

# RE:STOCK INDUSTRY: DIGITAL FRAMEWORK FOR THE CIRCULAR REUSE OF EXISTING STRUCTURES FOR VERTICAL PRODUCTION

Julia Reisinger<sup>1</sup>, Maria Antonia Zahlbruckner<sup>1</sup>, Peter Kán<sup>2</sup>, Iana Podkosova<sup>2</sup>, Hannes Kaufmann<sup>2</sup> and Iva Kovacic<sup>1</sup>

<sup>1</sup> Institute of Building and Industrial Construction, TU Wien, Austria

<sup>2</sup> Institute of Visual Computing and Human-Centered Technology, TU Wien, Austria

## Abstract

Despite numerous existing vacant industrial buildings and vast unused brownfield land, new production settlements are rarely integrated within existing structures. This paper presents the RE:STOCK INDUSTRY framework, aiming to develop a method for assessing the reuse potential of industrial structures, focusing on vertical expansion and circular economy principles. Utilizing scanning and photogrammetry data, a novel AI method will generate as-built FEM models for structural analysis and prediction of retrofitting measures under vertical expansion. An augmented reality app will aid visualization and decision-making on-site. Innovatively combining AI, computational structural design and AR, the project advocates sustainable reuse, reducing reliance on recycling or disposal.

## Introduction

Industry accounts for 30% of Austrian economic growth (Bolen, 2022), with over 1,000 new industrial enterprises annually (Statistik Austria, 2022a). There are more than 82,200 industrial and warehouse buildings, with over 1,000 new construction permits granted each year (Statistik Austria, 2022b,c). The significant land sealing resulting from horizontal production and storage processes is a problem: Austria has approximately 20,000 hectares of unused, derelict industrial and commercial areas (Enzinger, 2017), and up to 6,000 commercially or industrially pre-used buildings with potential for reuse (Janitsch, 2022). Companies and municipalities that want to relocate businesses are faced with the challenge of securing space for the expansion or relocation of production, warehousing and logistics (Lasi et.al, 2014, Vajna, 2014), but too rarely integrate these into existing buildings. Cost- and time-efficient concepts for integrating new production and logistic uses into existing buildings and solutions for vertical production processes must also be developed to relocate production back to Europe while minimizing new land sealing.

The potential of a building for reuse and vertical upgrading depends heavily on the actual condition of the load-bearing structure, as it must be able to cope with the new loads and space requirements. Information on the material and structural composition, the condition, the pollutant and contaminant content, and, consequently, the effective load-bearing capacity and serviceability of the existing structure for conversion and new use is often lacking. In addition, most building owners do not see their existing building stock as a valuable material resource

bank: existing structures are usually demolished and rebuilt, which increases the volume of waste and landfill, leaves valuable substances unused and results in increased resource and energy consumption.

The current challenge in evaluating the existing structural stock regarding its reuse capability is to accurately digitize, model and analyze the actual structural building stock and make it accessible to the life cycle-oriented economy. The creation of digital analytical as-built models using the finite element method (FEM) for structural analysis of existing structures is currently a predominantly manual, time-consuming, and error-prone process.

This paper deals with the question: "Which methods and technologies are suitable for digitally recording and documenting the structural properties and material composition of the existing building stock and evaluating its reuse, modernization and upgrading potential for vertical industrial uses from a circular economy perspective?"

The research is conducted within the research project RE:STOCK INDUSTRY, funded by the Austrian Research Promotion Agency FFG. The overall goal of the project is to reuse the existing load-bearing structures of industrial buildings in a targeted manner for new settlements, expansions, or conversions instead of resorting to recycling or disposal processes. Through innovative vertical production concepts and their integration into structural analysis, new soil sealing is to be avoided and the service life extended by reusing the building structure. In the research, missing automated methods for scan to FEM using artificial intelligence (AI) algorithms will be developed and innovative approaches for vertical retrofitting of industrial buildings and customized concepts for vertical production and storage processes in existing buildings researched. An interactive augmented reality (AR) application will enable the visualization of reuse concepts with real-time feedback directly at the construction site and it will aim at motivating planners and building owners to upgrade instead of demolishing and new construction.

