Holistic Quality Model for extending the existing building stock

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Key words: Quality Model, Quality Assessment, Existing Building Stock, Densification, SDG

SUMMARY

Global population growth is leading to an increase in the worldwide demand for living space. Urban areas, which already have a high building density, are particularly in demand. In order to create additional living space or office space in these already densely populated areas, the extension of existing buildings is becoming increasingly important. The development of new building systems that enable resource-efficient and sustainable construction in existing buildings is one of the central research topics of the Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC) at the University of Stuttgart. The building systems developed should meet social, economic, ecological and technical requirements. However, as these requirements influence each other, in addition to developing the building systems, an important part of the project is the development of a holistic quality model that can take into account both the individual quality aspects as well as the interrelations between these quality aspects. A particular focus here is on the integration of the holistic quality model for quality assessment in building renovation. Within the scope of this work, the quality model developed as part of the project and the associated quality assessment will first be examined. The different types of quality assessment in the planning and fabrication process will also be considered in more detail. These will then be adapted to the specific building requirements in existing buildings. The special requirements involved in building in existing building stock will be explained in more detail before integrating the model into the planning and construction process is examined more closely. When integrating the holistic quality model into the planning and fabrication process for building in existing buildings it became apparent it is possible, but requires some adjustments. In particular, it is evident that different quality aspects are represented to varying degrees at different stages of the planning process. Therefore, it is also important to consider the interrelations between the different stages.

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1. INTRODUCTION

With the global population having tripled over the last 70 years and expected to reach 10.3 billion people by 2080, housing construction is one of the key challenges of our era of expanding urbanisation. (Brenner & Schmid 2015, Röck et al. 2020, UN 2025). This means the existing living space will have to double over the next 30 years, even though the available space is already limited today. Nevertheless, the built environment is already responsible for 40% of global greenhouse gas emissions today (UN 2023). It functions as a setting for social interaction for a significant proportion of the world's population. It provides locations for people to live and work. It also serves as a foundation for economic capital and investments. Therefore, it is clear that the building sector exerts a significant influence on all dimensions of sustainability: society, the environment, and the economy, as also highlighted in the SDGs (UN 2015). The important role of the construction industry in achieving global sustainability goals is also reflected in the fact that five of the 17 Sustainable Development Goals (SDGs) are directly related to developing a sustainable building culture (UN 2015). These include affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), sustainable consumption and production (SDG 12), climate action (SDG 13), and life on land (SDG 15). Sustainability is ever more often defined as an urban issue, premised on cities' "transformative power" (WBGU 2016) to deliver it via future development (Angelo & Wachsmuth 2020), to which the construction sector is integral.
In particular, the EU has identified the need to address environmental impacts in the revised Energy Performance of Buildings Directive (EPBD) as part of the European Green Deal (Aragón 2024). Renovation and retrofitting are imperative to achieving the EU's 2050 net-zero targets. To satisfy the huge demand for inner-city living, minimise the need for additional large-scale transport infrastructure, and reduce the environmental impact and land consumption of greenfield developments, existing cities could be densified further, and space between or on top of existing buildings could be utilised for construction (Aigwi et al. 2023). For example, an additional 1.2 to 1.45 million residential units are required in Germany alone. 2.3 to 2.7 million of these could be realised by extending existing urban building stock, saving up to 250 million m² of non-built-up area (Tichelmann et al. 2019). This would help the government achieve its "net-zero land savings target" for land consumption by 2050 (BMUB 2023).
However, these measures will require significant investment and yet face several barriers, e.g., neglect of interaction between different building systems or late identification of building issues in the design phase (Kamari et al. 2019). Decisions of this magnitude and several trade-offs

should be carefully weighed, involving various stakeholders, different requirements, and a structured planning process. This is especially true because densification measures can have ambivalent effects, potentially worsening social inequality (Cavicchia 2023, Lutz et al., 2024) and increasing emissions (Rice et al. 2020).
The Integrative Computational Design and Construction for Architecture (IntCDC) cluster of excellence at the University of Stuttgart aims to contribute to achieving this goal. IntCDC's methods, technologies, and building systems for stock extension and conversion have the potential to provide sustainable solutions that meet the requirements of the United Nations Sustainable Development Goals (SDGs). The co-design approach forms the central element of these developments. This involves the simultaneous development of all necessary methods, processes, and systems in an interdisciplinary environment that includes architecture, civil engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics, and the humanities and social sciences (cf. Figure 1).

