Identifying cost-efficient alternatives to building designs based on building regulations

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Abstract. Fluctuations in the commodity and real estate markets are some examples that challenge architects to constantly adapt to rapidly changing circumstances. In addition, architects are required to match the design of new buildings to the local legal conditions, while at the same time they are expected to balance the budgetary and architectural aspirations of clients. Since the design phase requires significant amount of time and the estimated costs may vary during the design phase, customers frequently either have to spend more money or architects have to take more time to redesign and revise. This paper presents an approach to support architects in the early design stages to identify a matching existing building design for a legally regulated property as inspiration for the upcoming project. This assists in reducing the time required for the design phase and offers the possibility to customise the model considering the current estimated total costs.

1. Introduction

The construction sector is currently facing a number of challenges, including the scarcity of resources and the significant rise in prices on the resource market. On the one hand, the aim of cities and investors is to provide new living and working spaces for the growing population and, on the other hand, to keep costs as low as possible, as current trends in interest rates, inflation and thus the rising living costs are currently increasing rapidly in many countries. (Smith 2016) In addition, the inefficient planning and resource utilisation processes in many regions need to be overcome. For the elaboration of planning, early comparison and customisation of building designs is a major task of architects. It is up to them to match the individual desires of the client with the architectural freedom and their unique brand personality. (Zeiler et al. 2007) Since architects are primarily in the role of employees, their objective is to achieve the best possible and most efficient result for the client (e.g., future owner, investor or municipality).

Planning conditions often regulate the design and construction of new buildings, limiting the freedom of architectural designs in many countries. (Tricker 2022) While there are procedures for estimating costs, the problem arises that they are supposed to be applied after the model has been created. Thus, the architects initial need to develop a model in order to be able to calculate the resulting costs. Alternative designs are usually prepared if the price does not meet the customer's specifications. (Kolltveit and Grønhaug 2004) This process is time-consuming and depends on the current market, whose prices fluctuate due to varying supply and demand. Hence, architects must constantly adapt to changing circumstances and still stay within the legal framework. If a building project does not comply with the legal requirements, this can result in serious legal consequences and high costs for adaptation.

This paper is organised as follows: Section 2 introduces the related works concerning the early design phases with regard to the research background. This includes information on the design decision support and the Variant Management, to customise building elements. Moreover, it provides an overview of the focused legal regulations and their relevance of consideration as well as the cost estimation. Section 3 provides the methodological framework for the identification of cost-efficient alternatives. Section 4 demonstrates the applicability of the developed approach through a real-world case study. Finally, the paper concludes with a summary of the findings and provides suggestions for future research.

2. Background and related works

In recent years, the digitisation of the Architectural Engineering and Construction (AEC) industry has been enhanced by the extensive use of Building Information Modeling (BIM). Thereby, the geometric design is just as important as the stored information on the individual building components and their relationships. As an international standard, Industry Foundation Classes (IFC) support the work in a digital building model and ensure a loss-free exchange of the model's contents between all stakeholders. (Borrmann et al. 2018)

2.1 Design decision support

This paper focuses on the planning of buildings and in particular on the early design phases, which are becoming increasingly important in the AEC industry. They provide an enormous potential for minimising errors and for analysing different building parameters at an early stage, for example with regard to subsequent building performance or cost estimation. Herein, the planning process is determined and the material process can be partially influenced. Exploiting the potential that arises in this phase efficiently creates a basis for the subsequent specialised planning. (Zwikael 2009)

Napps et al. have already presented a decision-tool based on the case-based reasoning process by Aamodt and Plaza that is able to match architects' specified building requirements with similar existing BIM models from a case base in order to adapt and reuse them. (Napps et al. 2021) Here, a graph-based approach is applied to ensure that the comparison of the building parameters of the upcoming project with potential solutions from a database is efficient. This approach is also used by other researchers and is increasingly accepted in the construction industry as it is for example compatible with the IFC structure of the building models. Another facilitator for architects with regard to design decisions is the Variant Management, which was introduced by Mattern and König (Mattern and König 2018) and further developed (Napps et al. 2022). It provides the possibility to categorise components in digital models into three variant types in order to exchange them more easily with a most similar component of the same typ. Structure variants capture elements for relevant changes to the floor plan, function variants are strongly related and enable the categorisation of building elements, that have the same function (e.g. load bearing elements). Product variants have no influence on other building elements and are for example doors and windows in a building. This method allows changings of building components of the same variant type, for example a wooden door with a glass door, or to switch between a load-bearing wall and column under consideration of certain properties. Recent enhancements further address the change in detailing of these variants. (Napps and König 2023) The combination of these approaches thus leads to a graph-based decision tool, whereby architects are able to find similar buildings or building parts to a given project and customise the design and building components according to the client's preferences.