This paper presents the RE:STOCK INDUSTRY methodology and framework. The paper is structured as follows: A state-of-the-art review presents existing work on Scan to FEM, Vertical production, Re-use assessment models and AR technologies for retrofitting purposes. The next section describes the research design and methodology followed by the presentation and description of the RE:STOCK INDUSTRY framework. Within the

conclusion potentials and challenges of the research are discussed and future research steps highlighted.

## State-of-the-art

### Scan to FEM

Structural analysis models are essential for the reuse of industrial buildings. The level of knowledge about the load-bearing capacity and serviceability of existing buildings is currently achieved through extensive plan studies, former available structural calculations, and on-site inspections, followed by the creation of simplified digital twins or 2D plans. Digital as-built building modeling often focuses on scan-to-BIM approaches. Researchers are investigating the reconstruction of 3D building models for material quality analysis (Paral et al., 2021), structural analysis (Alfio et al., 2022) or reconstruction from point cloud data (Poullis, 2013). However, methods for the parametric representation of 3D models for FEM analysis out of scans are lacking. Scan to FEM is often investigated in architectural cases for historical buildings (Alfio et al., 2022, Barazzetti et al., 2015). Others include manual identification of properties for a procedural model to reconstruct geometric structures from point clouds (Funari et al., 2021), estimate elastic parameters of beams from point clouds (Riveiro et al., 2018), or detect cracks in reinforced concrete to ensure stability (Yu et al., 2021). Automatic methods for the recognition of cylinders in point clouds for the reconstruction of plants (Liu et al., 2013), FEM mesh structures for the numerical analysis of tunnels from point clouds (Cui et al., 2023), or the assignment of a B-spline representation to a point cloud for the purpose of FEM analysis (Xu and Neumann, 2020) are being investigated. Semi-automated methods for converting point clouds to BIM and using them for structural analysis (Rolin et al., 2019) or machine learning for monitoring the structural condition of buildings (Mishra, 2020) are used. The combination of point clouds with image data allows parts of point clouds to be segmented and classified as known classes of structural elements (Barrile et al., 2019). Most of the existing methods require manual intervention or work semi-automatically.

### Vertical production

A third of Vienna's added value comes from production. STEP2025 addresses the future of the productive sector and advocates sufficient space for trade and industry (Rosenberger et al., 2017). Vertical production, involving the multi-storey use of buildings for the production of goods, can reduce the space required for trade and industry and requires efficient material flows across several levels (Hompel et al., 2018). VERTICALurbanFACTORY explores stacked functions and vertical production for efficient space utilization (Haselsteiner et al., 2019). Haselsteiner et al. (2020) show utilization scenarios for different building types to implement vertical production. Vertical production and logistics solutions are already established in densely

populated regions such as Singapore and Hong Kong (Kuznetsova et al., 2018, Low et al., 2015). Vertical production concepts are being investigated in algorithmic optimization of material flows in a layout (Ahmadi et al., 2017, Karateke et al., 2022). Others are researching adaptive reuse of industrial buildings regarding critical factors (Vardopoulos, 2019) or for residential purposes (Glumac and Islam (2020)). The integration of 3D utilization concepts into structural analysis can be enabled by spatial zoning methods, reaction grammars and parametric planning methods (Claessens et al., 2020, Boonstra et al., 2020, Reisinger et al., 2022). To the best of our knowledge, a methodology that considers the effects of multi-story production in structural analysis has not been widely researched.

