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Article

Holistic Quality Model and Assessment—Supporting Decision-Making towards Sustainable Construction Using the Design and Production of Graded Concrete Components as an Example

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Citation: Frost, D.; Gericke, O.; Di Bari, R.; Balangé, L.; Zhang, L.; Blagojevic, B.; Nigl, D.; Haag, P.; Blandini, L.; Jünger, H.C.; et al. Holistic Quality Model and Assessment—Supporting Decision-Making towards Sustainable Construction Using the Design and Production of Graded Concrete Components as an Example. *Sustainability* **2022**, *14*, 11269. https://doi.org/10.3390/su141811269

Academic Editor: Antonio Caggiano

Received: 20 June 2022
Accepted: 5 September 2022
Published: 8 September 2022

Abstract: This paper describes a holistic quality model (HQM) and assessment to support decision-making processes in construction. A graded concrete slab serves as an example to illustrate how to consider technical, environmental, and social quality criteria and their interrelations. The evaluation of the design and production process of the graded concrete component shows that it has advantages compared to a conventional solid slab, especially in terms of environmental performance. At the same time, the holistic quality model identifies potential improvements for the technology of graded concrete. It will be shown that the holistic quality model can be used to (a) consider the whole life cycle in decision-making in the early phases and, thus, make the complexity of construction processes manageable for quality and sustainability assessments and (b) make visible interdependencies between different quality and sustainability criteria, to help designers make better-informed decisions regarding the overall quality. The results show how different quality aspects can be assessed and trade-offs are also possible through the understanding of the relationships among characteristics. For this purpose, in addition to the quality assessment of graded concrete, an overview of the interrelations of different quality characteristics is provided. While this article demonstrates how a HQM can support decision-making in design, the validity of the presented evaluation is limited by the data availability and methodological challenges, specifically regarding the quantification of interrelations.

Keywords: holistic quality model; holistic quality assessment; decision-making support; graded concrete; sustainable construction; social quality; environmental quality; technical quality; co-design; interrelation

1. Challenges for Sustainability and Quality in a Changing Construction Sector

The grand challenges of urbanization and climate change relate in particular to the construction industry. The construction industry is responsible for 36% of global energy use and 39% of process-related CO_2 emissions [1]. At the same time, the percentage of people living in urban areas is expected to increase from 55% in 2018 to 68% in 2050 [2]. This poses challenges for the building industry and for society as a whole, as more building consumes resources, while simultaneously releasing emissions. While the need for sustainability is recognized by most stakeholders, there is no consensus on what constitutes sustainable construction or what future cities should be able to achieve. Primary requirements for future cities are the achievement of environmental sustainability goals alongside the provision of buildings that meet technical and functional requirements. However, the implementation of measures for the achievement of this objective faces some challenges. The fragmentation and complexity of construction processes hinder the realization of quality and sustainability requirements over a building's life cycle. In addition, predicting the quality and sustainability related impacts of different processes, materials, building designs, and products over their life cycles is a challenge for numerous stakeholders [3].

As a solution, the construction industry is increasingly using digitalization, automation, and computational methods, which allow for more efficient, sustainable, and integrated processes [4,5]. While digital tools, such as *Building Information Modeling* (BIM), aim to achieve greater integration, transparency, and control in the construction process [6], automation processes promise greater precision and productivity. Computational design is also expected to provide new construction possibilities for the design of a sustainable built environment [7,8]. Multiple interrelated aspects influence the achievement of quality and sustainability requirements during the long life cycle of buildings [9].

Computational design and automation processes can be used to deal with a multitude of issues and, hence, with increased complexity, especially in the case of nonlinear design and construction approaches such as co-design [10]. In this case, multiple quality and sustainability requirements need to be compounded in a more holistic way. To address this problem, an interdisciplinary *holistic quality model* (HQM) is developed within the cluster of excellence, *Integrative Computation Design and Construction for Architecture* (IntCDC) [11]. The HQM is intended to support decision-making by informing about technical, environmental, and social quality, and, for this purpose, it makes predictive statements about different quality aspects and their interrelations.

Objective of This Paper

The objective of this paper is to present the operative methodology of the HQM through the application of an innovative graded concrete slab to support decision-making processes in construction. A graded concrete slab serves as an example to illustrate how to consider technical, environmental, and social quality requirements in the design through building life-cycle predictions. graded concrete technologies solve issues related to conventional concrete elements, which are heavier than technically necessary. The use of hollow bodies in concrete components and optimization during structural design can save non-renewable resources and emissions and fulfill technical requirements at the same time. graded concrete components have the potential to increase the efficiency of component production, so that the supposedly contradictory requirements of building more in a shorter period of time with less can be achieved [12]. Besides the general consideration of technical, environmental, and social characteristics in the development of graded concrete, the impacts of design decisions, production processes, and building components on the quality of buildings over their life cycle are as complex as they are relevant for quality performance. Applying the HQM to the process will enable developers, designers, and producers to make informed decisions about the design, processes, and products based on the three quality aspects—technical, environmental, and social—of the HQM and their interrelations. The case study was prepared to present the possibilities and conception of this approach.

2. Holistic Quality Assurance Concept

2.1. State of the Art—Critical Remarks on Sustainablity Assessment Systems

The sustainability sustainable development definition shaped in "our common future" as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [13], which has become in recent decades a paradigm for development. However, there is a lack of consensus when it comes to defining detailed and specific concepts that go beyond the generally agreed basics.

Especially when all relevant environmental, economic, and social elements are included, the different interpretations and their respective methods and models come into conflict. Debates about the meaning of sustainability and associated models interpret constitutive elements of sustainability, such as inter- and intragenerational justice, in different ways [14]. The fundamental openness of the definition characterizes the concept of sustainability. In this sense, as stated also in [15], sustainability is still evolving and its "final shape" has not yet been achieved, if a final shape is even achievable.

The Sustainable Development Goals (SDGs) are, in this regard, an achievement as well as a milestone [16]; however, as also outlined by Wulf et al. [17], the use of SDGs and the consequent development of SDG-based approaches are still in the developmental phase and face challenges. Fundamental for the establishment of a sustainability assessment method is considering processes that must:

- address sustainability imperatives for a positive progress;
- establish a workable concept of sustainability in the context of individual decisions/assessments;
- adopt formal mechanisms for managing unavoidable trade-offs in an open, participative, and accountable manner;
- embrace the pluralistic inevitabilities of sustainability assessment;
- engender learning throughout [18].

Some initiatives aimed to operationalize SGDs have been undertaken in the context of a Life Cycle Sustainability Assessment (LCSA) [19], encompassing a variety of concepts, interpretations, and corresponding methodologies. As a consequence, these methodologies present problems of consistency and comparability among different approaches and fields [20]. Furthermore, social assessment can be particularly weak in terms of the robustness of the results. Despite the development of several new approaches (for an overview see [21]), most of these problems remain unresolved.

With regard to the construction sector, in response to its current challenges, the field of sustainable construction has been particularly inspired by SDGs.

Bragança [22] et al. distinguished three types of assessment methods:

- Systems to manage building performance (performance-based design);
- Life-cycle assessment (LCA) systems;
- Sustainable building rating and certification systems [22].

The literature review highlighted common difficulties regarding data handling, complexity, and predictions. Technical requirements are only taken into account, to a limited extent, in the sustainability assessment systems. Moreover, according to this work, social quality refers mostly to the building operational phase, by disregarding social aspects related to the work environment and, therefore, the production process [22]. In the field of building certification systems, the German DGNB system [23] or the US LEED system [24] represent a significant step forward [25]. However, a comprehensive analysis of 11 sustainable building rating systems has shown not only, on the one hand, a broad variety of characteristics and criteria, considered requirements, and examination procedures but also, on the other hand, a somewhat narrow coverage [26]. A study carried out by Wen showed that, especially in the early systems, environmental aspects tended to be given precedence, overshadowing the importance of other aspects, which could be a problem [27]. Another shortcoming of the building certification system is its retrospective application. This conflicts with findings that the potential of sustainability assessment systems is higher when applied during the decision-making and design processes [28].

A more recent systematic review on developing sustainability assessment tools distinguished, among 63 studies, (1) criteria- and (2) model-based approaches [29].

Criteria-based approaches exploit sustainability indicators and respective criteria, often coming from a literature review and the triple bottom line concept. Accordingly, they comprised three aspects: people, profit, and the planet. Model-based approaches develop and are based on these proposed balanced scorecard methods.

While criteria-based approaches can easily formulate a set of indicators, dealing with the subjectivity of their selection and their slightly different definitions is a possibly critical issue. A model-based approach could create indicators that are more robust, based on a proven ideal model. Nevertheless, it might be difficult to find out how ideal a model is [29].

Overall, a model-based approach may appear more appropriate because a model can be an identifier to distinguish an assessment tool from others: a model can describe the constructs and their relationships. However, criteria, defined by a set of indicators that may enrich the sustainability analysis, are easier to be integrated with the current organization strategy as new key performance indicators [29].

2.2. HQM as Innovative Approach for Sustainaibility Assessment

The innovation of the HQM is not only to assess retrospectively, like most other certification systems, but also to predict how decisions in specific situations may affect the overall quality of the building. Its taking into account of the interrelationships between the different aspects of quality in decision support and assessment also distinguishes the HQM from other assessment and decision support systems. The concept of control and decision points makes the HQM applicable not only to conventional linear design and to construction processes but also to non-linear approaches such as co-design.

