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From Grasshopper to finite element analysis: A parametric workflow for metro station design

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ABSTRACT: The design of metro stations typically follows standardized layouts and principles. However, achieving an optimal and sustainable design still requires of multiple iterations. Engineers continuously face design changes under tight deadlines, performing repetitive tasks to reach the optimal solution, resulting in an inefficient and slow process with a substantial investment of time in manual operations. Over the past decade, computational and parametric methodologies have become more popular among engineers and architects, becoming key approaches in the design process. The use of parametric models allows designers to deal with complex geometries, generate multiple layout options and optimise the design, all of it with high efficiency. Such capabilities are often beyond the reach of standard and traditional manual approaches. This paper presents a parametric workflow, developed to streamline metro station designs, applied to a case study. Geometric data is collected in a user-friendly environment and automatically processed into a model ready for analysis and design, reducing the manual effort and improving efficiency. The workflow has been successfully implemented in the reference design for Copenhagen's future metro line, designed to be significantly more environmentally sustainable than previous metro lines in the city. Many iterations have been necessary to design the underground stations as shallow as possible, reducing the use of concrete and consequently minimizing CO2 emissions. These tools have provided quick responses to continuous design modifications, contributing to a more sustainable design process.

1 INTRODUCTION

1.1 *Background*

Nowadays, urban areas are becoming more complex due to population growth, higher density, and the integration of multiples infrastructures within very limited space. At the same time, sustainability targets are becoming more demanding, requiring designers to minimize energy consumption, reduce environmental impacts, and optimize resource use throughout the project lifecycle. With these new requirements, engineers need to face these challenges, providing efficient solutions under tight deadlines. The traditional approach, defined by repetitive manual tasks when dealing with the design changes, often limits efficiency, quality, and competitiveness.

Parametric design has been a game-changing method that enables iterative procedures to towards more optimized designs. By using a parametric design, engineers can create models

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that rely on adjustable variables, such as dimensions, materials, and properties, that can be modified to meet specific needs and fuse interfaces coordination in reduced time. This approach allows designers to quickly assess different design options and adapt them to specific project requirements, saving much time and effort in designing.

Metro stations, despite their location and context, typically share common design principles that guide both architectural and structural decisions. Elements such as platforms, tunnels, entrances, and ventilation systems usually follow similar patterns according to safety codes, passenger flow needs and building conditions. Likewise, structural elements behave in similar ways, as the loads on a station are alike and distributed consistently throughout the structure. This consistency across projects provides a unique opportunity to parametrize the fundamental principles of the designs, making them more flexible while improving efficiency and quality.

1.2 *Aim and scope*

The aim of this paper is to present a workflow for designing a metro station through parametric modeling techniques to improve efficiency, flexibility, and work quality. This workflow is specifically designed to have a better respond to the growing challenges of a competitive market, allowing designers to address effectively the project requirements while promoting sustainable design goals. This approach can be applied throughout different phases of the project, from input specification to report generation, with particular emphasis on the creation of a fully automated analytical model. It also plays an important role in supporting key decision-making, allowing engineers and architects to evaluate multiple design alternatives quickly and ensure compliance with technical, regulatory, and sustainability standards.

1.3 *Assumptions, limitations and future developments*

The workflow developed to assess metro station designs is based on the following assumptions and limitations:

- Metro stations share common architectural and structural principles, with similar layouts and consistent structural behavior and construction methodology.
- The analytical model is mainly focused on structural elements, while the integration of architectural, mechanical, and electrical systems may require additional customization.
- Circular or irregular layouts are not supported.
- Retaining walls, such as secant piles or diaphragm walls, are excluded from the design.
- Post-tensioned cables are not considered within the current version due to their complexity and limited use in the type of metro stations analyzed.
- Soil interaction is simplified by the application of nonlinear springs on the lining walls.
- The workflow uses international units (SI) and follows the Eurocode standard.

The workflow is designed to be extensible, allowing future improvements to be easily incorporated. Planned future developments include:

- Integration of retaining wall systems to better capture the interaction between the soil and the structure, allowing a comparison with geotechnical analysis results.
- Implementation of construction stages to provide a more detailed model.