### Re-use assessment models and resource passports

The uncertainty in predicting the future use of materials and buildings is a challenge in circular economy approaches (De Wolf et al., 2020). BIM4eco is developing a web tool that automatically imports BIM information of a building model in early phases into a life cycle assessment program, records it component by component and calculates environmental impacts (SOLID, 2022). Reuse-Life Cycle Assessment (Escamilla, 2023) analyzes the potential for reducing the environmental impact of reusing materials in buildings. In Build-Re-Use (Lead AEE, 2022), basic principles for the construction and dismantling of buildings with short utilization cycles - supermarkets, office buildings, interim buildings, sanitary facilities - are developed. The buildings are constructed with reusable components and can be dismantled and returned after use. Gebäudepass (Umweltbundesamt, 2013) is developing the basis for the standardization of building passports as building material information systems. M-DAB (2019) uses BIM-based digital technologies to digitize, analyze and sustainably manage the city's material resources. BAMB, (2020) aims to involve the construction industry in the circular economy and increase the value of used materials. PlattformCB'23 (2023) has created a guideline for the circular economy, circular tenders, and future reuse. Existing digital material register platforms (Madaster, 2024, Concular, 2024, Rosen, 2024, EcoDesign Circle, 2023) document the products and materials used in buildings in terms of quality and quantity and enable the creation of building resource passports. The focus is on circularity, the environment, life cycle assessment and financial evaluation. Raw material utilization is mapped in Madaster and status descriptions are possible in the form of certificates and archive documents. The RhinoCircular (Heisel, 2021) and Phoenix (EPFL, 2024) tools deal with structural components and parameters relevant to the circular economy. There are few approaches for documenting and assessing the load-bearing capacity and serviceability of existing buildings for new use. Re-use assessment and documentation methods often focus on materials, elements, compounds, and chemical constituents. Structural aspects are

neglected, and the focus is primarily on recycling and deconstruct ability. RE:STOCK INDUSTRY is investigating ways of evaluating and documenting structural information relating to the reusability of the building.

### Augmented Reality for retrofitting measures

One of the main advantages of AR is situated visualization, where the simulated content is closely linked to the environment and decision-making processes are supported by facilitating the calculation and understanding of domain knowledge (Martins et al., 2022). In the construction industry, AR is used in education for on-site training (Tan et al., 2022) and quality testing of HVAC systems (Schrantz et al., 2021). GAMMA AR (Gramma, 2024) is used for construction site monitoring and documentation with BIM. The combined use of BIM and AR is gaining increasing interest. AR enables the display of BIM elements directly in the building to make annotations or show hidden installations (Chai et al., 2019, Urban et al., 2019, Hugo Silva et al., 2021). When displayed on AR glasses, the addition of AR data enables hands-free exploration of the built structure. The use of AR for interactive finite element analysis has also been investigated (Huang et al., 2017, Huang et al., 2023). The research methods in which conversion and retrofitting options of buildings can be visualized as scenarios on site within AR are sparse.

### Research Design and Methodology

The research objective is to develop a framework for the end-to-end digital recording, modeling, and analysis of the load-bearing stock of industrial buildings for circular re-use and vertical expansion. The potential for reuse, modernization and upgrading in vertical extensions, considering circular economy aspects, should be determined, and recorded by documenting structure-specific information in resource passports and material registers. Through efficient visualization stakeholders should be able to foresee vertical retrofitting possibilities including modernization measures directly on the construction site and to have an assessment model which evaluates the planned retrofitting measures in comparison to demolition and new construction through ecological and economic assessment.

Figure 1 shows the research design of the project for the method and framework development. The data collection and method development are based on industrial buildings in steel and reinforced concrete skeleton construction, as 80% of the industrial building stock consists of these types of structures. Ten buildings in Austria with different geometries and structural systems are defined as use cases. The existing buildings will be captured using scanning and photogrammetry, on-site inspections by experts with knowledge of deconstruction and structural retrofitting and supplemented by the analysis of planning documentation. During the inspection, contaminated elements and damages will also be digitally recorded and localized.

In the first step, two novel methods for automated generation of the analytical as-built FEM model by coupling point clouds and image data with AI algorithms will be researched and developed: a.) Reconstruction of the parametric FEM model from 3D point clouds by heuristic optimization methods. The reconstructed model will contain information on the geometry, material and condition of the existing structure. A digital process enables the integration of additional information on damage assessment, detailed material properties such as material grades and contaminants. b.) Development of a deep neural network (DNN) for the automated recognition of structural joint connections from geometric and image data. Real as well as synthetic data from existing use cases and BIM models will be used to train the DNN.