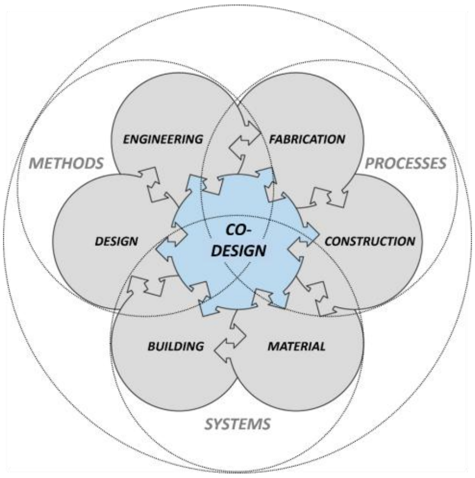

Figure 1: Co-Design approach for the parallel development of methods, processes, and systems (Knippers et al. 2021).

In order to carry out such a complex and interdisciplinary design and manufacturing process, continuous quality assurance is of crucial importance; therefore, the development of a holistic quality model, that include economic, technical, environmental and social aspects, also has an important role to play within the project (Zhang et al. 2020, Frost et al. 2022, Haag et al. 2024). Previous applications have focused on individual components or new building projects. However, the consideration of existing buildings comes with new challenges. This paper, therefore, takes a closer look at applications for existing buildings. Previous methods that can be used to support sustainable decision support for the design and planning phases often only cover individual quality aspects and often do not take social aspects into account. In addition, the interrelations between the quality aspects are not taken into consideration. For a collection of different methods, the authors refer to Haag et al. (2024). The holistic quality model 2.0 (HQM) offers this structure but has only been applied to planning of new buildings. The advantage of new buildings is that they afford the designer much greater freedom in terms of design, material, structure, etc. By contrast, addressing existing buildings entails a certain degree of limitation in these parameters, and the building has to be seen in a broader context. The main goal of this work is to propose a concept facilitating HQM 2.0 that applies to existing buildings and their particular framework conditions and identifies the interrelations between different decision points, pointing out the importance of different quality dimensions within different planning stages. Taking into account not only the building in the current status, but also the surrounding neighborhood, the original type of usage, etc. Including different perspectives alters the assessment and the stakeholders along the decision path for existing buildings compared to new ones. Within the scope of this work, the fundamentals of quality modelling and the structure of the holistic quality model are first presented. The necessary adjustments and challenges for application in building existing structures are then presented, and the timeline of the construction process is examined in more detail. Finally, the goals achieved by the model and its current limitations are presented.

2. HOLISTIC QUALITY MODEL AND ASSESSMENT: FUNDAMENTALS

To develop a quality model, it is first necessary to define the term of quality. Within the scope of this work the authors refer to the definition provided by the international standard DIN EN ISO 9000:2005, which defines quality as “the degree to which a set of inherent characteristics fulfils requirements”. The characteristics refer to the requirements for evaluating the product or process (DIN EN ISO 9000:2005). These requirements, therefore, form the basis for the subsequent quality modelling and assessment. Different approaches are available for developing a quality model (Ortega et al. 2003, Wiltschko 2004). A detailed literature review on various quality models can be found in Zhang et al. (2020). The structure used for quality modelling and assessment in this project is shown in Figure 2. It shows the division into requirements that must be explicitly analyzed for the project, the resulting quality modelling (cf. section 2.1), which takes into account aspects of different disciplines, and the quality assessment (cf section 2.2). The following sections take a closer look at quality modelling and quality assessment.

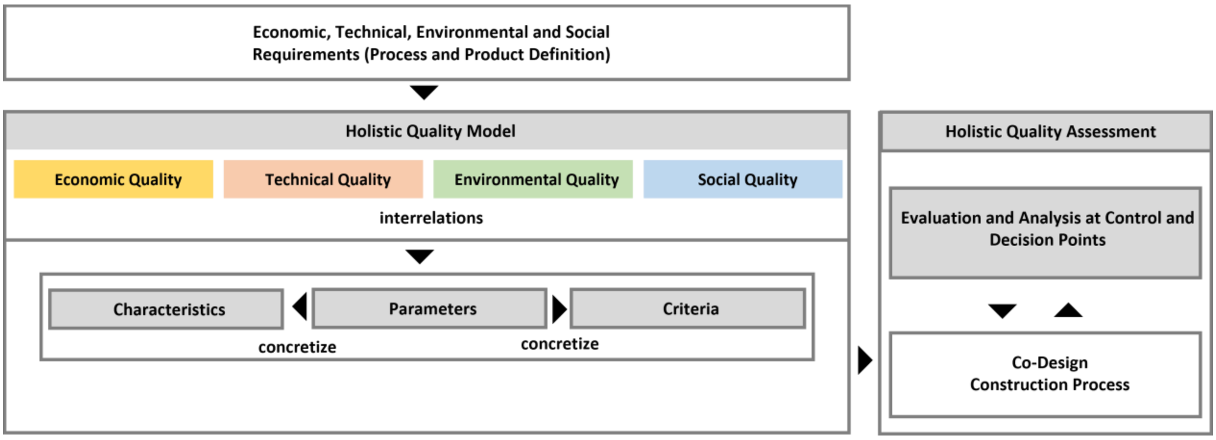

Figure 2: Holistic Quality Model and Assessment (Haag et al. 2024).