Schwartz et al. introduced a design decision tool to automate the generation of buildings, resulting in an optimal building, in respect of their Life Cycle Carbon Footprint (LCCF) and Life Cycle Costing (LCC). (Schwartz et al. 2021) This similar approach, however, is not considering the legal conditions on site and is not using existing and checked real building models.

2.2 Legal requirements

There are different regulations for the development of building sites in multiple countries, which differ due to the respective planning system, but overlap in many of the regulatory contents as well. In Germany, many legal regulations are restricted in the *Bebauungsplan* (B-Plan). Comparable regulations with some similar consequences for the design of buildings are the *Local Plan* in England, the *Plan local d'urbanisme* in France, the *Bestemmingplan* or *Inpassingsplan* in the Netherlands and the *Zoning Resolution* in the United States of America.

B-Plans in Germany are adopted by the municipalities and the content specifications, which directly affect the planned building are regulated in §9 of the *Federal Building Code* (BauGB 2023). These specifications are specified in the development plans in Germany by the *Building Use Ordinance* (BauNVO 2023). They are therefore legally effective and the development must comply with them. From these legal requirements, the architects then correspondingly design suggestions for a possible development. Furthermore, the Federal Building Code defines exceptions where buildings can be built on without an existing B-Plan. Since planning rights and planning law organisations are very complex and differ from one country to another or even within the country, (Rehfisch et al. 2016) it is not always possible to assign a valid foreign counterpart to the German B-Plan. Some of the plans even differ in their scales and the restrictions on building construction. Germany is quite strict in its specifications, which turns out to be a disadvantage for architectural flexibility, but an advantage for design decisions, as the design is strictly limited in the case there is a B-Plan. In England, for example, the *Planning Permission* and *Building Permission* are important in addition to the Local Plan. In this paper, the term development plan is used to refer to plans that provide regulations regarding building developments. This allows general statements about such plans to be distinguished from specific statements about particular plans. Due to the 2017 introduced XPlanning data standard in Germany, which is mandatory for the digital exchange of the plans, the previous paper form is being obsolete, so that they are increasingly made available digitally by the municipalities. (Fertner et al. 2021) It is very beneficial as it provides the plans publicly accessible and facilitates the extraction of the data from them.

2.3 Cost estimation

To estimate the costs, the DIN 276:2018-12 is applied. Therein project costs are divided into eight cost groups (CG), which in turn can be subdivided into several levels. In the early design phases and the design decisions based on them, cost groups one to three are particularly relevant (CG 100 to CG 300), as they include property costs, preparation and building construction costs. By determining the costs, an assessment of the life cycle costings can be made in subsequent phases. There are currently some applications that can be used to calculate costs according to this method. Nearly none of this software is available free of charge.

In order to estimate costs in the context of BIM for the entire building life cycle, the life cycle costing method (LCC) is frequently utilised. As life cycle costs and environmental impacts are strongly interdependent, the LCC is usually applied in addition to the method for determining the live cycle environmental impact, which provides detailed results of the ecological effects from the phases of production, construction, maintenance and demolition of a building. ISO 15686 describes the requirements and guidelines for performing LCC of buildings and their components. LCC considers all relevant costs incurred from the acquisition through the operation to the disposal. Typically, LCC involves a comparison between design alternatives or an estimate of future costs at the portfolio, project, or component level. (ISO 15686) In particular, by integrating LCC into BIM and combining it with the similar method for recording sustainability over the life cycle of the building, the added design benefit is maximised. The Life Cycle Assessment (LCA) is structured similarly and specified in ISO 14040. (ISO 14040)

Primary identified benefits of linking BIM and LCC are the reduction of costs supported by the use of open standards and comprehensible data visualisations. By combining BIM with LCC, significant LCC savings can be achieved for specific building components or areas. (Rashed et al. 2019) Lammers and Forth focus on the open Industry Foundation Classes in their approach to BIM-LCA/LCC integration. Design variations can be compared by combining relevant information from the IFC model and multiple LCA and LCC databases. (Lammers and Forth 2022) Further Viscuso et al. link the LCC results to visualisation tools in the form of dashboards and detailed coloured 3D models, thus increasing the understanding and accessibility of the information for selecting multiple design alternatives during project design in the context of BIM. (Viscuso et al. 2022)