A novel holistic quality assurance concept, entailing the holistic quality model (HQM), has already been presented in our previous work. In contrast to the above-discussed state of the art, the HQM aims to address the five objectives of sustainability assessment methods, as outlined in [18]. Furthermore, in comparison with the building sustainability assessment methods that support interactive decision-making processes over the entire building design phase and the building's life cycle, the HQM provides predictions of impacts of decisions on technical, environmental, and social quality and their interrelations.

The HQM solves shortcomings related to the criteria and model-based approach, by following a "hybrid" model. The sustainability assessment approach can be claimed as model-based, according to the definitions of [29] and with regard to the quality assessment (see Section 2.4), but it also exploits features of a criteria-based approach, through the establishment of quality characteristics and criteria (see Section 2.3). The HQM also refers to the "high holistic quality" of a building over its life cycle, understood as:

(a) conformity with standards (technical quality);
(b) a fair and decent production process and livable, user-friendly buildings that allow for social wellbeing and a good life for a diversity of users (social quality);
(c) compliance with planetary boundaries and the least possible impact on the natural environment (environmental quality).

Whereas our previous work [11] aimed, for the most part, to outline the HQM and its background concept, this work aims to operationalize the developed concept with the help of a case study. To this end, design decisions are evaluated with regard to their consequences for the further life cycle of the component, especially the production. While the evaluation of the component in the design phase is done retrospectively, asking whether all necessary requirements have been sufficiently considered, the evaluation of the production of the slab is done predictively. This work demonstrates that the HQM can be used to consider the whole life cycle early in the decision-making stage. Thus, the complexity of construction processes can be made more manageable in terms of quality and sustainability assessments. Another advantage of the HQM is the consideration it gives to the interrelations between the different quality aspects, which can help designers be more informed regarding the overall co-design process and, more specifically, promote synergies, as well as agreements and trade-off to be found between different quality aspects.

Although this application of the HQM methodology illustrates how the different aspects and their interrelations can be considered together for decision-making support, this case study has some limitations. The case studied is fictitious and based on a technology in development, and, therefore, the analysis provided lacks information and data. In terms of applicability, the HQM should be extended and further tested through a) analyses on different building levels and b) analyses on different building process stages. From a methodological perspective, the characteristics' interrelations assessment is a critical issue. The limitations are discussed in Section 6 in more detail.

2.3. Holistic Quality Assurance Concept

The holistic quality concept builds on a global perspective about questions of inter- and intragenerative, social, and environmental justice and is, in this sense, fundamentally oriented towards sustainable development [27].

Figure 1 shows the quality assurance concept we developed for the construction process [11]. This is comprised of the holistic quality model and the ensuing holistic quality assessment. The holistic quality assessment also serves as feedback and verification of the previously established HQM (see Section 2.4).

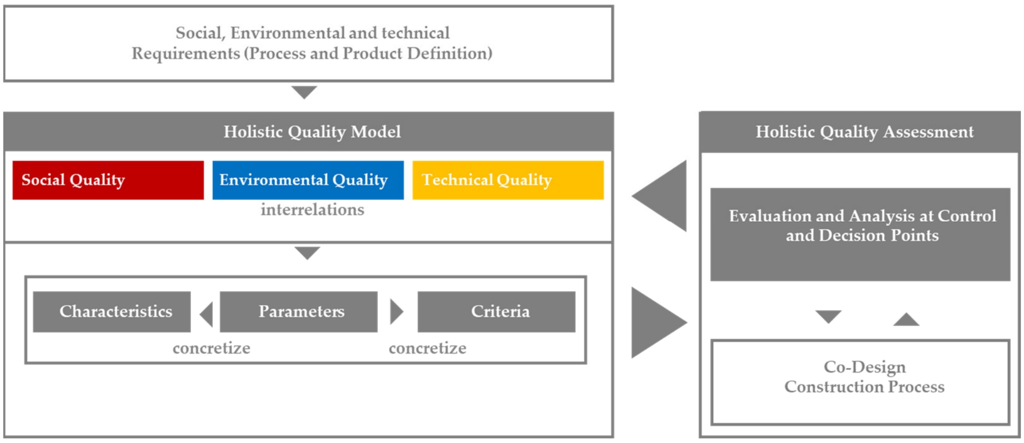


Figure 1. Quality assurance concept for the construction process [11].

Our HQM considers three quality aspects: social, environmental, and technical. In this sense, the HQM approach can be understood as a multi-dimensional analysis of the different quality aspects and, therefore, different fields. This holistic perspective allows for the consideration of quality not only as a parallel and independent evaluation of the social, environmental, and technical aspects but also for the joint consideration of these aspects and the trade-offs between them.

In addition, the developed model and consequent assessment take into account interrelations between the different quality and sustainability aspects. Consideration of these interrelations presents a challenge for the implementation of the HQM but offers the possibility to safeguard and trade off different requirements of environmental sustainability, technical functionality, and social quality [2].

The *quality characteristics* define the structure of the quality model and describe the particular qualitative aspects of the object to be evaluated. One or more *quality parameters* (quantitative measures) concretize the quality characteristics and allow the quantified measurement of them. Furthermore, the *quality criteria* define the target of the quality parameter assessment. The quality characteristics and parameters are based on the requirements of the product and the process.

The requirements integrated in the HQM can be divided into mandatory and elective requirements. Mandatory requirements are those with an application and fulfillment that are required in order to be legally approved. As mandatory requirements are obligatory, their consideration in the quality assurance concept is indispensable. Elective requirements are any additional requirements that may be imposed by the client, designer, or other stakeholders. The inclusion of elective requirements in the HQM offers the possibility to use design opportunities in a way that corresponds to the ideas of the respective stakeholders, while taking into account other quality requirements. In the HQM, technical, environmental, and social requirements, both mandatory and elective, were considered as follows.

2.3.1. Environmental Quality and Requirements

According to Johnson, "environmental quality" represents a measure of the condition of an environment relative to the requirements of one or more species and/or to any human need or purpose [30]. In recent decades, this concept has been related to the stability of environmental systems, grouped in areas of protection. This relationship is also now included in the field of sustainability assessment methodologies, and, among others, life-cycle assessment (LCA) [31,32]. Compared to other sustainability assessment methodologies, LCA has several benefits. LCA quantifies the potential damage of technical systems to these areas of protection through environmental impact assessment, following cause and effect chains and attributing anthropogenic activities to their potential destabilization of the Earth's system [11]. Environmental quality requirements refer to systems, with regard to their impact on areas of protection derived from biogeophysical system stability. Quality characteristics are LCA-related impact categories, which address the areas of protection. Quality parameters represent life-cycle inventory values related to impact category through their respective characterization factors. Based on, for example, the requirement of climate system stability (planetary boundaries), global warming potential (GWP—also called climate change—CC—in EN 15804 + A2:2020 [33]) is considered as a quality characteristic. According to ISO 14040 [31], ISO 14044 [32], and EN 15804 [33], this provides insights into the derivation of their respective quality parameters (e.g., kg CO_2 eq. for CC). With regard to resource stability, attention is also paid to topics such as the consumption of resources and non-renewable resources, recyclability of products, and a product's embodied energy (see Table 1).

Table 1. Characteristics of the different quality aspects included in HQM.

	Requirement	Quality Characteristics	Exemplary Parameter	
Environmental Quality	Climate stability	Climate change total (CC tot)	GHG emissions in kg CO_2 eq.	
	Resource efficiency	Total material	Mass in kg	
		Non-renewable resources savings (NRM)	Percentage of NRM	
	Anthropocene activity efficiency	Recycling rate	Percentage of recyclable resources	
		Primary energy total (PEtot)	Total primary energy in MJ	
		Primary energy non-renewable (PENRT)	Total non-renewable energy in MJ	
		Share of renewable energy (PERT/PEtot)	Percentage of consumed renewable energy	
Social Quality	Decent work	Control (Contr)	Influence on work	Likert-Scale (Given? In what form?)
		Safety (Safe)	Physically hard work	
		Work intensity (WorkInt)	Requirements to reconcile	
		Job security (JobSec)	Creation of jobs	
	Wellbeing	Building physics characteristics (BuiPhy)	Indoor air quality Acoustic comfort	
	Sociotechnical robustness	Competences (Comp)	Manual takeover	
		Digital accessibility (DigAcc)	Screen elements	
		Transparency (Transp)	Documentation	
		Human agency (Hagen)	Human activity level	
	Process quality	Process quality of design (PQDes)	Feedback loops Stakeholder participation Quality assurance concept	
Technical Quality	Eurocode 2 [34]	Load-bearing behavior (SLS)	Stresses in N/mm^2 and component deflection in mm	
	Eurocode 2-2 [35]	Fire insulation (FR)	Slab thickness in mm	
	DIN 4109-1 [36,37]	Sound insulation (SI)	Sound reduction index and standardized impact sound pressure level in dB	

2.3.2. Social Quality and Requirements

Social quality focuses on the relation of technology and society. It refers not only to the social impacts of technical systems but also to the effect of social structures on technical systems. This perspective is applied to the case study by understanding graded concrete design and production as a sociotechnical system. This means that the human actors should be considered in their technical context and vice versa, and their influence on one another also taken into consideration [11]. This opens up different perspectives on what has to be assessed: on the one hand, a technology-centered perspective in which the implications of the technology on its (social) environment are considered; on the other hand, a focus on the design of the (social) environment of the processes, which may contain certain qualities. Finally, the linkage of these two perspectives, which focuses on the mutual influence of social and technical conditions, especially with regard to sociotechnical robustness. In order to specify the requirements of such a normative-functional concept of social quality for buildings and construction processes, the social aspects of the HQM are drawn from established policies pertaining to sustainable constructions, as formulated by international organizations (e.g., the International Labour Organization [38]; the UN's SDGs [16]); national governments (e.g., [39]); and national or international stakeholders (see Table 1). In addition, expert discussions are useful to specify social quality requirements for the HQM that have not yet been explicitly and institutionally defined in the building context. Debates about human–machine interaction, cyber–physical workspaces, futureproof co-design processes and products, and socio-aesthetic requirements, have gained significance in recent years.