2.1 Holistic Quality Model

The quality model is shown on the left side of Figure 2. It considers requirements that may be economic, technical, environmental, or social. The model is divided into three components: the quality characteristics, parameters, and criteria (cf. Figure 2). The quality characteristics are derived from the requirements and are not directly measurable. Therefore, these characteristics are further concretized by the quality parameters. The quality parameters are measurable quantities. For example, one quality characteristic could be the accuracy with the standard deviation as the associated quality parameter. Also several parameters can be assigned to a quality characteristic (cf. Figure 3). To decide whether the required quality has been achieved or not, the quality criteria are introduced. The quality criteria form the base for decision-making in quality assessment and therefore represent a minimum value or threshold value for the quality parameter under consideration, which must be met to comply with the quality requirements. In the previous example, the quality criteria would be to meet a specified limit for the standard deviation or, more generally, to minimise it.

This structure is applied to all quality aspects under consideration. Since the processes and products to be evaluated are mostly complex, their quality is not assessed using a single quality parameter, but rather a number of different parameters. . These parameters influence each other, which makes the consideration of their interrelations a central part of the assessment. Here, it should be noted that improving one quality parameter can lead to a decrease in another quality parameter. These interrelations can exist between the parameters of a quality aspect and different quality aspects. The quality model is constantly developed with a specific application in mind. However, in many cases, the structure of the characteristics and parameters can be adopted for similar products and processes, meaning that only the criteria need to be adjusted accordingly. The quality model is constantly developed with a specific application in mind. However, in many cases, the structure of the characteristics and parameters can be adopted for similar products and processes, meaning that only the criteria need to be adjusted accordingly.

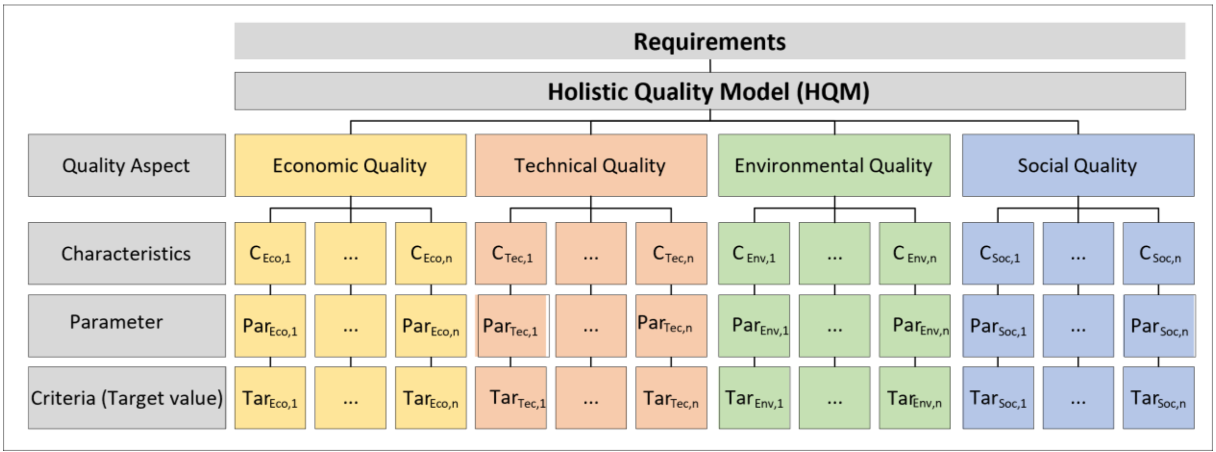

Figure 3: Exemplary set-up of the HQM for the four considered quality aspects.

2.2 Holistic Quality Assessment

The quality assessment is the measurement of the quality parameters and the evaluation based on the quality criteria to support decision-making. The quality assurance concept used in this work distinguishes between control points and decision points at which quality is assessed (Zhang et al. 2020). In contrast to the generally common use of the term “control point” in the field of geodesy a control point is here defined as a point in time during production or in the process at which a process or sub-process is completed and its result is assessed. The fulfilment or non-fulfilment of the criteria is decisive. In contrast, decision points represent a point in time in the process at which decisions regarding further proceedings are made based on the quality achieved so far. In addition to evaluate the quality of different aspects individually, it is now also possible to determine how the parameters interact. This enables interrelations between the parameters to be identified, which is particularly important when evaluating different options (Haag et al. 2024). The assessment of the overall quality of a product or process always depends on the required target; therefore, the same product may receive a different quality assessment with different quality requirements. By integrating feedback regarding the quality of a product or process within the construction process, it is possible to adapt current processes and optimize them with regard to the construction components that have already been produced. This integration therefore enables a transition from a linear to a circular construction process (Zhang et al. 2020).