By improving the model, these extensions will lead to more reliable results to support decisions in later stages of the project.

2 METHODOLOGY

The current design workflow combines different software such as Excel, Grasshopper, and SOFiSTiK into one parametric process, enabling repeatable and efficient design options.

Figure 1. Overview of the computational workflow.

2.1 *Data input and management*

All the project inputs are collected and stored in one place, an excel-based interface, which is used as a Single Point Of Truth (SPOT) for the workflow. This approach ensures data consistency, reduces the risk of errors that can occur when information comes from multiple sources, and provides clear traceability from the early stages of the project. Excel was chosen as a data layer because it is widely known across the roles of a multidisciplinary project and offers clear, easy-to-use graphical displays.

The interface is divided into several tabs that guide the user through the process of defining the station step by step. The process starts by filling in the metadata and material properties, continues with defining the grid layout, and concludes with the main structural elements such as slabs, beams, columns, and lining walls. Each tab is structured to guide the user through the Excel interface in a clear and intuitive way.

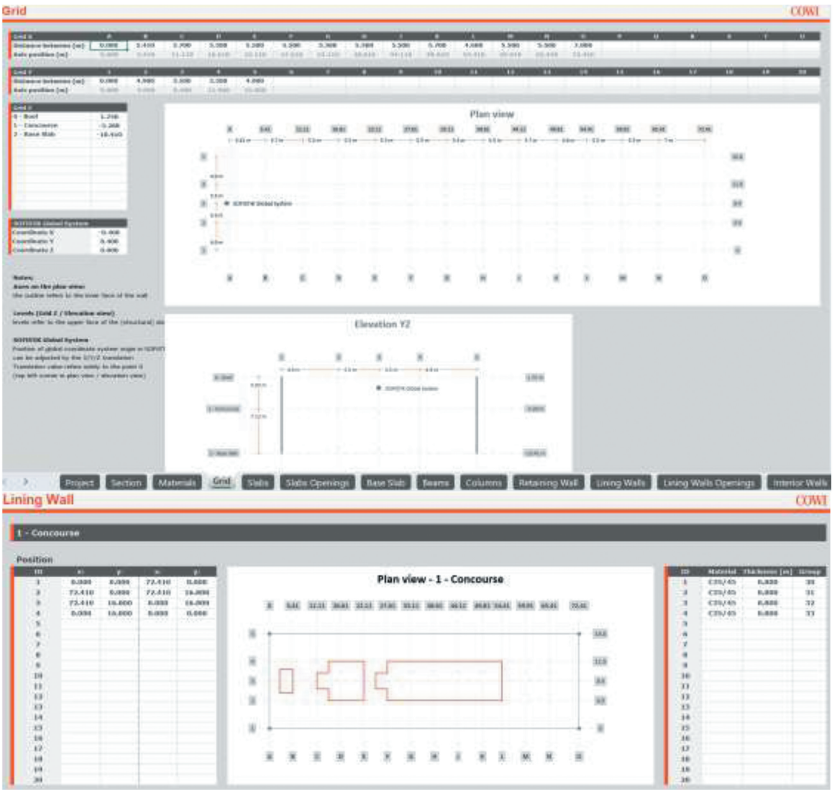

Figure 2. Excel-based interfaced use as a single point of truth (SPOT) in the workflow.

Once all the data is filled, it is exported as a single structured JSON file by using a Visual Basic script. Storing all the station information in one file maintains the concept of a single source of truth, keeping the data aligned with the initial inputs. This format was chosen because it is lightweight, can organize complex hierarchical data, and can be read by many different software tools. This also allows the same file to be used as a starting point for other applications, such as geotechnical analyses, while preserving the integrity and consistency of the data throughout the project.

2.2 *Parametric geometry model*

To postprocess all the data coming from SPOT, Grasshopper was chosen. This visual programming software integrated within Rhino 3D is well known for its flexibility, intuitive interface, and interoperability with other software.

The Grasshopper script is structured to provide an intuitive, step-by-step modeling workflow, providing prompts and notifications to the user whenever input data is incomplete or inconsistent and ensuring the integrity of the model from the initial design stages to the final analysis.