2.3.3. Technical Quality and Requirements

Technical quality is of huge importance in many different disciplines, and there are many quality models for different applications [40–43]. Technical quality plays an important role in the construction process and includes quality characteristics from different disciplines. These characteristics include timeliness, correctness, and load-bearing capacity [44]. Geometric quality, which is ensured by compliance with tolerances for all forming elements (e.g., [45]) and compliance with building physics limits are of central importance (e.g., [46]). The requirements for technical quality, thus, go together generally with the mandatory design requirements. Sound insulation, fire protection, and exposure class are also considered here. In order to apply the quality model to graded concrete, the quality characteristics listed in Section 4.2 are also included in the model. A detailed list of all characteristics used in this case study can be found in Table 1.

2.4. Holistic Quality Assessment

Holistic quality assessment is carried out at the control and decision points of the design and construction processes. Within the latter, the quality characteristics of the previously established HQM are determined quantitatively (see also [11], for some generic examples).

The quality characteristics and parameters of a process or product are then measured and assessed in relation to the established quality requirements (i.e., by comparing parameters with target values defined by quality criteria). To enable a clear and understandable communication of results, a scoring system is devised. Concurrently, the interrelations analysis is carried out (see Figure 2).

The scores obtained and the interrelation matrices are then prepared and delivered at established decision and control points. At decision points, the information serves to support the decision-making, while at control points the actual holistic quality of the considered process and/or product is assessed.

In this regard, it is important to underline that, at decision points, the potential implications of decisions are estimated, and this may imply a certain level of results uncertainty. Such uncertainty can be caused by:

- the methods and tools used, (e.g., Monte Carlo simulation);
- subjective factors, where the prediction is provided, e.g., through expert experience;

- the collected data.

For this reason, a verification and feedback system is necessary and is realized between the HQM and assessment. At control points, a subsequent retrospective evaluation is carried out to verify internally the accuracy and likelihood of predictions. This allows for feedback and updates the background data, methods, and tools by enhancing the results' robustness.

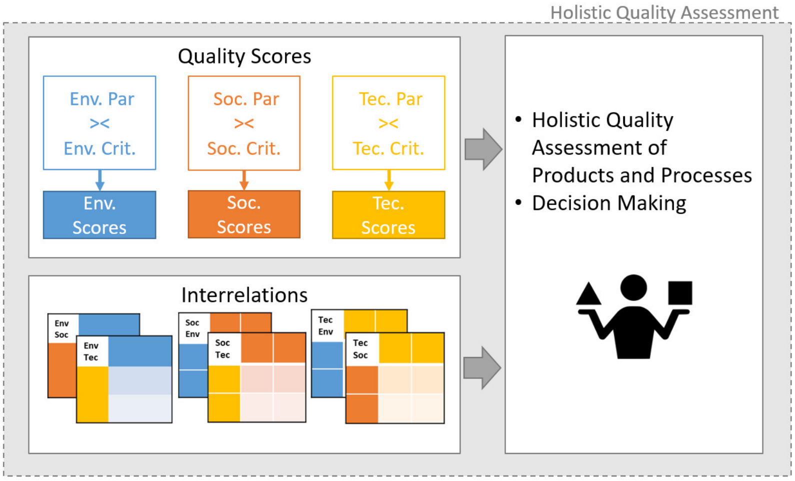


Figure 2. Holistic quality assessment.

Figure 3, below, explains in more detail how holistic quality assessment works and how it interacts with the previously established HQM.

As a preliminary step, the holistic quality parameters are measured and determined in an absolute form. Holistic quality assessment starts with the evaluation of each quality characteristic and its quality parameters' calculation.

The quality characteristics and parameters are then assessed with regard to quality requirements and converted into a score. Scores are reached following a series of steps (see Figure 3).

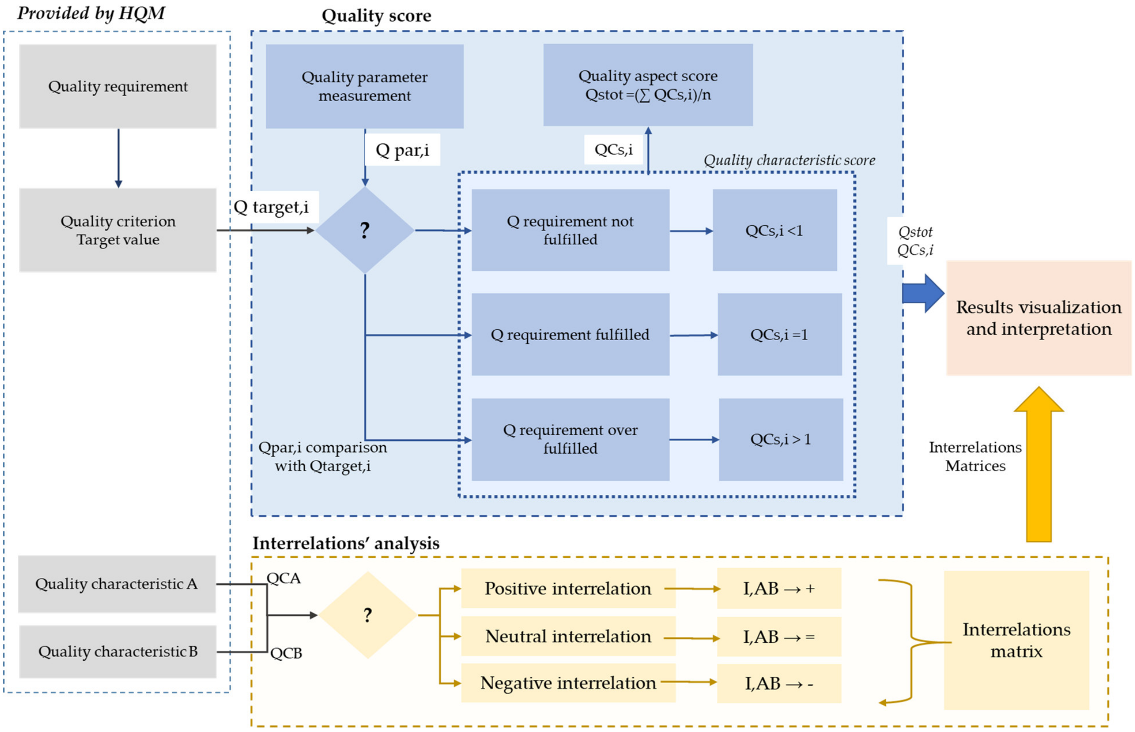


Figure 3. Holistic quality assessment. Workflow for quality score calculation and interrelations analysis.

(A) Quality score (single characteristic—monodimensional)

1. Quality criteria established based on quality requirements for design and production (provided in HQM).
2. Quantification of quality characteristics through quality parameters. The quantification occurs through measurements, calculations, or direct questionnaires.
3. Comparison between actual (e.g., measured) quality parameter values and target values related to quality criteria. For each characteristic, it is necessary to verify if quality criteria are fulfilled. The quantitative comparison can demonstrate a missing achievement but also an overfulfillment of the established target.
4. The fulfillment level is converted into a singular characteristic score. Singular score calculation is entrusted to expertise in the relevant field. The score ranges between 0 and 2. This rating system makes it possible to standardize the different parameters and their scales, to make the characteristics comparable, and, therefore, to perform the quality assessment:
    - score < 1 indicates a falling short of quality requirements according to the established criteria;
    - a score = 1 indicates achievement of sufficient quality, according to the established criteria;
    - score > 1 is related to eventual overfulfillment.
5. The total quality score of every quality aspect is calculated as the product of all characteristics. Thus, the total score is given by the mean value of all characteristics scores. Q_t is the total quality score, and q_{ti} is the assessment for one single quality characteristic.

$$Q_t = \frac{(q_{t1} + q_{t2} + \cdots + q_{tn})}{n} \tag{1}$$

The assessment of the total score is now equivalent to the assessment of the individual characteristics and a value of 0 points is given for a failure to meet the quality requirements in one or more characteristics and, thus, the need for a revision of the design. A value of 1 confirms the adherence to all required limit values and the possible production of the component. A value of 2 points to eventual overfulfillment. The following example has been selected in order to clearly explain the established HQ assessment score system. In the instance of environmental quality and climate change, the EU's initial nationally determined contribution (NDC) under the Paris Agreement and the European Green Deal was the commitment to reduce greenhouse gas emissions by at least 55% by 2050, compared to 1990 [47]. This concept has been transferred to building certification and, e.g., in the German DGNB system [23]. According to DGNB, it is required to achieve 30% fewer life-cycle emissions in comparison with reference values, defined for several building types and with consideration of the current status [23]. This situation reflects the achievement of sufficient quality (score = 1, see Section 5.2). However, environmental performance can be further enhanced, with higher emissions savings, earning a quality score of 2 and reflecting the achievement of certain "absolute" quality requirements and goals. In the example of climate change, the absolute goal is climate neutrality, or zero Greenhouse Gases (GHGs) emitted by fossil fuels (see Section 5.2). Quality scores equal to 1 reflect the achievement of mandatory requirements such as load-bearing capacity or the same environmental performance as the respective benchmark. Quality scores equal to 0 point to certain requirements being unfulfilled.

