited extent—even though there exist normative principles, as well as a clear ecological advantage for using recycled concrete in load-bearing components.

The ecological advantages are obvious. Above all, the protection of gravel deposits and landfill capacities plays an important role. Since the production of recycled aggregates consumes about as much energy as the extraction of natural gravel, transport routes play an important role in the energy and CO_2 balance sheets of RC concrete. The building rubble required for the extraction of RC concrete typically accumulates "locally" in the immediate urban environment—and therefore requires only relatively short transport distances. The composition of RC concrete essentially corresponds to that of normal concrete, even the amount of cement in RC concrete is not higher than that in normal concrete (although this is still claimed in some publications).

An example project in which RC concrete was used extensively in Germany is the five-story new district building in Ludwigsburg, planned by the Berlin office Kubeneck Architekten in cooperation with Werner Sobek as structural engineer. In this building, all ceilings and walls were made of RC concrete in quality C30/37, many of them in exposed concrete quality. Only the columns required a higher concrete strength, so that they were constructed in conventional concrete.

Case Study 4: Urban Refurbishment

Just as important as the use of recycled materials in new construction projects is to first check whether a new construction is necessary at all. Often the renovation and redesign of existing buildings is ecologically more sensible than the construction of a new building. Repurposing of existing buildings, especially of inner urban and tall buildings, is therefore an adequate method and has been applied all over the world. An example where this aspect was discussed

Figure 8. The Aktivhaus development near Stuttgart. © Zooey Braun

Figure 9. **B95, Munich—the refurbishment of an existing building allowed for a massive reduction in the consumption of building materials.** © Rainer Viertlböck

in detail and where the decision was made to refurbish a building on the basis of its ecological advantages is the Munich Re project B95 at Berliner Strasse 95 in Munich (see Figure 9). The building, erected in the 1980s, was recycled based on plans by Sauerbruch Hutton Architekten in collaboration with Werner Sobek. In addition to renewing the façade, the floor plans were redesigned, ceilings were cut back to a small extent and new ones added, so that after renovation the building was of the same quality as a new building. Compared to a new building, 19,000 square meters of concrete and 3,325 tons of reinforcement steel were saved. The pure cost savings amounted to six million euros, which was about 10 percent of the total project costs. The savings of 37.6 million kWa of embodied energy was much more significant and therefore motivating for the client.

Another example of radical refurbishment and thus cost and embodied energy savings is the River Park Tower currently being planned by architect Ole Scheeren. Here, an office building is being converted into a residential building. For this purpose, technical stories will be demolished and replaced by new stories, but the substance of the core structure and office floors will be retained (see Figure 10). A total of 10,000 cubic meters of the original 24,900 cubic meters of concrete from the existing building will be demolished and 23,000 cubic meters added but compared to a complete new building this still means a savings of 40 percent of the material—and this with a complete change in all floor plans and uses.

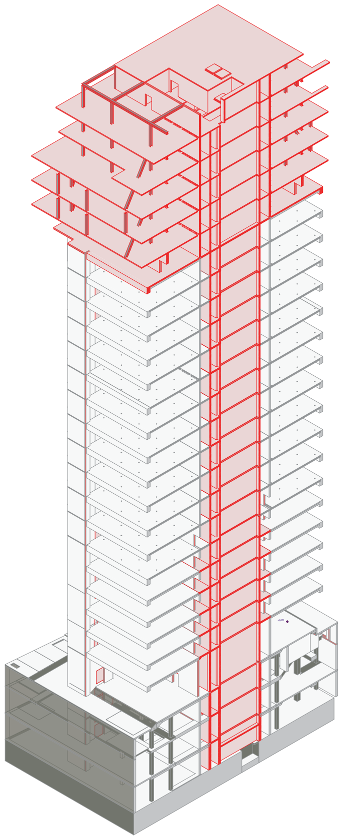

Figure 10. Isometric drawing of a tower refurbishment, with the addition in red.
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