It converts input parameters from simple text into fully three-dimensional geometries, creating a 3D model organized by layers that allows engineers to visually inspect the station, check dimensions, materials, and structural elements to ensure that everything is properly defined. To make the workflow more efficient, the script operates with data trees structures to manage the large sets of information coming from the JSON file, allowing a high degree of parametrization (Issa 2019). Figure 3 shows an example of the logic behind the postprocessing used to generate the beam elements.

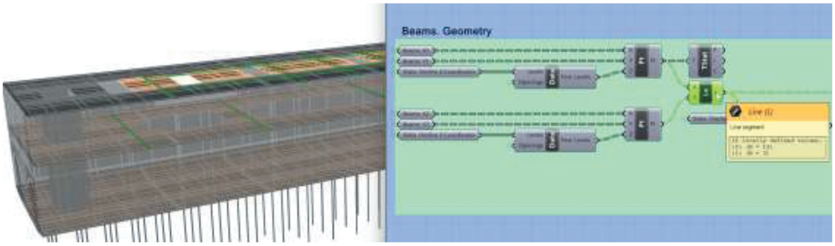

Figure 3. Example of the data tree logic used in Grasshopper to generate beam elements.

The 3D model is built with special consideration to how the structural elements are defined, as the goal is to create an accurate analytical model. The way elements are modeled affects the mesh quality, and a poor mesh will lead to unreliable results, but also can be used for controlling the design in different maturity levels of the model Figure 4 shows the 3D model visualization in the Rhino environment.

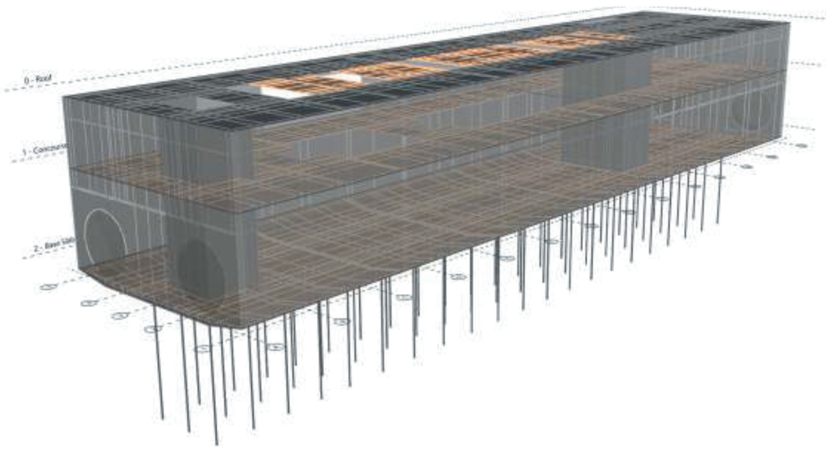

Figure 4. Visualization of a metro station in Rhino, showing the division of the structural elements.

Once the model is verified, Grasshopper exports text files to SOFiSTiK to generate the analytical model, connecting the parametric geometry directly to the structural analysis software.

2.3 *Structural analysis*

The structural analysis of the metro stations is performed by using SOFiSTiK, a software chosen not only because of its capability to execute parametric tasks but also for compatibility with automated workflows (SOFiSTiK AG. 2024).

Grasshopper exports a text file containing the geometry of the metro station, while a separate file defines the loads. Both files are read by CADiNP, the scripting module of SOFiSTiK, which builds the model, applies the loads, and performs the structural analysis. Finally, it generates a detailed report with all the results.

2.3.1 *Modelling approach*

The result from the Grasshopper model consists of a set of structural element geometries with defined divisions, which SOFiSTiK automatically converts into an optimized mesh for analysis.

All the mechanical properties, materials, thicknesses, and section parameters that had originally been defined within the Excel environment are accurately mapped to the corresponding structural elements. The analytical model uses three types of elements: shells, beams, and cables. Walls and slabs are modeled as shells to accurately capture their response to applied loads; beams and columns are modeled as beam elements, and finally, the uplift anchors in the base slab are represented with cable elements.