The quality assessment is based on the quality aspect score (see Figure 4). This takes into account the quotient of the quality parameter and the quality criterion. Three cases are distinguished for the assessment: fulfilment of the requirements, non-fulfilment, or even overfulfilment. By calculating the arithmetic mean, a common quality aspect score can be determined from all considered quality parameters (Frost et al. 2022).

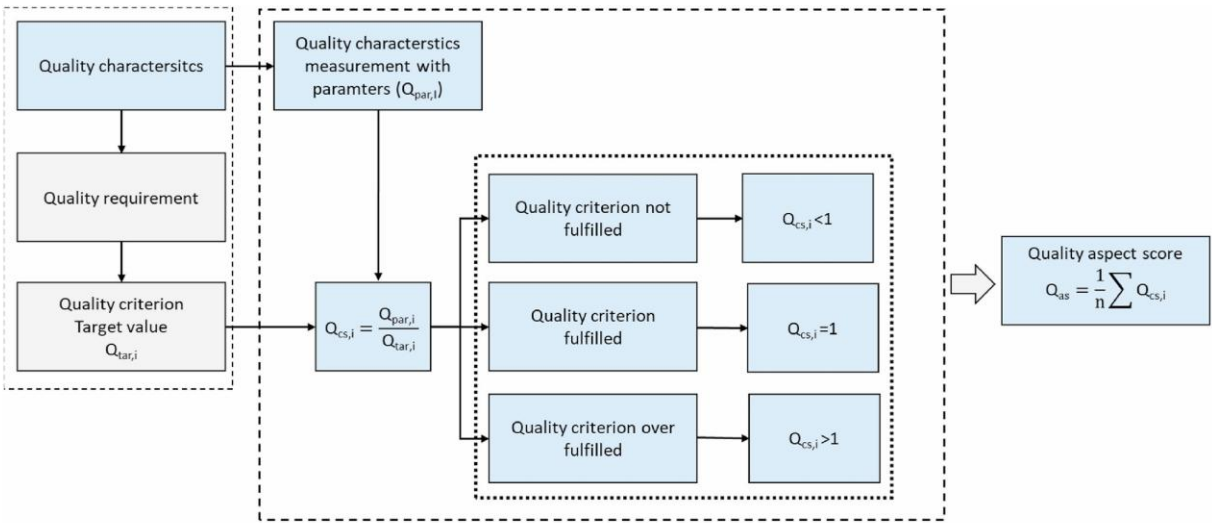

Figure 4: Concept for calculating the Quality Aspect Score (Frost et al. 2022).

In order to visualize the results of the quality assessment of the individual characteristics, these are displayed in a radar plot. An example of this is shown in Figure 5. Characteristics within the yellow circle do not meet the requirements. Characteristics in the green circle shows an overfulfill of the requirements. If different options are displayed in one radar plot, this provides visual support for decision-making.

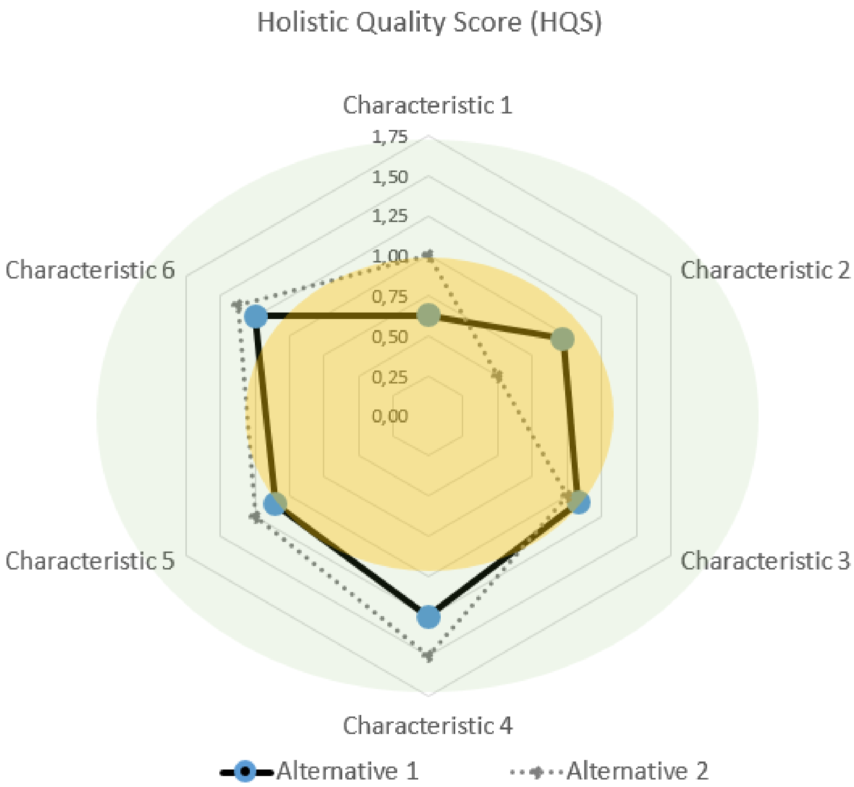

Figure 5: Conceptual visualization of quality scores.