However, as also explained in Section 5.2, it is not always possible to define absolute "goals" for each quality characteristic, and the system itself may require some adjustments, depending on the aspect under analysis. Overall, the score system can vary among different aspects, depending also on the *disciplinary* requirements. Details and documentation on quality requirements and established criteria are provided in the following sections.

(B) Interrelations evaluation (multidimensional)

Based on the characteristics of the different quality aspects, we could identify *interrelations* between the different characteristics belonging to different disciplinary aspects (see Figure 3). Due to the interdisciplinary and holistic nature of the established model, interrelations among characteristics of the same aspect are not assessed in this work.

Interrelations among characteristics belonging to two different aspects can be reciprocal, i.e., by presenting a logical equivalence (see Formula (2)):

$$\mathrm{QC_A}\ (\mathrm{x}) \rightarrow \mathrm{QC_B}\ (\mathrm{y}) \wedge \mathrm{QC_B}\ (\mathrm{y}) \rightarrow \mathrm{QC_A}\ (\mathrm{x}) \Rightarrow \mathrm{QC_A}\ (\mathrm{x}) \leftrightarrow \mathrm{QC_B}\ (\mathrm{y}) \tag{2}$$

where:

$\mathrm{QC_A}$ and $\mathrm{QC_B}$ are two selected quality characteristics;
x and y represent the aspect with which the characteristic is associated (technical, environmental, or social).

However, such a logical equivalence between two quality characteristics and their interrelations is not always assured [48]. $\mathrm{QC_A}$ can influence, for instance, $\mathrm{QC_B}$ but not vice versa. Therefore, it is necessary to specify:

- **Agent**: the characteristic that affects;
- **Object**: the affected characteristic.

An interrelations visualization possibility can be enabled through an interrelation matrix, in which each interrelation can be analyzed in both directions. As a reference, the interrelation matrix presents the agent characteristics horizontally, while the far-left vertical columns list the object characteristics.

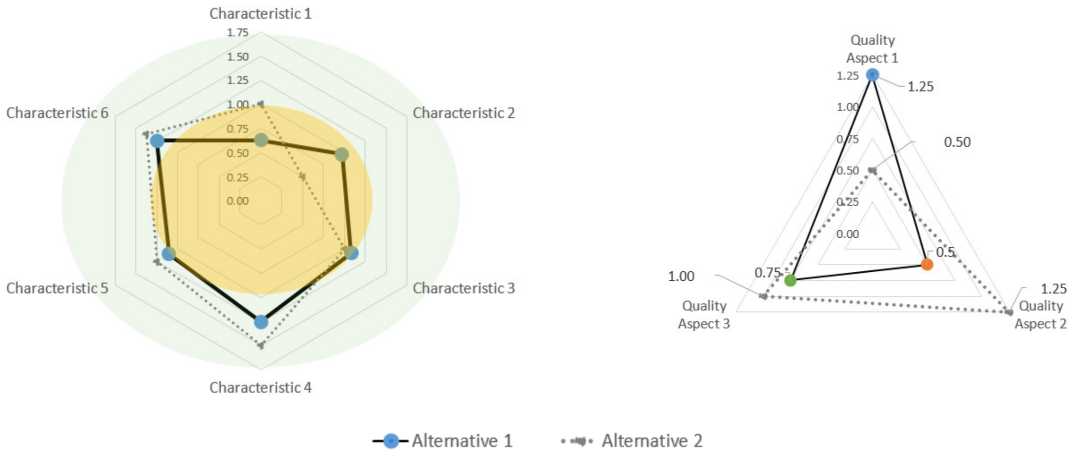
Interrelations can be classified as:

- **Positive**: the agent characteristic affects the object characteristic in a positive way (enhances);
- **Negative**: the agent characteristic affects the object characteristic in a negative way (worsens);
- **Neutral**: the agent characteristics does not affect the object characteristic, and, if this occurs also in the other direction, then the two characteristics are *independent* (no interrelations).

(C) Results preparation and visualization

Table 2 shows how the interrelations of the different quality characteristics can be represented by agent–object relations and different relation categories.

The results of the single characteristic quality scores and total quality scores are presented using radar diagrams (see Figure 4). The unified score that ranges from 0 to 2 makes it possible to interpret the results of the (predictive) evaluation in a simplified way and to compare the different characteristics, aspects, and quality of different design alternatives. This can support decision-making according to the holistic quality approach.



(a) (b)

Figure 4. Conceptual visualization of (**a**) quality scores and (**b**) total quality scores for two different alternatives.

Table 2. Conceptual visualization of the interrelations between quality characteristics of different quality aspects.

	AGENT	Quality Aspect 1		Quality Aspect 2		Quality Aspect 3	
OBJECT		Characteristic 1	Characteristic 2	Characteristic 3	Characteristic 4	Characteristic 5	Characteristic 6
Quality Aspect 1	Characteristic 1			0	-	0	+
	Characteristic 2			0	-	0	+
Quality Aspect 2	Characteristic 3	0	+			0	+
	Characteristic 4	0	+			0	+
Quality Aspect 3	Characteristic 5	0	+	0	-		
	Characteristic 6	0	+	0	-		

3. Case Study: Graded Concrete Slab

To present the operative methodology of the HQM as applied to a graded concrete slab, the following section will give a summary of the relevant design and production aspects of graded concrete components. This is intended to provide an understanding of the application of the HQM and assessment that follow. The HQM is applied to the design of a concrete slab measuring 7.2 m square and 180 mm high (Figure 5). The case study includes two specimens: a solid slab, with a design that corresponds to the widely used state of the art, and a slab made of graded concrete, whose interior is designed with hollow spheres in a cubic close packing to achieve a lighter component while maintaining the limits in load-bearing capacity. The hollow spheres have an outer diameter of 150 mm and a wall thickness of 2 mm. Consequently, the required concrete volume for the solid and the graded slab is 450 kg/m^2 and 254 kg/m^2, respectively. The comparison of the two concrete slabs will show how the HQM supports decision-making with regard to different component options.

This section describes the fundamentals of graded concrete, the slab's design process, the quality criteria most relevant to the design, the simulation-based check for compliance with these criteria, and the envisaged cyber–physical production of the slab.

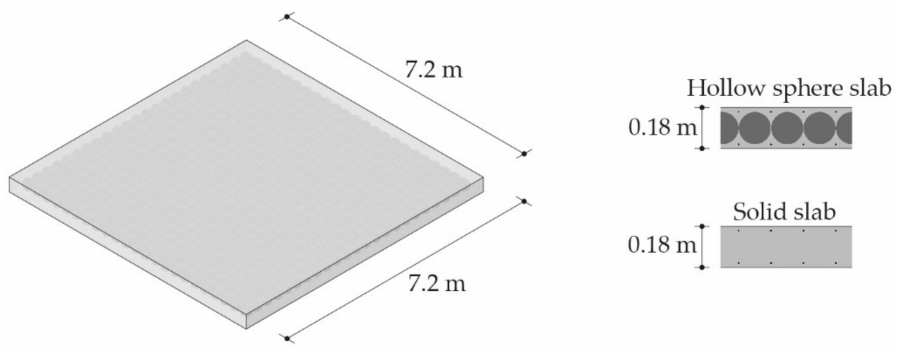


Figure 5. Isometric view of the simply supported slab made of graded concrete.

3.1. Fundamentals of Graded Concrete

In concrete construction, building components usually have a solid cross section, although their utilization along with the spatial directions is inhomogeneous. Consequently, their mass is higher than required for load-bearing capacity. Graded concrete is an innovative technology for minimizing the mass of components, while maintaining the limits for load-bearing capacity [49]. This mass reduction rests on a stress-appropriate arrangement of internal cavities with a distribution and size that depend on structural and physical building requirements [49] (see Figure 6).

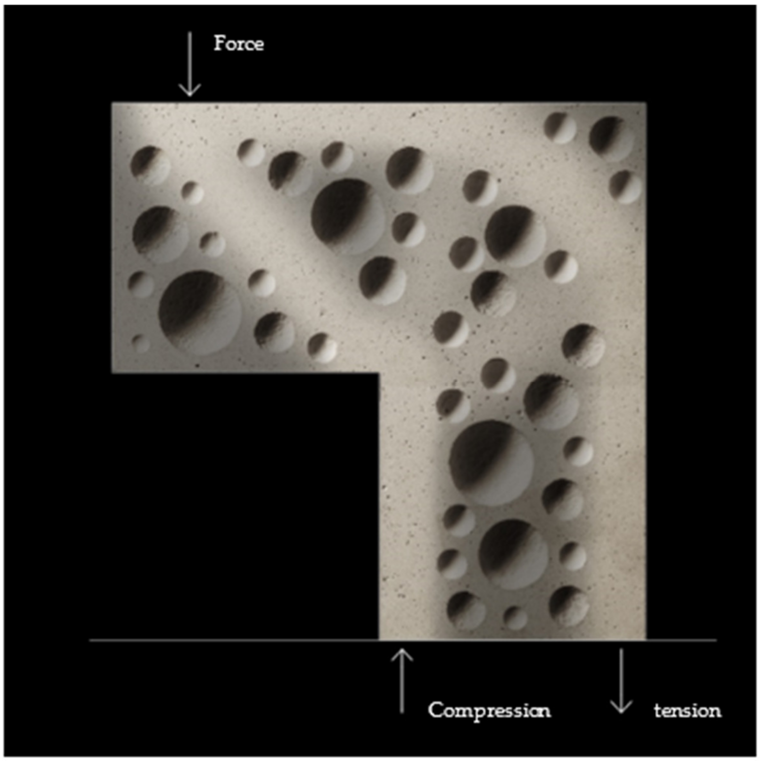


Figure 6. Meso-graded cantilever with defined tension and compression struts and corresponding distribution of hollow spheres.