3. Methodology

In order to provide architects with stronger support and inspiration for the design in the early planning phases, specifically to identify and adapt more cost-efficient alternatives and enable them to use legal input information, a framework was developed. (cf. Figure 1) Thereby architects are able to acquire legal information and conditions in the B-Plan, resulting from a new building site, in order to find matching building models from a database for the development, including their cost estimation. The presented methodology is designed to extend the current version of an existing retrieval tool for similar buildings (Napps and König 2023) and enables additional input options and an increase in its functionality. (cf. Figure 1)

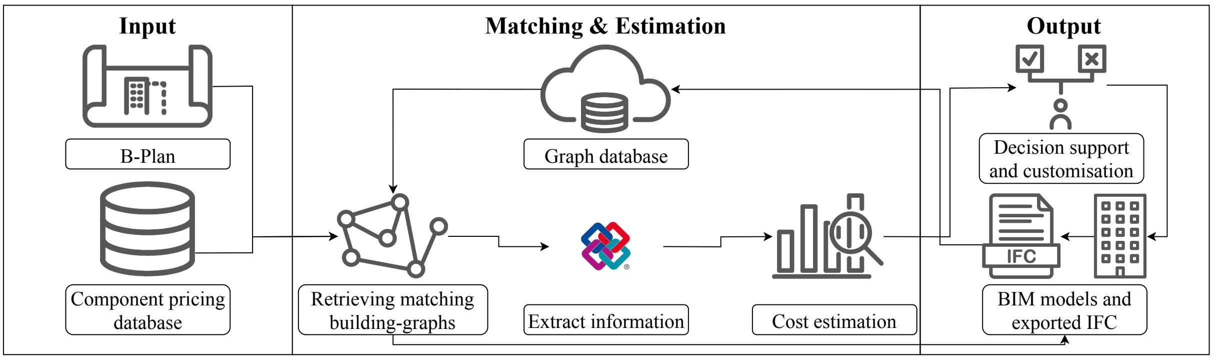


Figure 1: Methodological approach.

The matching process between the information in the B-Plan and suitable models in the database is based on a graphical approach. Thereby, the IFC files of the building models are transformed into a graph representation according to the labeled property graph (LPG) approach and stored in a graph database. In addition to efficient storage, the LPG approach allows fast querying, which is essential for many graph analytical applications. (Purohit et al. 2020) The matching of input parameters or models with existing graphs in the database is performed by matching procedures and developed similarity calculations, varying between 0 (not similar) and 1 (very similar). These process steps, which are necessary for the retrieval process, have already been presented in previous work, allowing them to be reused and extended for the application. The component pricing database contains cost parameters for construction elements and local land prices. For the cost estimation, corresponding information is extracted from the IFC file.

3.1 Processing input data

The presented procedure for retrieving similar buildings is based on the architects making various specifications, which are converted into a search query for the database and subsequently compared with existing buildings in terms of their degree of similarity and accordingly the most similar of these are returned. Making use of information from development plans makes the architect's work easier, as these already contain many input parameters for the future development. This methodology is initially limited to Germany, which is why it is assumed that a B-Plan exists for a specific area. In order to be able to use the information from an existing B-Plan the architects can determine at the beginning of the design process whether it is available for the design of the building.

First, essential information is extracted from the B-Plan in order to search a database of BIM models for similar legally conforming buildings that are adapted to the building site. This identification of a matching building model to a specifically regulated construction area is done in the form of data reconciliation. For this task, an approach is evolved, which enables the calculation of similarities between a defined input (based on the development plan) and a possible output from the database (BIM model). Legal information from the development plan is thus directly considered. Due to their importance for the early design phases, the focus is initially directed to four regulatory contents of the B-Plan, which are shown in the following table (cf. Table 1).

Table 1: Focused German regulatory contents.