3. ADAPTATION OF HQM FOR THE EXISTING BUILDING STOCK

To apply HQM to building in existing buildings, the first step is to identify the relevant stages within the planning process where the quality assessment is needed. In particular, as the relevant stages, the location decision, the decision on measures, and the detailed analysis, must be taken into account.

3.1 Holistic Quality Model Set-Up

In order to carry out a quality assessment for the extension of the existing building stock, it is necessary to integrate the HQM into the planning and construction process. Therefore, a general overview of the entire process will first be presented, and afterwards, the integrated feedback loops and the options for decision-making will be further explained. In the end, the structure of the HQM is examined in more detail based on the location decision.

A general representation of the relevant stages and the integration of the holistic quality assessment can be found in Figure 6. The figure shows a structured methodology for evaluating locations, sites, and potential measures to transform existing building stock. Potential measures for this include, for example, by adding additional floors or repurposing building space. The evaluation relies on the Holistic Quality Model, which ensures that comprehensive criteria from all quality aspects guide decisions. This process involves three key stages, each involving critical evaluations and decisions. Each of the three stages has different requirements. In this paper, these requirements are divided into mandatory requirements and additional requirements. Mandatory requirements include specifications derived from design regulations and legislation, for example, and must be fulfilled to enable the project to be implemented. Additional requirements, on the other hand, arise from the requirements of different stakeholders. Here, too, the goal of the measures is compliance. Still, these requirements can be balanced in the decision-making process, allowing measures that offer the highest possible quality in terms of the quality model to be selected.

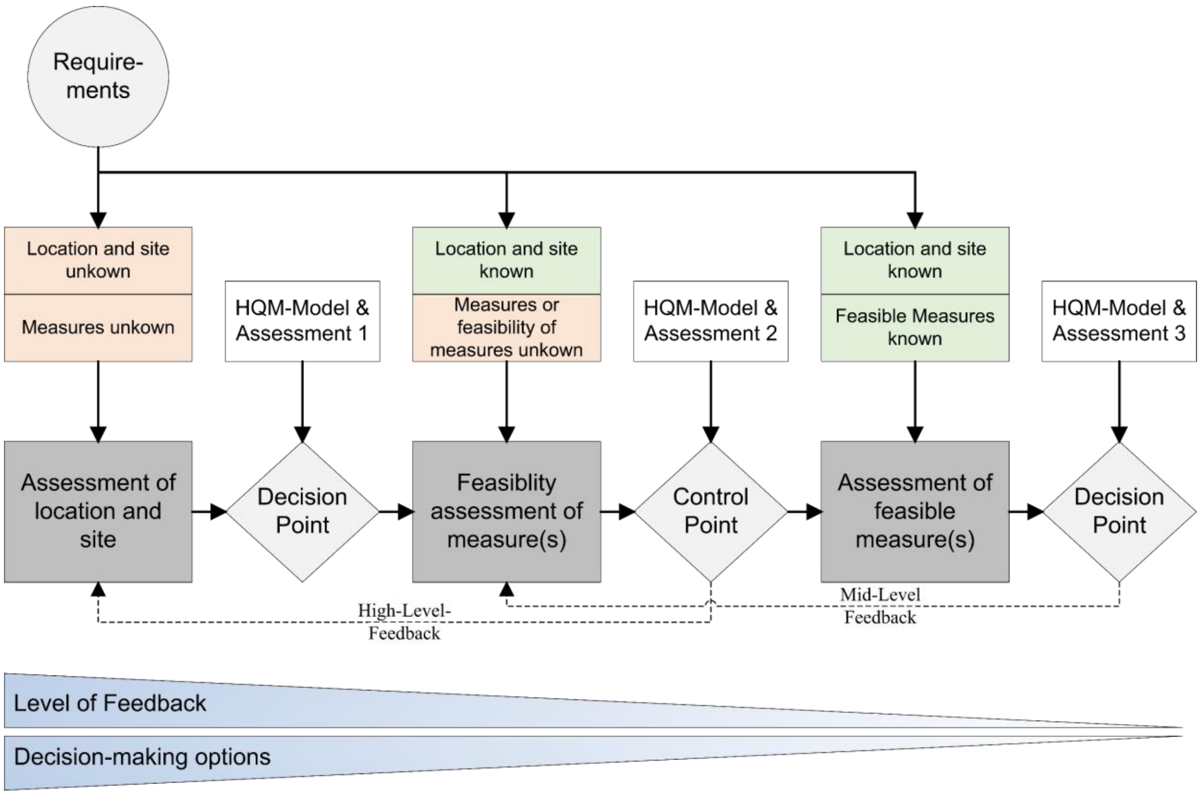

Figure 6: General Process Diagram for the transformation of the existing building stock.