The research on design principles and production processes for graded concrete components has—since its invention by Werner Sobek—been deepened in interdisciplinary projects and is ongoing [50]. In the so-called meso gradation, hollow concrete spheres of different diameters greater than 10 mm are placed between the reinforcement layers before casting. The concrete is then poured layer by layer in a time-controlled process to prevent them from floating [49,51]. The embedded hollow concrete spheres allow for a material replacement, leading to a significant mass reduction.

3.2. Design Process

The design process was developed specifically for the design of graded concrete slabs. It comprises three basic steps: (a) gathering of information on restrictions and design requirements; (b) iterative design of the components; and (c) post processing of the design for data transfer to fabrication. A process description of the Business Process Model and Notation (BPMN) format, together with HQM decision and control points, is given in Section 4.1.

For this case study, it was assumed that the underlying project was already so far advanced that—as proposed in [52]—an architect's brief and the structural climate were available. The architect's brief mainly includes the requirements of the client and the concept of the building, and the structural climate provides information such as ground conditions, weather conditions, and information on the availability and quality of craft and materials. Based on this information, requirements and criteria for the design are collected and formulated, providing the designer with a design space and enabling them to evaluate the quality of individual solutions.

Structural design comprises three main steps: (1) formulation of a design proposal, (2) analysis, and (3) evaluation. These steps are carried out iteratively, starting with a rough level of detail. Throughout the process, designers increase the level of detail, while constantly evaluating and adjusting the design proposal. If necessary, some requirements or criteria may be adjusted during the process. The final solution must meet all requirements, perform well within chosen design criteria, and have a sufficient level of detail for production planning.

Finally, in the post-processing step, all data relevant to the fabrication process are determined. For the example of a quadratic plate with hollow spheres, these are the plates' width, length, and height as well as the spheres' center positions, radius, and height above the formwork base [53].

3.3. Quality Requirements for Graded Concrete Components

This section presents quality requirements that are commonly used in the design of structures and building constructions. They are included for the assessment of the social, technical, and environmental quality characteristics of the HQM.

The requirements can be classified in several ways. Mandatory requirements are those with an application and fulfillment that are required in order for a structure to be legally approved for construction. Elective requirements are any additional requirements that may be imposed by the client or a designer. Across these two categories, the requirements can take different forms: for example, as threshold values, the exceeding of which could lead to the exclusion of a design solution; the required existence of certain properties such as reusability; or a criterion that allows the ranking of several design solutions, such as the lowest possible weight.

Mandatory requirements are divided into structural, building physics, and production-related requirements.

The structural requirements are mostly so-called limit states given by building codes [34] that must be proven not to be exceeded for standardized loads [54] and material resistances. A distinction is made between the ultimate limit state (ULS) and the serviceability limit state (SLS) [34,55]. An exceeded ULS corresponds to an unacceptably high risk of structural failure. On the other hand, the SLS refers to whether a building is still usable in the sense of its designated use. Serviceability limits for concrete comprise deflection of a component, the opening width of cracks, stresses in the concrete, stresses in the reinforcement, and the acceleration caused by dynamic excitement. In addition to the limit states, the codes also specify certain geometric constraints on which a component design is based. In this case study, these are essentially the maximum permissible distance between the steel rebars to prevent excessive crack opening and the minimum concrete cover to protect rebars from corrosion.

Sound insulation and fire protection are the decisive building physics phenomena for a slab inside a building. In sound insulation, the essential phenomena for consideration in a component design are airborne sound and impact sound transmission [36]. Since both values depend directly on the component mass, they can be interpreted in a first approximation as a threshold value for a minimum required mass. In the event of a fire, a building component must be able to carry loads (resist), prevent fires from spreading to other rooms (envelop), and prevent excessive heating of the building component on the side away from the fire (insulate) for a given time [35]. Eurocode 2 formulates geometric threshold values for these requirements, namely the total thickness of a slab and the distance of reinforcement steel from the surface exposed to fire.

Production-related requirements result from components' preparation, production, transport, and assembly. For cast-in-place concrete components, these are primarily construction tolerances and variations in material quality. For example, the concrete cover of rebar is generally increased by 10 mm to prevent deviations that could impair the bearing capacity [34]. In addition, due to unpredictable environmental conditions, a larger scatter of material properties is assumed for material properties such as compressive strength [34].

Elective requirements occur in a broad spectrum. Compared to the requirements set out in codes, they may impose more severe restrictions on the design. Concerning the case study shown, the following classification is proposed here for elective requirements: tightening of mandatory requirements and formulations of target values for optimal design.

An elective criterion tightening existing limits is established, for example, by the Association of German Engineers (*Verein Deutscher Ingenieure*—VDI) and, specifically, in [56]. It defines user comfort levels, leading to sharp increases in demanded sound insulation levels. An example of a target value for optimal design is Werner Sobek's Triple Zero principle [57,58]. Triple Zero stands for zero non-renewable energy, zero waste, and zero emissions. It originates directly from recognizing the building industry's responsibility for a livable environment in the face of today's challenges. For the concrete slab, the requirement of high recyclability, as well as the lowest possible GWP and weight, are derived from these design criteria, which are used to compare different design solutions.

In the field of building design, as a more systemic and holistic mindset spreads in the context of an increasing environmental and social awareness that began in the 1960s and 1970s, more integral approaches are required. This results in more complex designer workflows, involving a variety of expertise, and takes into account all aspects of building construction and technology [7,8]. In the field of integral planning, and in the here-presented co-design, unlike in previously applied approaches, elective requirements can be considered simultaneously with mandatory ones. This is due to the need for higher building quality (social and environmental, in particular), to be ensured during the early design stages.

Elective requirements are specifically relevant for the application of the HQM, which aims to support decision-making within these design opportunities with regard to the achievement of the product intention under the best possible agreement with social and environmental requirements. This assumes that at the start of the planning process there is a particular underlying product intention that is subject to certain mandatory requirements and, therefore, cannot be influenced by decision-making.

3.4. Automated Cyber–Physical Fabrication of Graded Concrete Components

For the fabrication of graded concrete components, a multi-stage process is currently under development. With an initial preparation step and two production stages, the process is structured as follows:

1. Formwork preparation and trajectory planning;
2. Insertion of embedded elements;
3. Concrete application.

In the first stage, the geometric information from the design is used to calculate reference trajectories for the application system, namely a semi-autonomous minicrane and a pumping system (see Figure 7). The minicrane is actuated by a hydraulic system, and it possesses additional electric joints. These succeed the previous endeffector for increased working space, and the pumping system consists of a conventional concrete piston pump, a hose, and a concrete extrusion unit mounted on the minicrane's endeffector.

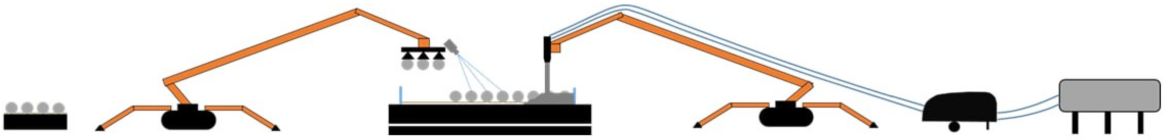


Figure 7. Production process of hollow-sphere components, as envisaged.

In the second stage, the necessary insert elements (hollow spheres and reinforcement) are placed inside the formwork by the minicrane. The minicrane is equipped with a stereo camera and a tailored navigation algorithm, which explores its environment in a first step, building up a height map of potential obstacles and searching for the formwork and insert elements. Following the localization, the elements are put into the formwork. For the hollow spheres, a vacuum gripper delivers this task. For the reinforcement bars, a mechanical gripper is employed, as the weight of the reinforcement is considerably higher.

In the third stage, the pumping system delivers the concrete from a reservoir to the prepared formwork, based on the previously calculated reference trajectories. The necessary models describing the outflow dynamics are based on those derived in [59]. For both online- and offline-calculated input trajectories, it is advisable to check after each layer if buoyancy can be avoided and whether layer height is being achieved to a sufficient degree of accuracy, thus necessitating another control point [60].

In this case study, the production process of graded concrete is fictitious, as the production of the graded concrete slab was not carried out. The description is based on the production process developed by the graded concrete research team. Although the production process was not carried out, this article will show how a holistic quality evaluation can be executed predictively for the production process based on information from the design phase.

4. Application of the HQM on Graded Concrete Processes

4.1. Application of the HQM to Graded Concrete BPMN

The graded concrete design and production processes are summarized as Business Process Model and Notation (BPMN) graphs. BPMN is a graphical representation of business processes including all aspects seen as relevant by the creators [61]. For this case study, only the design phase and the production processes of graded concrete building components are considered. Other life-cycle and process phases are not assessed because of the fictitious nature of the component. For the setup of the holistic quality assessment, it is essential to establish decision points and control points, which are included in the BPMN.