	Type of use	Extent of use	Design	Overbuilding area
Description	Determination of which type of building is permissible	Determination of the building density of the construction site	Determination of the design of the building	Marking of the construction sites
Example	Determination of an area as a commercial building area.	Determination of the height of buildings.	Determination of buildings with lateral boundary distance.	Definition of red building lines on which must be built.
Regulation in Germany	§§1-15 BauNVO	§§16-21a BauNVO	§22 BauNVO	§23 BauNVO

A further important input for the evaluation of the costs is a database containing the prices for the elements identified in the cost groups with an actual minimum, maximum and average price. Initially, this is structured in a way that it contains the prices for construction elements. In Germany, for example, these prices can be taken from the table of the Building Cost Information Center of the German Chambers of Architects (BKI) for new buildings. (BKI 2023) However, in order to keep the database as updated as possible, it is enabled to adjust the prices on a daily basis to be able to react to changing circumstances on the market. Capturing construction elements enables to determine the costs according to the CG 300. Data for property prices (CG 100) are provided as inputs in two different manners. In some parts of Germany, the price per square meter corresponding to the street and house number included in the B-Plan can be taken from the Land Value Information System (BORIS). (BORIS.NRW 2023) An additional possibility is the definition of minimum values, maximum values and average values for the corresponding city. These costs are considered according to differentiated locations in order to be able to make a local calculation. This approach enables a location-specific and current market price-oriented cost estimation for the early design phases. However, this can lead to strong distortions of the calculation, but still offers a basis if the information is not available on BORIS or is not up to date. In case of the costings concerning CG 200 they have to be set by the architects depending on the location of the project. In this context, for example, construction measurements for the connection to the public and technical infrastructure, as well as the communal fees, are included.

3.2 Cost estimation and output data

Determined costs are classified according to DIN 276:2018-12 to calculate the estimated project costs. For this methodological approach, initially for the early planning phases the relevant cost groups 100 to 300 are included. For CG 100 and 200, only level 1 is considered to ensure that the cost estimate is as generally applicable as possible. For CG 300, a subdivision of the cost group into specific elements is included to some parts of level 3 to be able to identify cost-efficient alternatives of building components using the Variant Management. (cf. Figure 2)