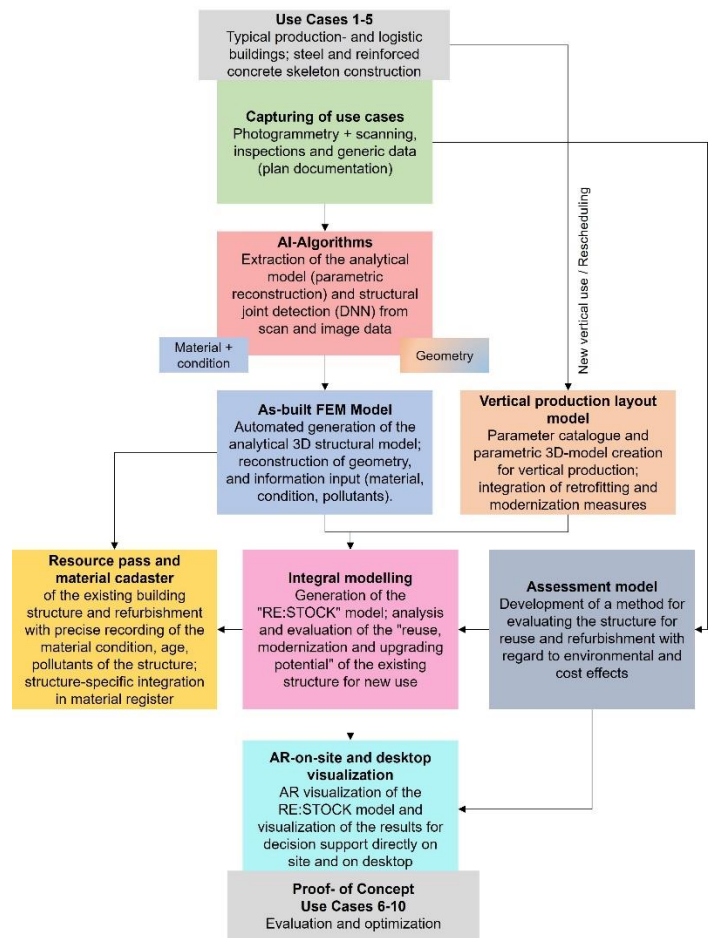


Figure 1: The research design and methodology of RE:STOCK INDUSTRY

Furthermore, vertical production and modernization concepts for integration into structural analysis processes are researched to quickly determine the load-bearing and strengthening capacity of the existing building for new use: By analyzing use cases, best practice, literature and interviews, requirements and processes for vertical production, the dependencies with the supporting structure and modernization concepts for vertical strengthening are defined, documented in a catalog of requirements and transferred into parametric planning

rules. Developments from the authors previous research (Reisinger et al., 2022), in which a concept for the integration of 2D horizontal production processes into structural design was developed, serve as the basis for the development of the parametric RE:STOCK model, which couples the as-built FEM model with 3D vertical production concepts.

To integrate circular economy aspects into the analysis of existing structures two methods are being researched: a) Development of a method for evaluating the reuse and retrofitting of load-bearing structures. Clear evaluation criteria for reuse and retrofitting, such as environmental and cost effects, quality, functionality, and technical feasibility, are defined and integrated into existing methods of ecological and economic life cycle analysis in order to take specific reuse requirements into account. The aim is to use the RE:STOCK model to compare the existing structure including retrofitting with demolition and new construction scenarios and to compare their environmental impacts and costs. b) Development of a method to efficiently document the digitized inventory and retrofitting planning in building resource passports and material registers. This is done by analyzing available databases and cadasters and standardizing data and interfaces with the RE:STOCK model. As a result, detailed structural information such as material composition, quantity, load-bearing capacity, condition, year of construction and pollutant content can be efficiently recorded.

Finally, a method for integrating AR technology as a visual decision support tool for planners and clients into the early retrofitting process will be researched. The aim is to visualize the effects of reusing the structure, the vertical strengthening and the ecological and economic evaluation feedback directly on the construction site. The proof-of concept will be conducted on real use cases and validated with experts.