The illustration of the computer-based design and automated cyber–physical fabrication processes through the BPMN allow the definition of two main decision points (DPX):

- DP1 occurs during early design development (see Figure 8). Decisions taken here concern the structural framework and the cross-section planning.
- DP2 overlaps design analysis and evaluation (see Figure 8). With the verification of fulfilled criteria, decisions regarding the construction site and its management are taken.

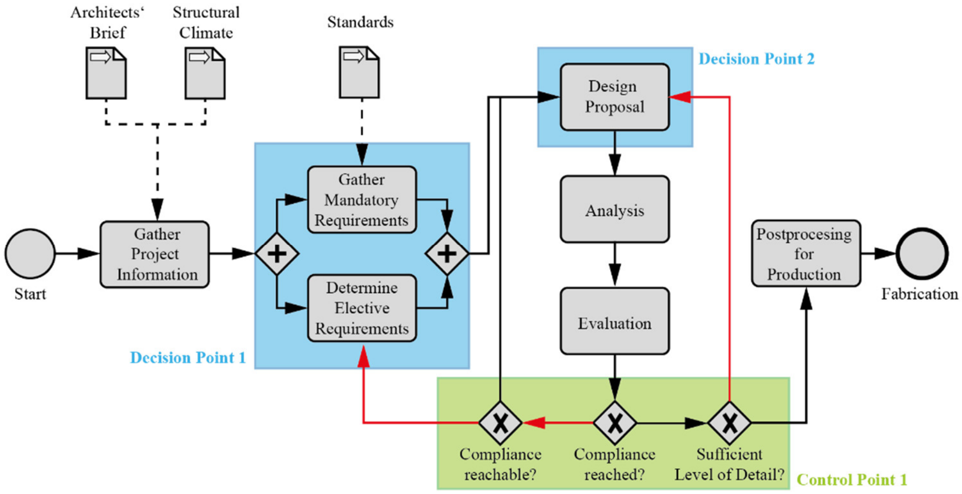


Figure 8. Design process of a concrete slab in BPMN formulation with HQM decision and control points.

At DP1 and DP2, information about the quality related performance of processes or products is provided by predicting the quality of the respective control points (CP1) related to the design process. Depending on the derived elements' design performance, minimal requirements are conditionally verified.

Control points (CPX) for the graded concrete case study are (see Figures 8 and 9):

- CP1 → Control of the design proposal;

- CP2 → Control of the production process;
- CP3 → Control of the final product.

In this work, the holistic quality was assessed at DP2, which allowed us also to derive results for CP1 and make predications for CP2, especially with regard to the social quality of the graded concrete production process, and CP3 with regard to the technical and environmental quality performance of the produced component.

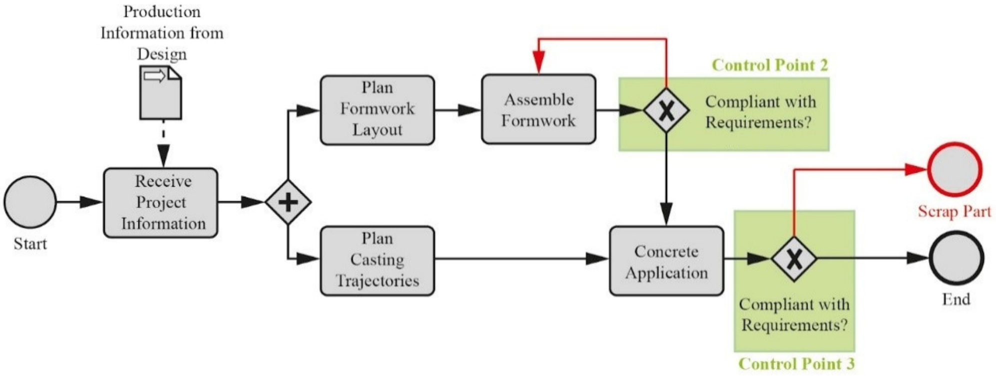


Figure 9. Production process of a concrete slab in BPMN formulation with HQM decision and control points.

The graded concrete design and production process, which is currently under development, was used as the basis for the evaluation. Therefore, the derivation of all quality parameters and characteristics included in the HQM was not possible in the case study provided here. Some parameters can be calculated only after building production (e.g., user-dependent characteristics) or when the building is further specified. This required information could not be provided during the slab design process for a fictive, not-further-specified building.

All steps in the BPNM process presented were either retrospective (CP1) or predictive (CP2; CP3, see Figure 9) and evaluated for this case study, but only for the design phase (DP2).

4.2. Technical, Environmental, and Social Characteristics of Graded Concrete Process

Along the described control and decision points, relevant requirements for the design and manufacture of the graded concrete slab were evaluated with the help of associated quality characteristics and parameters. The requirements, characteristics, and related exemplary parameters used are shown in Table 1.

5. Results

The assessment is carried out for the graded concrete slab and compared with a conventional massive concrete construction. This allows for a better understanding of the holistic quality of the final graded concrete product. It also enables an evaluation of the advantages and disadvantages of common techniques and technologies. In this sense, holistic quality assessment is aimed not only at product and processes assessment but also at the comparison of alternatives, the evaluation of improvement potential, and the decision-making during the overall planning. Quality scores can be differently calculated, depending on the related requirements and the established criteria for the assessment. The requirements and criteria for each of the three aspects considered are listed below, followed by a description of the interrelation assessment.

5.1. Technical Quality Score and Discussion

For the compliance check, this subsection compares the numerical simulation results of the slab with concrete hollow spheres and a solid reference system with the mandatory requirements.

While this design step is legally mandatory, it also represents a technical quality assessment and is, therefore, included in the HQM.

The numerical simulations are conducted with the FE software Abaqus, using the material model, according to Schmeer [51]. Following investigations on the biaxial load-bearing behavior, the load distribution method according to Henri Marcus is considered [62]. This method assumes that a simply supported slab is subdivided into perpendicularly crossing beams obtaining an equal deflection in their point of intersection [63].

In addition to the dead weight, the load assumption considers an extension load of 75 kg/m^2, including a floor construction of 35 mm lightweight screed, 30 mm thermal insulation by EPS, and a separation layer to the concrete slab. The live loads are designed for office use and, consequently, amount to 200 kg/m^2. In this context, the load assumption abstains from a partition wall surcharge.

In the *serviceability limit state* (SLS), the deflections and crack widths, as well as the steel and concrete stresses of the two systems, comply with the normative limits. Figure 10 shows the comparison of the deflections in the governing load case. In SLS, the hollow sphere slab is cracked while the solid reference system remains uncracked. Thus, the reinforcement's effect is of minor importance for the massive slab in SLS.

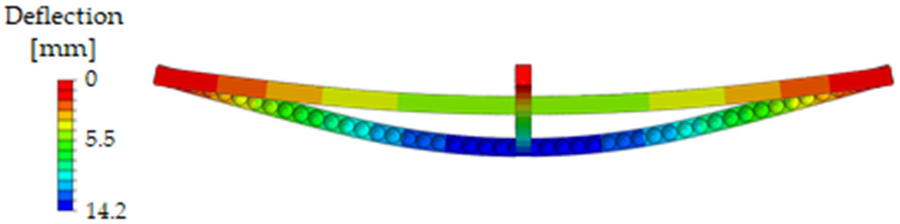


Figure 10. Comparison of deflection figures for the solid and hollow sphere slab in SLS.

Both systems fulfill the load-bearing capacity at the *ultimate limit state* (ULS). However, the reinforcement in the solid reference system increases, since its stress exceeds the design yield strength at an equal reinforcement diameter to the hollow sphere slab, due to the higher dead weight of the massive construction, of 450 kg/m^2. With 254 kg/m^2, the hollow sphere slab has a significant mass saving potential of about 45%, compared to the solid reference system. The results of these calculations are used for the following evaluation as a quality parameter for technical quality.

For the evaluation of technical quality, a compliance check with the mandatory requirements is now carried out. Therefore, a binary evaluation scheme with 0 and 1 is used. Here, 0 means the requirements are not met, while 1 means the limits are met. The summarized results of the numerical simulation results of hollow spheres and solid slabs are shown in Table 3. These then result in the quality scores shown in Table 4.

Table 3. Technical quality characteristics evaluated for the end of design phase graded and massive concrete slabs.

Characteristic	**Sound Insulation**		**Load-Bearing Behavior**					
Parameter	**Sound Reduction Index**	**Impact Sound Pressure Level**	**Component Deflection**	**Opening Width of Cracks**	**Stresses in the Reinforcements**	**Stresses in the Concrete**	**Load Bearing Capacity—Steel Stress**	**Load Bearing Capacity—Concrete Stress**
Requirement/criteria	$R'_w \geq 54$ dB	$L'_{n,w} \leq 50$ dB	$f \leq 14.4$ mm	$w = 0.4$ mm	$\sigma_{t,SLS} \leq 400$ N/mm^2	$\sigma_{c,SLS} \leq 22.5$ N/mm^2	$\sigma_{t,ULS} \leq 435$ N/mm^2	$\sigma_{c,ULS} \leq 28.3$ N/mm^2
Graded concrete slab	55 dB	50 dB	14.2 mm	0.4 mm	234 N/mm^2	8 N/mm^2	371 N/mm^2	21.4 N/mm^2
Massive concrete slab	62 dB	41 dB	5.5 mm	<0.1 mm	174 N/mm^2	6 N/mm^2	380 N/mm^2	26.2 N/mm^2

Table 4. Technical quality characteristics' scores for graded and massive concrete slabs.