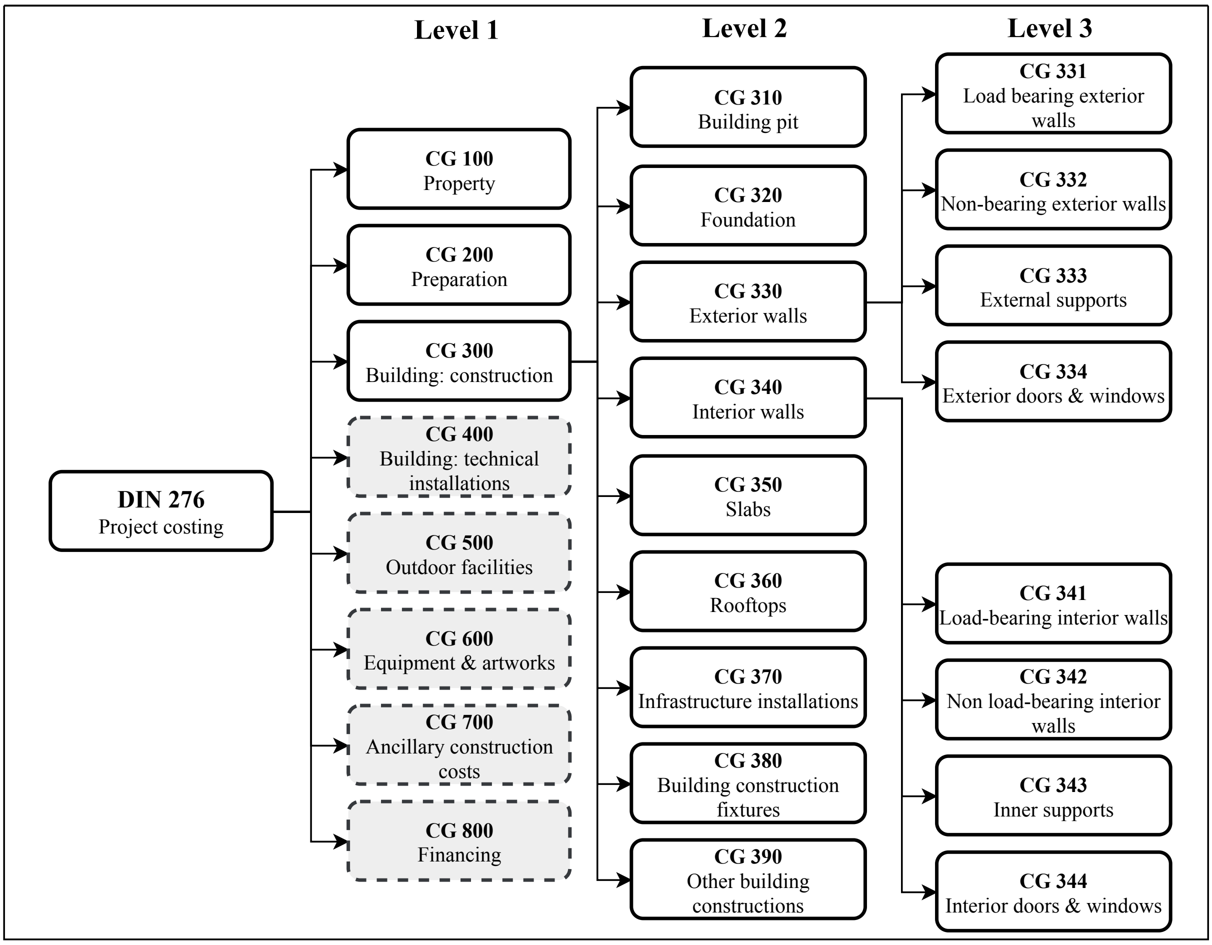


Figure 2: Considered cost groups and levels.

The IFC format, which is frequently used for BIM-compliant construction planning, offers the possibility of providing important information for the calculation of the project costing. Information stored in the pricing database is transferred to a document which is made available to the architects at the end of the calculation. This table contains general information of the IFC model, such as the property site area (IfcSite) or the gross floor area (IfcBuilding). Specifically for costing, it contains the respective cost groups and their levels, the applicable unit as well as the price. While the calculation of cost groups 100 and 200 is based on the plot area, cost group 300 depends on the gross floor area. The quantities can be retrieved and transferred directly from the IFC model, the units are fixed and the prices are imported from the respective database. In terms of performance of the approach, the costs of a building are provided to architects after a retrieved matching building design. Subsequently, the estimated costs are compared with the total costs specified by the client at the beginning.

Once architects retrieved a similar building to the specific regulations that exceeds the client's price expectations, it is possible for the client to search for similar individual components of the building in a further similarity search in order to find cost-efficient alternatives. In this context, users can take advantage of the current prices and, for example, choose currently less expensive doors and windows or even adjust the structure of the floor plan. Afterwards, the adapted file is stored, which on the one hand results in a filling of the database and on the other hand it can be handed over to specialist planners or other stakeholders for verification.

4. Case study

For the verification of the presented methodology, a real-world scenario is chosen to demonstrate how the price calculation is performed and how the Variant Management can be used to identify similar cost-efficient alternatives. Therefore, a building site in Munich, Germany, is given, for which the following B-Plan is valid (cf. Figure 3).