The SOFiSTiK model is organized into a series of tasks, each simulating a specific step of the analysis and modelling process. These tasks contain parameterized text-based scripts that are made to be generic in a wide range of project circumstances. Core parameters such as load magnitudes, bedding coefficients, and other design parameters are consolidated at the beginning of the process to facilitate modification.

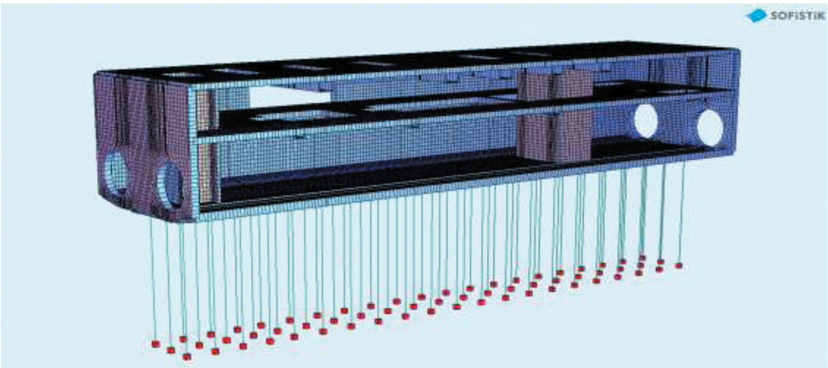

Figure 5. SOFiSTiK SSD overview.

2.3.2 *Loads and analysis*

The load application to the metro station is fully parametrized thanks to the definition of group numbers assigned to the different structural elements. This guarantees that loads automatically adapt to any changes in the geometry of these elements, eliminating the need for manual adjustments. The magnitude of these loads is referred to as a variable parameter to be easily modified as project requirements evolve. A non-linear analysis is performed to accurately model the soil–structure interaction using compression-only springs.

2.3.3 *Reports*

Version control and proper documentation are crucial in iterative workflows with frequent design updates. They ensure that all changes are tracked, design decisions remain transparent, and team members can consistently work with the most up-to-date information. To address this need, automated reporting and version control for the entire project were implemented through a custom-designed script.

By using the script, it became possible to systematically monitor and compare different versions of the project and its development. Generated reports allowed for immediate visual inspection of differences between iterations and maintained a neat record of design progress without having to reopen models or using manual copy-and-paste operations. This approach improved traceability and efficiency, minimized repetitive tasks, and reduced the risk of errors during the review process. Standard reports generated for the project include applied loads, structural forces in shells and beams for each load combination, maximum bending moments and associated axial forces, and reinforcement diagrams.

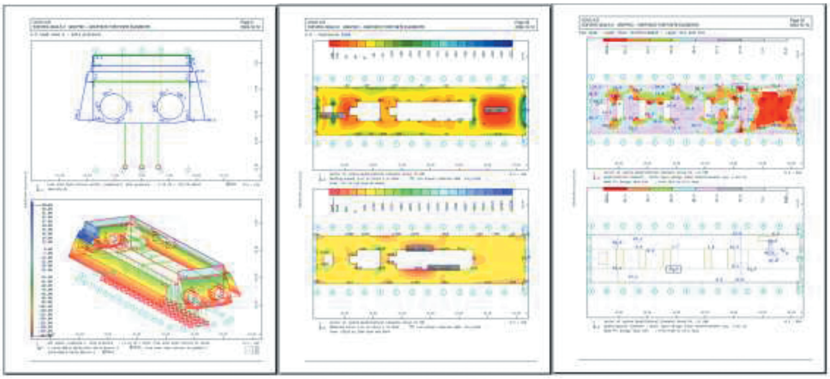

Figure 6. Script output for the reports.

3 CASE STUDY

3.1 *Description*

The current workflow has been applied to the design of the new Copenhagen M5 Metro line.

Figure 7. M5 metro alignment.

The M5 project represents the next major expansion of the Copenhagen Metro network, designed to address the challenges of a growing city and an evolving urban landscape (Metroselskabet. *M5)*.