The requirements arise, on the one hand, from the stakeholders and may have a societal, economic, environmental or technical background, for example a lack of housing, the achievement of climate targets, or urban development models. Further requirements arise from the individual requirements of stakeholders, such as the demand for good profitability, affordability of the project (Debrunner & Hartmann 2020), or the wish to create a location for certain industries. These requirements are comparable to those of a new construction project. In addition to these requirements, additional requirements arise from the existing building itself, which must be considered during planning and execution. These include, for example, the aesthetic conditions, the structural performance and the energy performance of the existing building, the urban regulations, or landmark protection regulations, which may restrict a possible construction project (Friedrichsen 2024). Another important component of the requirements for building in existing buildings is the availability of all relevant data regarding the current state of the building.

The initial stage begins without prior knowledge of specific locations, sites, or potential measures. The focus here is on assessing the location and site using the HQM, referred to as 'Assessment 1'. This analysis considers economic and social quality aspects, such as macro-location factors like infrastructure and neighbourhood and micro-location factors like economic or political developments (Ali et al. 2019, Bramley & Power 2009, Bramley et al, 2009, Lutz et al. 2024). Based on the quality assessment of this stage, a decision is made as to whether the location and site are suitable for further consideration (Jayantha & Yung 2018). The process moves to the second stage if the location and site are deemed suitable. This involves evaluating the feasibility of potential measures, such as building extensions, retrofitting, renovations, or other interventions aimed at transforming the building stock (Toader et al. 2025).

The second stage is identified as "Assessment 2". It assesses the compatibility of proposed measures with the site-specific conditions and overarching objectives. This stage predominantly emphasizes technical quality aspects, focusing on the structural feasibility of the existing building. At the subsequent control point, only technically and strategically viable measures proceed to the final stage. At this point, it is also important to capture the existing building stock, as a decision regarding the feasibility of various measures can only be made on the basis of complete and accurate planning information. This includes the geometry of the building as well as the materials used and their condition. The geometry must be captured in order to determine whether there has been a change compared to the floor plan that needs to be taken into account during planning. For example, an extension may not be fully documented, meaning that the geometry of the outer shell in the floor plan differs from reality. The same applies to the material. For instance, if the building is a masonry work, it is not possible to apply some external insulation on the envelope, because it damages the aesthetics, because it is hard to maintain the wall's ability to manage moisture, which is why breathable materials and systems are often preferred, and finally because sealing the insulation layer and detailing junctions, such as around windows and eaves, can be complex and requires careful attention to prevent moisture

problems. Therefore, some impermeable synthetic rigid foam boards like XPS and EPS are not suitable. Meanwhile materials like wood fibre, hemp-lime or sheep's wool are suitable.
In the third and final stage, the selected measures undergo a comprehensive quality assessment using the HQM in "Assessment 3". This stage integrates all four quality dimensions - economic, social, technical, and environmental- to ensure quality criteria alignment. The outcome of this evaluation is the selection of the most suitable measures for implementation.
This iterative process embeds sustainability and quality assurance into every stage of decision-making. The HQM serves as a consistent framework to evaluate and compare options.
Depending on the project under consideration, the possibilities that arise in the three individual steps can vary significantly. For example, this becomes obvious when considering the location. If the aim of the construction project in a particular city or district is to increase density, the choice of location for the project is an essential factor. At this point, however, the choice may already have been made due to a predefined requirement. This is often the case when it is already clear that a project will be carried out for a specific building.

3.2 Holistic quality assessment

As continuous quality assurance in the planning and construction process also offers the opportunity to transform the process from a linear process into a circular process, feedback loops need to be integrated within the quality setup of the quality model. This offers the crucial advantage that feedback can be directly integrated and direct adjustments can be made within the process. This feedback can be, according to Kannenberg et al. (2024), divided into three kinds of feedback:

- high-level feedback,
- mid-level feedback,
- low-level feedback.