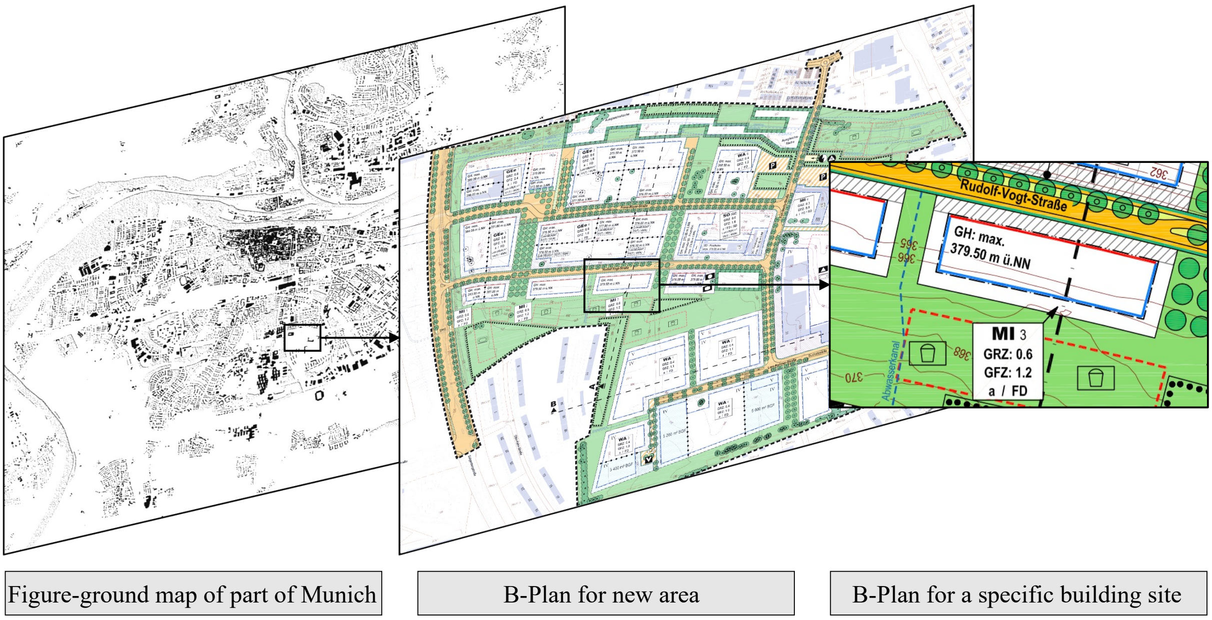


Figure 3: Demonstration of a part of a B-Plan in Munich.

From an economic perspective, the construction project assumes that the building will be designed to maximise the use of the building area. Accordingly, the red building limits and blue building lines should be legally exhausted in the B-Plan (cf. Figure 3).

Starting the application, the user declares that a B-Plan for the planning is available and based on this and the textual information provided with the plan, the user is able to enter the initially required information (cf. Figure 4 (left)). The opportunity to upload the plan enables to save it together with the search query as an emerging problem. A price framework needs to be specified (maximum costs) for the project and afterwards the calculation can be started. This information is used for the CG 100-200 cost calculations, as it enables them to be determined locally.

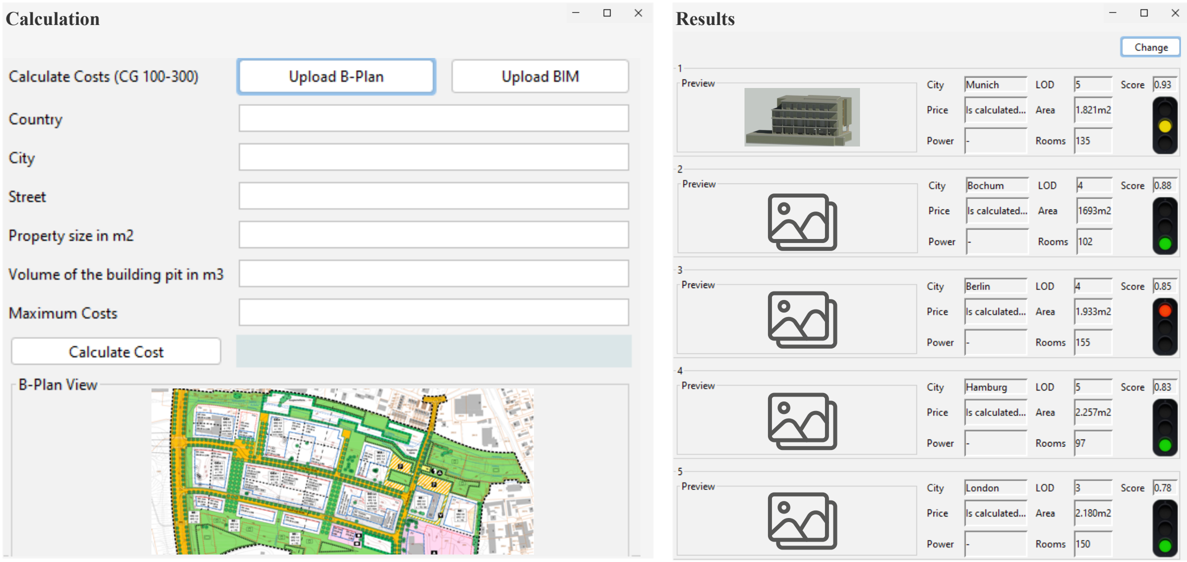


Figure 4: Calculation interface (left) and returned results to the specified requirements (right).

In the next step, information regarding the legally restricted type of use, extent of use, design specifications and overbuilding area according to the BauNVO is captured. (cf. Table 1) Such information is used for similarity determination to existing projects. Referring specifically to the part of the Munich B-Plan displayed in Figure 3, the following information can be extracted:

Table 2: Information extraction from the B-Plan.