It will provide efficient public transport to both existing areas that currently do not have metro service such as the Amager area, as well as new urban development, including the east Harbour. The construction is divided into two phases, with expected openings in 2036 and 2045. The first phase consists of five underground stations and one elevated station, running from Copenhagen central station to Lynetteholm, an artificial island which is currently under construction.

The main goal of the M5 is to reduce congestion on the current metro lines, promote sustainable urban development, and improve connectivity in the city, keeping sustainability as a key parameter during the design. The project also prioritizes operational flexibility, future-proofing the system to enable easy upgrades and maintenance, providing high-quality passenger experience. The methodology described in the paper aligns with the project's central objective: placing sustainability at the core of the design. The new metro system is specifically planned to minimize its carbon footprint in comparison to previous lines.

To achieve this, the stations have been designed as shallow as possible, minimizing excavation depth and optimizing the structural layout, in order to reduce material consumption and limit the environmental impact of the construction. Shallower stations require less energy for excavation and logistics, while the reduced use of concrete, a material with a high embodied carbon footprint, directly lowers greenhouse gas emissions. This design approach ensures that optimization for sustainability is embedded in every stage of the project.

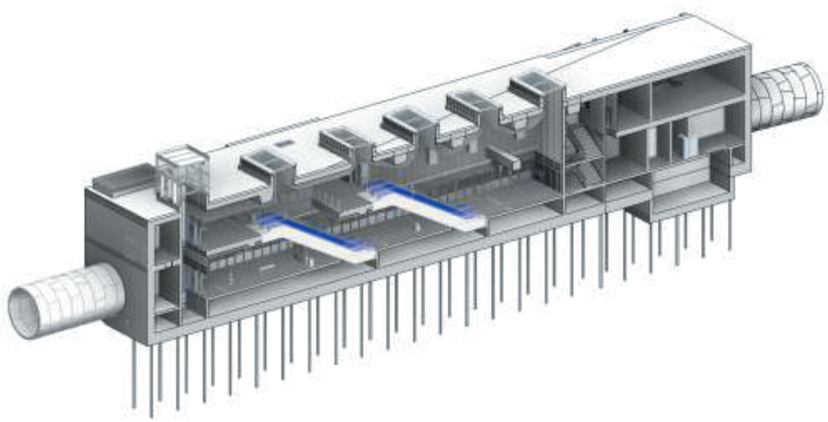

Figure 8. Example of a shallow station.

3.2 *Results*

The implementation of the workflow has significantly accelerated the design process, resulting in substantial time savings when compared to conventional methods. A key advantage was the immediate visualization of the geometrical model within Rhino 3D environment, enabling direct comparison with the architectural concept and facilitating the early identification of potential discrepancies. Throughout the project's development, frequent modifications were required, such as introducing new openings in slabs or adjusting the beam locations. The workflow enabled engineers to quickly adjust element positions by updating coordinates, eliminating manual redrawing, saving time, and reducing the risk of errors during frequent design modifications.

Another advantage was the automated documentation produced by the script, which met key client submission requirements and supported internal quality checks throughout the design phase. The automatically generated reports made it easier for engineers to quickly verify that the model was accurate and aligned with design expectations, providing significant time savings by avoiding repetitive tasks.

4 CONCLUSION

This paper showcased a parametric workflow that automates metro station design, developed to improve efficiency, flexibility, and work quality. The workflow stores all the project inputs in an Excel-based single point of truth (SPOT), generates a 3D model in Grasshopper, and performs a structural analysis in SOFiSTiK producing an automated report with the results. This approach makes design iterations faster, lowers the risk of errors, provides transparency and structure of key interfacing parameters across discipline outlets, and allows engineers to respond quickly to changes, supporting the delivery of a high-quality outcome.

The workflow was successfully applied to a shallow, rectangular metro station for Copenhagen's M5 line. It is flexible enough to accommodate a wide variety of station types and to meet future project needs. Its scalable design supports more complex geometries, additional structural features, and integration with other analysis platforms.

Overall, the workflow goes beyond the case study presented, providing a robust foundation for advanced, efficient, and sustainable infrastructure design.

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