Considering these types of feedback in the context of expanding the existing building stock, high-level feedback is particularly evident in the early planning phases. If neither the location nor the measure to be conducted has been determined at the start, high-level feedback can be used to achieve the highest possible increase in quality. If the location of the measure has already been determined, the feedback can only refer to the measure itself. If this has also been determined, only individual details in the detailed planning can be changed, which is why mid-level feedback is used. The last type of feedback, low-level feedback, is used when the project has already been completed. At this point, feedback and thus an improvement in the quality of the current building process is only possible to a very limited extent. However, this type of feedback can be used to improve the quality of future projects.
This shows that the different types of feedback are directly linked to the number of options (see Figure 6). As the process becomes more developed, the number of options for improvement

after a quality check has been carried out decreases. However, it should be noted that this is not applicable to the minimum requirements for a process or product. Those must always be met, even if this means rescheduling or changing the production in a late construction phase. Nevertheless, it is important to avoid this through continuous quality assurance.

4. APPLICATION OF HQM TO LOCATION SITE DECISION

In order to illustrate its application in existing buildings, the following section takes a closer look at the exemplary structure of the HQM when selecting a location. The process is shown in Figure 7. When considering the application of the HQM to the location decision, it is now assumed that no preliminary decision has been made regarding the location. The process, therefore, begins with a search for possible locations. Since, for reasons of time and cost, it is not possible to carry out a complete investigation and planning for all locations that are available after an initial analysis, the first decision point is made at this stage. At this decision point, the HQM is now applied. The figure shows a possible quality parameter for each of the four quality aspects. In this case, the technical requirements relate to compliance with building regulations. This is a mandatory requirement, as a construction project that does not comply with building regulations cannot be carried out. A quality score can then be determined for all quality parameters considered, which provides the basis for ranking the different location options. The ranking now represents an initial interim result, which stakeholders can use as a basis for further decision-making. It should be noted that at this point, only the legally possible locations are considered further.

To examine the individual options in more detail, the stakeholders now select one or more of their favourites. The generated ranking supports this selection. It should also be noted that the different quality aspects are generally weighted equally. If the stakeholders consider one aspect particularly relevant, a weighted ranking can be used for decision-making. At this point, it should also be noted that the ranking based on the HQM is intended to support the decision, but does not make the final decision. For example, the HQM assessment considers site 1 to be the best option. However, the personal preferences of the stakeholder's favour site 2, therefore this site will be examined in more detail in the next steps. This means that decisions are finally always made by humans in the loop.

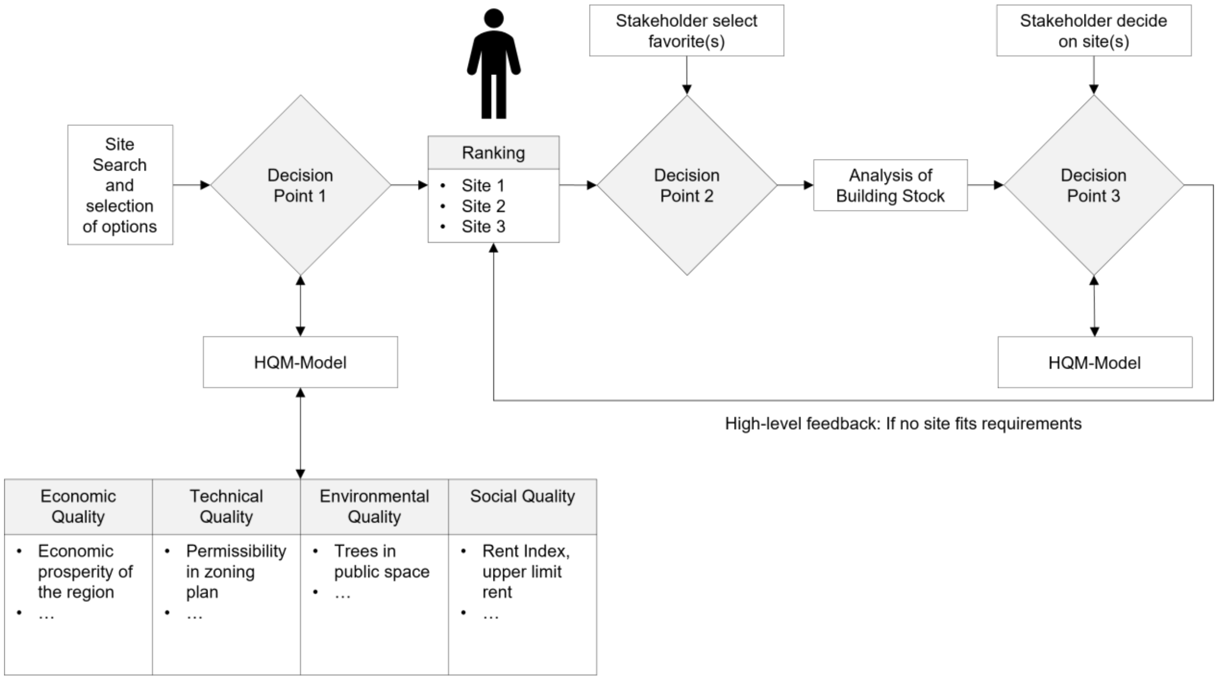

Figure 7: Exemplary application of the HQM to the process of the location site decision.