### RE:STOCK INDUSTRY framework

The RE:STOCK INDUSTRY framework will integrate all of the aforementioned research developments into a digital platform to guarantee a holistic planning process and decision support tool for early re-use, expansion and retrofitting processes. The framework aids to automatically generate accurate FEM models of the building structure inventory from point clouds and photogrammetry data and document the structure-specific information in resource passports. A computational tool, the RE:STOCK model, will generate re-use plans of the existing structure for vertical upgrades and evaluate them from a circular economy perspective. By linking an AR method to the integral RE:STOCK model, the visualization of possible expansion and reinforcement measures will be displayed directly on site in the existing building.

Figure 2 shows the framework of RE:STOCK Industry and the most relevant developments with the parametric RE:STOCK Model (6) as the central part:

*1 and 2 - Scan Data to as-built FEM Model:* An as-built FEM model will be generated out of received point clouds and photogrammetry data and enriched with the exact geometry and material properties. Optimization-based techniques will be used to reconstruct the main shape of vertical and horizontal structural elements and their parameters (e.g. size, thickness). The elements will be initialized by heuristic search for vertical and horizontal point beams and the parameters of the model will be optimized to fit the scanned point cloud. Deep learning will be used with geometry and image data to classify the joint connections of the structural elements and describe their properties in relation to the connected elements. The neural network will be trained with real and synthetic data from existing use cases and BIMs. The recognized joint connections and status descriptions will be added to the parametric model to enable the structural analysis in the as-built FEM model. The proposed algorithms will significantly accelerate the as-built analysis of skeleton constructions. This model can be used not only for traditional structural analysis but also for cycle-oriented documentation and evaluation of the re-use capability of the structure.

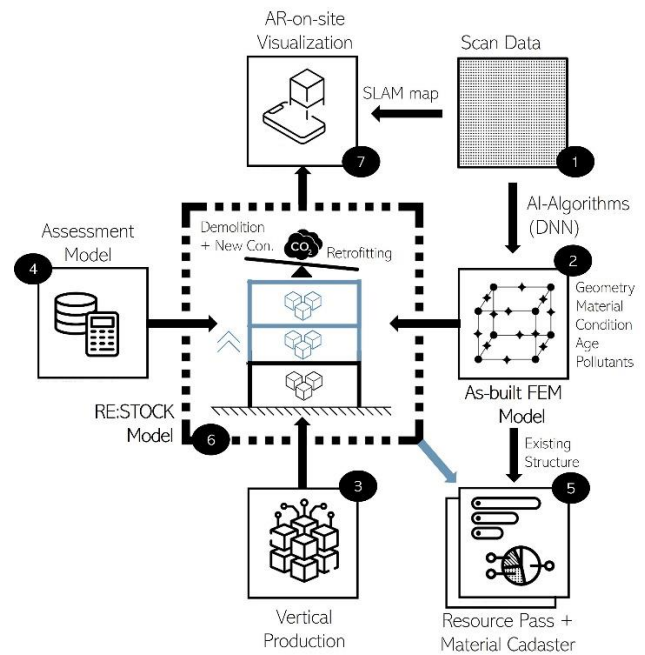


Figure 2: The RE:STOCK INDUSTRY framework

*3 - Vertical Production:* The goal is to create a 3D-layout generator for vertical production planning. Requirements and processes for vertical production as well as modernization concepts for structural vertical upgrading are defined, documented in a catalog of requirements and transferred into parametric planning rules. Parametric methods from the previous developed 2D production layout generator (Reisinger et al., 2022) are used to develop the vertical 3D layout model. For the integral RE:STOCK model, the as-built FEM model is extended

with the vertical production layout model through parametric and generative design methods.