Characteristics (Abb.)	Graded Concrete Slab	Massive Concrete Slab
Fire insulation (FR)	1	1
Exposition class (EXC)	1	1
Sound insulation (Sins)	1	1
Load-bearing capacity (SLS)	1	1

A comparison of the technical quality assessments shows that all technical requirements are met for both components. In general, it can be seen that the limit values are fulfilled much more tightly with the graded concrete slab. For example, the comparison of the deflections in the governing load case shows a vertical deformation of 14.2 mm for the cracked graded slab, thus satisfying the sharply selected limit criterion of 14.4 mm, while the deformation of the uncracked solid reference system is approximately 5.5 mm. In addition, for all characteristics, the graded concrete slab reaches the boundaries set by the limit values because of the targeted optimization and the reduced use of resources. On the other hand, there is still potential for optimization in the case of the massive concrete slab.

5.2. Environmental Quality Score and Discussion

As also documented in Appendix A, environmental quality assessment occurred on the basis of the currently applied environmental building sustainability assessment (DGNB, for the German building context [23]). The reference construction is a conventional massive concrete construction with the following characteristics (see Table 5).

Table 5. Considered quality characteristics and calculated parameters of reference concrete slab.

	CCtot (kg CO_2 eq)	PEtot (MJ)	PENRT (MJ)	PERT/PEtot (%)	Weight Tot (kg)	Non-Renewable Resources Savings (%)	Recycling (%)
1 m^2 massive concrete slab	62.3	380.3	213.1	40	448	0	0
1 m^2 graded concrete slab	36.9	304.1	154.5	50	280	40	0

Quality criteria and the consequent score calculation are in line with the DGNB system (version 2018) [23] and are presented in Table 6.

Table 6. Calculation quality characteristics' scores.

	Score	CCtot	PEtot	PENRT	PERT/PEtot	Weight tot	Non-Renewable Resources Savings	Recycling
Limit	=0	1.4	1.4	1.4	0.05	1.2	−0.1	0.05
Target	≤1	0.7	0.7	0.7	0.3	0.7	0.3	0.1
Overfulfillment	≤1.5	0.5	0.5	0.5	0.375	0.6	0.375	0.2
ENV target	=2	0	0.3	0	1	-	1	1

As a result, the following scores are derived, as shown in Table 7.

Table 7. Environmental quality characteristics' scores for graded and massive concrete slabs.

Characteristics (Abb.)	Graded Concrete Slab	Massive Concrete Slab
Climate change total (CCtot)	0.91	0.46
Primary energy total (PEtot)	0.69	0.46
Primary energy non-renewable (PENRT)	0.77	0.46
Share of renewable energy (PERT/PEtot)	1.09	1.05
Non-renewable materials savings (NRM)	1.50	0.2
Total weight (Weight tot)	0.95	0.32
Recycling (REC)	0.16	0.16
Mean ENV	0.87	0.44

The graded concrete slab achieves higher scores for most of the considered environmental quality characteristics. This is due to the reduction in consumed concrete mix and environmentally aware choices. In fact, for the whole production processes, renewable energy sources have been chosen instead of fossil fuels. The share of renewable energy is higher than the minimum requested and, therefore, the PERT/PEtot score is higher than 1. This is also the case with the PENRT score. Due to a lesser energy demand within the slab production process, the graded concrete technology overly fulfills the requested minimum environmental performance. This also results in a reduced climate change potential and a reduction in emitted GHGs (40%). Overall, however, the mean score does not reach 1. This is mostly due to the end-of-life routes, which are based on current concrete elements disposal processes and do not allow credits due to recycling. Improvements in terms of consumed energy and energy sources could also lead to an improvement in terms of CCtot and PEtot, in order to reach the environmental quality requirements. The LCA results are collected in Appendix A.

5.3. Social Quality Score and Discussion

The social quality model uses social quality requirements, characteristics, and parameters derived from various sources. On the level of requirements, an analysis of public policies at the international and national level (e.g., SDG) defined what is at stake, e.g., decent work or wellbeing. The subordinate characteristics are established concepts for describing the requirements and are based, among other things, on the results of stakeholder reports and given certification systems (e.g., ILO declarations, DGB *Gute Arbeit Index*, DGNB). For some of these concepts, parameters already exist and have been integrated into the model. We developed further parameters based on qualitative requirements derived from the requirements and characteristics.

In order to standardize the parameters and to follow the consistency of the HQM, we operationalized the parameters using the logic of Likert scales. Likert scales are scales commonly used in the social sciences that enable qualitative data to be collected quantitatively. They define value ranges, which can be measured in different degrees between absolute statements (e.g., completely true, partly true, not true at all). By using an odd number of gradations, it is possible to create a middle category, which can be understood as neutral, or in the logic of the HQM, as a minimum requirement that is fulfilled. Most quality characteristics are described based on several parameters, which are summarized as an unweighted additive index. They describe each characteristic as a score corresponding to the mean value.

The created Likert scales with a range of 1–5 were transformed into the common score value range of 0–2. Some characteristics and parameters are excluded from this logic. For example, the parameters of the characteristic "unacceptable work" (includes forced and child labor) do not include a middle category. For other characteristics such as "human agency", the minimum requirement was defined as higher than the middle category in order to better meet policy and stakeholder requirements. Since the minimum social requirements can be interpreted in different ways, an attempt was made to determine them based on policies and stakeholder analyses. However, open documentation can empower users of a possible future digital HQM tool to adjust them. The documentation of the parameters used in this case study can be found in the Appendix A. In addition, for this case study, an attempt was made to provide benchmarks to better classify the results. These are based on a report by the DGB [64], a literature review [65], and interviews with developers of graded concrete.

In the context of the case study, requirements and associated characteristics were used that relate to the design and production processes. These requirements relate to the quality of digital design processes, production conditions (decent work and socio-technical robustness), wellbeing of users, and material-related characteristics (building physical properties). The investigation of graded concrete carried out here shows that product-related characteristics such as physical building properties are sufficient (=1, see Table 8). Physical building properties represent a characteristic of the wellbeing requirement of future building users. The rating of 1 is due to the fact that the parameters used overlap with the mandatory criteria for technical quality (building physics properties) and, therefore, correspond to the technical quality binary evaluation scheme described in Section 5.1.

Table 8. Social quality characteristics scores for graded and massive concrete slabs.

	Characteristics (Abb.)	**Graded Concrete Slab Quality Assessment Score**	**Massive Concrete Slab Quality Assessment Score**
Decent Work	Control (Contr)	0.63	1.00
	Safety (Safe)	0.97	0.50
	Work intensity (WorkInt)	1.08	1.00
Socio-Technical Robustness	Job security (JobSec)	1.25	1.50
	Competences (Comp)	1.10	1.25
	Digital accessibility (DigAcc)	1.25	1.38
	Transparency (Transp)	1.00	1.63
	Human agency (HAgen)	0.93	1.45
Well-Being	Building physics (BuiPhy)	1.00	1.00
	Process quality of design (PQDesi)	1.33	0.50

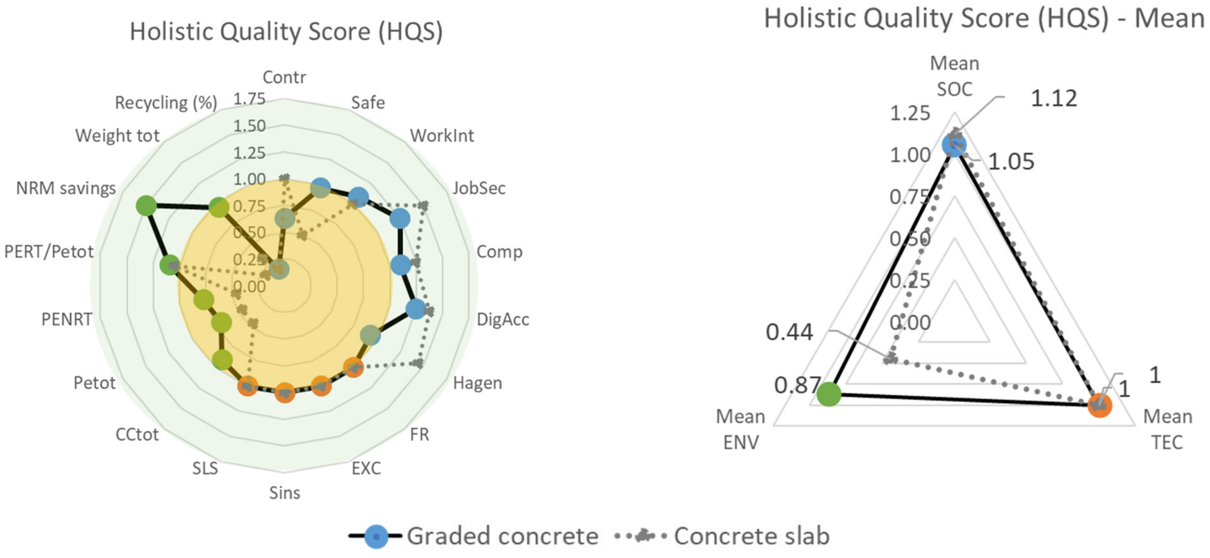
All parameters and measures can be seen in Appendix B.

The social quality of the digital design process exceeds the minimum requirements (1.33), due to the fact that the design process is based on a co-design approach that involves different stakeholders and includes different disciplinary knowledge; digital tools are used that comply with open data standards and include feedback loops, which enable better cooperation.