The options selected here have now been examined in more detail. At this point, the quality assessment of the existing building itself is relevant. First of all, it is crucial to check that all available planning data is complete. In addition to completeness, the correctness of the planning data is a key component for further planning. Often, modifications to the building are not documented or are only partially documented. For this reason, it is necessary to capture the existing building stock in order to obtain the actual state of the building. The actual state includes, on the one hand, the geometry. This can be captured, for example, using terrestrial laser scanning (TLS), and a BIM model can then be created from the measured point cloud (Blankenbach 2018, Chen 2022). Reliable surveying of the existing structure is a key part of the planning phase, as it forms the basis for all further analyses. In addition to the geometry, documentation of the used materials as well as the condition of the material is necessary (Zahiri et al. 2021). Both the type and condition of the material must be evaluated, as this will affect the feasibility as outlined in the previous. If several options have been selected for this consideration, the next decision point follows, where the stakeholders decide on an existing building for which the possible measures are now to be analysed. At this point, it is also possible to continue analysing different sites, although this involves increased time and, therefore, increased costs. However, if different sites are analysed the time and effort in the following stages can be reduced significantly. Also, the risk of a non-fulfilment of the quality requirements at a later stage which can lead to a more time-consuming review and new assessment can be reduced significantly.

Suppose the assessment of the existing building reveals that none of the available locations meet the specified requirements. In that case, this assessment is also communicated to the stakeholders, and the ranking of the preselected locations is reviewed again, and a new selection is made. This can be considered high-level feedback, as feasibility was already deemed insufficient early, allowing a new choice.
The process for selecting a location shown here has been simplified for clarity and focuses on the most relevant decisions that have to be made. Each step is similarly based on an optional number of sub-processes for which HQM can also be applied.

5. CONCLUSION AND OUTLOOK

Within the scope of this work, the general concept of the HQM was presented, and the basic concept of quality assessment was outlined. Afterwards, the differences in application for new buildings compared to building in existing buildings were examined in more detail. In contrast to the previously developed HQM for new buildings, applying HQM to existing buildings involves unique challenges that necessitate a tailored methodology. The primary goal is to assess the current state of the building and determine feasible interventions, such as retrofitting, renovations, or extensions, to improve its performance and align it with contemporary standards. The key differences between the application of HQM in new and existing buildings stem from the nature of the projects. New constructions offer greater design flexibility, allowing for the proactive inclusion of quality criteria from the outset. In contrast, existing buildings require adaptation based on current conditions, often prioritizing retrofitting and renovation to enhance energy efficiency and sustainability. The assessment focus also differs; while new buildings emphasize design and construction quality, existing building projects concentrate on evaluating current conditions like the location and site, as well as the condition of the building itself, to identify viable measures aimed at restoring or improving the original building performance.
However, the holistic quality model developed can be applied to existing buildings. The various feedback options that can be integrated into the planning process are also especially relevant here. The analysis also showed that, initially, all four quality aspects considered are equally included in the assessment. However, design regulations or other requirements that cannot be amended are mandatory requirements. These must be met under all circumstances. In addition, the preferences of stakeholders and their specific requirements can lead to different weightings. However, this does not mean that the requirements of a particular quality aspect are generally weighted higher, but rather that the individual quality parameters are weighted differently. On a sociopolitical level, the selection of stakeholders included in the decision-making process forms a key external influencing factor on the model and should be critically reflected upon, as they may have different interests and motives, e.g., local residents versus developers.
In addition, it should be noted that the more mandatory requirements there are, the more the possible scope for decision-making in the planning and fabrication process is restricted at an early stage. In order to derive maximum benefit from the application of the HQM, the goal

should therefore be to begin planning with as open an outcome as possible so that a holistic assessment of different options can be carried out.

From a surveying perspective, recording existing buildings is a key task, as further planning can only be carried out using complete and accurate building geometry. This is crucial in order to avoid delays and rising production costs or additional material consumption in the further course of the project.

As the planning and execution of large construction projects usually takes several years and thus extends well beyond the project duration, it has not been possible to fully accompany a process to date. For further work, however, it is also of great interest to focus on individual sub-processes specific to existing buildings, such as the assessment of the condition of an existing building. In addition to the application to a real object, further investigation of the interrelations is also relevant at this point. In particular, the interrelations between the individual quality parameters at different points in time in the planning and fabrication process are an important issue that must be further considered in the future.

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