*4 and 5 - Assessment Model and Resource Pass + Material Cadaster:* The interfaces to existing material registers and resource passports are examined so that relevant structural information from the RE:STOCK model can be transferred and recorded in material passports and building cadasters. An ecological-economic method will be developed to evaluate the reusability of the structure in terms of retrofitting vs. demolition/new construction. For this purpose, qualitative and quantitative sustainability principles (life cycle assessment, circular construction, adaptability, preservation of existing buildings, CO<sub>2</sub> storage capacity, reusable structure, legal and technical feasibility) are defined. The method integrates ecological and economic life cycle analyses to determine the gray energy of the existing building, CO<sub>2</sub> savings through structural preservation, and the evaluation of retrofitting measures to promote reuse instead of demolition/new construction. Argumentation aids and proposed solutions, such as CO<sub>2</sub> pricing and climate impact costs, will be included, so that not primarily the option with the lowest costs is chosen.

*7 - AR-on-site Visualization:* For this purpose, the RE:STOCK model will be integrated into a specially developed situated AR application. On site, the model will be aligned with the real building by locally comparing the initial point cloud scan - from which the RE:STOCK model was generated - with the sparse point cloud provided by the AR device. The registration between original scanned point cloud and the point cloud provided by the AR device will be achieved using iterative closest point algorithm (Besl and McKay, 1992). Once the RE:STOCK model has been aligned with the real building, the AR view is correctly updated in perspective as the user walks around using Simultaneous Localization and Mapping (SLAM).

## Conclusion

The presented digital framework for the circular reuse of existing industrial building structures for vertical production addresses industrial companies, builders and architects, production and structural engineers or life cycle management stakeholders. By digitally capturing the structural stock and assessing and visualizing the retrofit potential using the AR visualization approach, stakeholders should be motivated to reuse the building stock as it is, increase its value through vertical retrofit measures and extend the life of their buildings. The research promotes vertical production and logistic processes, optimizes operations and resource utilization, and maximizes business efficiency and productivity. The automation and standardization of the data basis for the structural stock of industrial buildings is essential for the long-term optimization and permanent monitoring of building waste management, whereby the central linking and provision of structural data with building geometry information plays a key role for numerous other fields of research and applications. The methods to be developed

aim to avoid manual, error-prone processes in inventory recording and modeling as well as lengthy iterations in interdisciplinary planning processes. Integral analysis and evaluation can be expected to lower the inhibition threshold for stakeholders to make changes and investments in their buildings and production facilities. The methods will enable sustainable structural modernization under vertical use and lead to an extension of the building's service life and avoidance of soil sealing. Land recycling enables the resettlement and return of production companies from surrounding areas and abroad. By upgrading populated areas, economic added value is achieved, and social structures and workplace situations are expected to be improved. The methods should reduce the ecological impact by up to 50% and waste volumes by up to 70%, this will be examined in a case-study of real industrial buildings.

In the context of the presented study several limitations need attention in future scientific research. The framework's applicability is currently focused on the specific building type of industrial skeleton construction and the geographic region of Austria, necessitating further research to evaluate its generalizability across diverse contexts and construction practices. Furthermore, the framework relies heavily on emerging technologies such as AI, AR, and novel structural analysis methods, whose interoperability and integration into existing systems need to be fully explored. The quality of input data—scanning, photogrammetry, material properties, and structural details—directly influences the framework's output accuracy, highlighting the need for rigorous validation and sensitivity analyses in future. Economic viability, encompassing lifecycle cost analysis need to consider dynamic market conditions, which poses to be challenging. Regulatory, legal, and policy barriers present additional impediments to practical adoption, which highlights the importance of in-depth analysis and close work with municipalities to identify ways for regulatory reform and policy advocacy. A holistic environmental impact assessment extending beyond the CO<sub>2</sub> emissions and waste reduction of the structural system but to include environmental impacts of the whole building systems as facades and built in components will be crucial for understanding the full environmental footprint. The project solely focuses on the resource efficiency of the structure to avoid CO<sub>2</sub>-equivalent emissions; however, energy efficiency is not addressed. Lastly, the technological and methodological advancements proposed necessitate a change in traditional practices among stakeholders in the planning and construction industry. The adoption of such new technologies and methods is influenced by behavioral factors, including perceived utility, ease of use, and cultural aspects and will be respected in user studies with practitioners and students on real use-cases.

With a focus on industrial and logistic buildings, the results of this project will be also beneficial for numerous

planning areas that require (automated) recording and evaluation of existing buildings for new use in long term.

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