B-Plan information	Meaning
MI	Mixed-use areas, they are intended for residential use and the accommodation of commercial units that do not significantly interfere with residential use.
GRZ: 0,6	The owner of the property is allowed to build on 60 percent of the site.
GFZ: 1,2	GFZ of 1.2 specifies how many m² of floor area per m² of property site area are allowed. In this case, it is 120 percent.
a	Means that the construction method is defined in a text document.
FD	Only a flat roof is allowed.
GH	The maximum building height may not exceed 379.50m (standard elevation zero).

This information is then formulated as a request to the graph database and resulting buildings that match the query are retrieved. During this process, the costs for the components included in the model are already recorded for the five most similar results, so that architects already receive the cost estimates for cost groups 100-300. A traffic light rating system evaluates the price range. The similarity score can be compared and some important information of these buildings. Once identified, the data can be downloaded from the database. (cf. Figure 4 (right)).

By applying the Variant Management, building components can be modified cost-efficiently or floor plans can be varied to reduce the overall costs. In Figure 5, the retrieved building and identified expensive building components as well as the customisation of a floorplan is carried out as an example. It demonstrates that the costs for a storey (CG 300) can be reduced using the provided component pricing database. Identified components that are more expensive than assumed due to changes in the market price can be replaced via the Variant Management. Currently costly elements, such as wooden doors in this example, can be replaced by presently more affordable glass doors (Product Variant), or load-bearing walls can be replaced by cheaper columns (Functional Variant). Through cost-efficient customisations based on market conditions, the model complies with local regulations and to the price framework.

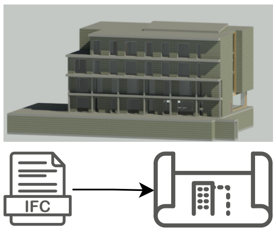
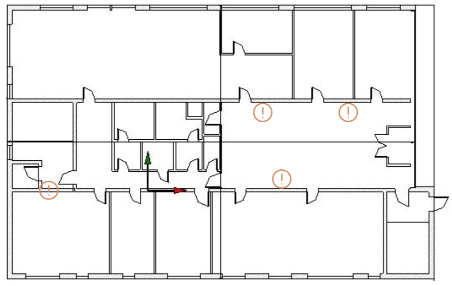
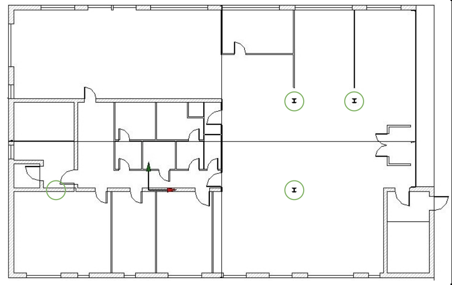
Retrieved building and floor plans	**Identifying expensive components on a building floor**	**Customising cost-efficient alternatives on a building floor**
		

Figure 5: Identification and customisation process.

5. Conclusion and future work

Considering the example of a legally mandatory B-plan in Germany, this paper demonstrates how architects can use site-specific building regulations and a developed retrieval methodology, to identify cost-efficient legal designs as inspiration in the early design phases. For the implementation of this resulting cost estimate, the calculation framework of DIN 276 is used. The Variant Management is used to identify and exchange cost-efficient components. This adaptive approach is intended to demonstrate the building regulations as a useful example of extended inputs for finding building designs and the cost consideration as a possible proxy variable consideration for the multiple applicability of the method. An extension with regard to the possibility of capturing costs over the entire life cycle is thus possible. However, it is recommended that the scope be limited to a specific country, as dealing with accessibility to location-specific material prices has proven difficult. Regarding the use of development plans, other countries have likewise regulations, but these in turn require an adjustment of the input options, so that it becomes obvious at the beginning of the retrieval process which development plan is involved. Based on this, the contained regulations and their specifications can be used for the database query. Nevertheless, the use of analogue or digital plans has been proven to have great potential for design decisions and is thus a useful addition to the decision-making tool in early design phases. In the future, the approach will be complemented by the inclusion of sustainability assessment systems. The considered costs are just one part of the LCC and can be included together with LCA in a holistic sustainability assessment. To address important practical aspects in the architects' daily work and to overcome the previously mentioned challenges, future work will include other possible considerations as both inputs and outputs to this methodology, for example regarding the energy efficiency of building elements. In addition, methods can be investigated and integrated that enable the automatic import of information from plans and texts, such as text and image recognition.

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