In contrast, the rating for process-related social quality requirement of decent work is in parts below the minimum requirements. This rating is not solely due to the graded concrete production process in development but rather to general, still-unresolved difficulties of automated/digitalized processes (specifically human control in cyber–physical systems and possible job loss due to eventual unqualified employees). Here, potential for improvement was identified especially in the interface design for human–machine interaction and possibilities for human intervention in the manufacturing process.

5.4. Holistic Quality Scores

Figure 11 provides a recap of the results. Figure 11a collects all quality characteristics, while Figure 11b shows the mean results for each aspect (technical, environmental, and social). graded concrete slabs are compared with conventional massive concrete slabs. Overall, graded concrete slabs proved to be advantageous from the technical perspective, the social perspective, and, especially, the environmental perspective.



(**a**) (**b**)

Figure 11. Visualization of (**a**) quality characteristics and (**b**) mean quality characteristics scores for each aspect (technical—red; environmental—green; social—blue). Calculation for massive and graded concrete slabs.

Based on the holistic quality evaluation, designers are encouraged to consider graded concrete as a valid construction option. The novel techniques used ensure better environmental quality, without undermining technical quality. Social quality, on the other hand, is less satisfactory compared to conventional concrete construction, primarily due to challenges in the use of cyber–physical production systems (which are often problematic) and the lack of accessibility and transparency of those systems (largely because the systems are still under development and, therefore, accessible documentation is absent). This, however, does not undermine the achievement of the established social quality requirements.

While technical requirements are already represented to a large extent in the mandatory requirements, the question arises whether overfulfillment has a positive effect on holistic quality through the interrelations of the different quality aspects.

5.5. Interrelations Analysis

Table 9 shows how each characteristic interacts differently with characteristics of other aspects. The overall technical quality, e.g., mostly *influences* other aspects and characteristics, while the environmental quality seldom influences other characteristics. On the contrary, other aspects influence the environmental quality.

Serviceability limit states (technical quality), e.g., as an agent, negatively influence environmental emissions. This is due to the amount of material required. The more material used, the higher the stiffness and load-bearing capacity of the slab and, consequently, the lower its deflection. With the improvement of technical quality, social aspects such as wellbeing interact positively. Emissions and resource consumptions, which belong to environmental quality, can be mostly seen as objects, namely as the results of choices taken during the design. Referring to the graded concrete slab example, fire regulations dictate the design and this, in turn, influences the production emissions. Greenhouse gases and other environmental emissions cannot be held responsible for fire regulations. For these reasons, after accurate analyses, CC, as for all environmental emissions, consumed material as well as consumed primary energy, which are displayed only as interrelating objects.

Social quality, unlike the others, influences other aspects only in a positive or neutral way. This means that social quality does not conflict with other aspects, but enhances environmental and technical performance, at least for the characteristics considered in this case study.

Table 9. Interrelations of the different quality characteristics included in HQM.

AGENT		TEC				ENV							SOC									
OBJECT		FR	EX CL	SI	SLS	CCtot	PEtot	PENRT	PERT/PEtot	NRM	Weight tot	REC	Contr	Safe	WorkInt	JobSec	Comp	DigAcc	Transp	Hagen	BuiPhy	PQDes
ENV	CCtot	-	+	-	-								0	0	0	0	0	0	0	0	0	0
	PEtot	-	+	-	-								0	0	0	0	0	0	0	0	0	0
	PENRT	-	0	0	0								0	0	0	0	0	0	0	0	+	+
	PERT/PEtot	0	0	0	0								0	0	0	0	0	0	0	0	0	+
	NRM	-	+	-	-								0	0	0	0	0	0	0	0	0	0
	Weight tot	-	-	-	-								0	0	0	0	0	0	0	0	0	0
	REC	0	0	0	0								0	0	0	0	0	0	0	0	0	0
SOC	Contr	0	0	0	0	0	0	0	0	0	0	0										
	Safe	0	0	0	0	0	0	0	0	0	0	0										
	WorkInt	0	0	0	0	0	0	0	0	0	0	0										
	JobSec	0	0	0	0	0	0	0	0	0	0	0										
	Comp	0	0	0	0	0	0	0	0	0	0	0										
	DigAcc	0	0	0	0	0	0	0	0	0	0	0										
	Transp	0	0	0	0	0	0	0	0	0	0	0										
	HAgen	0	0	0	0	0	0	0	0	0	0	0										
	BuiPhy	+	+	0	+	0	0	0	0	0	0	0										
	PQDesi	0	0	0	0	0	+	+	+	+	+	0										
TEC	FR					0	0	0	0	0	-	0	0	0	0	0	+	+	+	+	0	0
	EX CL					0	0	0	0	0	-	0	0	0	0	0	+	+	+	+	0	0
	SI					0	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0
	SLS					0	0	0	0	0	-	0	0	0	0	0	0	0	0	0	0	0

Here, in Table 10 the results of interrelations counting are provided.

Table 10. Interrelation analysis. Amount of positive, neutral, and negative interrelations among three aspects.

Interrelations (Agent—Object)	Technical—Environmental	Technical—Social	Environmental—Technical	Environmental—Social	Social—Technical	Social—Environmental
Positive Interrelation	3	3	0	5	8	3
Negative Interrelation	14	0	4	0	0	0
Neutral Interrelation	11	37	24	65	32	67
Total	28	40	28	70	40	70

Table 10 shows that negative interrelations do not occur in the design process of graded concrete slabs, except for technical quality.

Technical quality can represent a barrier to the achievement of the required environmental quality. In fact, the materials consumed and construction thickness dictate the achievement of minimal technical performance. This, consequently, worsens the environmental profile of the building element over its whole life cycle. This especially occurs in concrete elements, where production processes are energy consuming and recycling rates are low. This represents barriers, on which technical quality and environmental quality need to reach agreements (14 times over 28). Environmental quality can be claimed as a consequence of design choices. Therefore, as already mentioned, it does not affect social and technical quality. Social quality has the advantage of not being conflict-ridden, and its inclusion within the design process proved to be strategic for the achievement of quality requirements.

In conclusion, within design processes, there is a need for agreements and compromises to be reached between the designer and technical quality and environmental sustainability experts.

6. Summary

In this work, the novel developed holistic quality assurance concepts have been presented and applied for the evaluation of a graded concrete slab.

The HQM and the assessment concept is intended for evaluating the holistic quality of construction processes and supporting better decisions regarding technical, environmental, and social quality, by also solving communication barriers among different experts.

An additional value of the present work, the (retrospective) evaluation of the design phase and the predictive estimation of the subsequent production phase enable consideration of the whole building life cycle from the early stages of the decision-making process. Moreover, the conceived framework facilitates the construction processes' management, by ensuring a clear and transparent quality and sustainability assessment system. Lastly, a further novelty of the developed methodology, the analysis of the interrelations among different quality aspects, even if still in a qualitative way, can help designers identify synergies to be encouraged and trade-offs to be considered.

With regard to the case study presented here, despite the lack of information and data (due to the study being partially fictitious and based on a technology in development), the holistic quality approach provided relevant decision criteria at relevant decision points. The analysis carried out through the HQM and the following assessment demonstrated the advantages of graded concrete technology, when compared with conventional massive elements. Significant benefits can be found, especially in terms of environmental performance, while the minimal technical quality requirements are not undermined. In terms of social quality, graded concrete seems to be weaker at first glance, but this is mainly due to the use of insufficiently advanced technologies and is not exclusively attributable to graded concrete technology. Overall, the technology presents room for further improvement.

Therefore, the HQM and holistic quality assessment have the potential to fulfill the requirements formulated in [18] for sustainability assessment systems, by addressing suitability imperatives through a workable concept for decision-making. It provides a basis to resolve trade-offs between different quality aspects by taking the pluralism of sustainability assessment, through the description of interrelations, into account. Furthermore, the HQM resolves shortcomings related to criteria- and model-based approaches [22], by following a "hybrid" model.

Limitations and Outlook

Despite resolving shortcomings of current sustainability assessment, some improvements in the developed holistic quality concepts are still necessary. The HQM methodology is in need of two main developments: (1) in terms of applicability and (2) in terms of methodology.

With respect to applicability, the HQM should be extended and further tested through (a) analyses of different building levels and (b) analyses of different building process stages.

In the first instance, this extension will allow for investigation into how holistic quality evolves at different building levels (e.g., component, construction, whole building) and how such levels are interconnected. The extension of the analysis application for different building-process stages, i.e., during operation, would help in understanding and ensuring the overall quality and sustainability of buildings. Overall, the HQM applicability can be extended by considering not only the "building new" process but also processes related to measures on existing buildings, such as building renovation. This is also a major limitation of this case study, as it only examines the design of a specific building component and its associated production. Future work needs to provide proof of concept for the evaluation of a real component in a building system.

From the methodological perspective, characteristics' interrelations analysis needs to be improved with a stronger and more systematic quantitative approach. Going beyond the positive/negative interrelation assessment and interrelations counting was not feasible, due to a lack of data and analyses on quality characteristics with regard to quantitative cause and effect. A larger database would enable a quantification of the interrelation level and, finally, the creation of an "interrelation score", to be integrated along with quality scores into the holistic quality assessment, which would enable better results communication and interpretation.

Future research will provide an improved validation of the HQM with the help of more data and information. In addition, several beta test runs will be carried out for a first provision of feedback between the application of the HQM and assessment.

Lastly, the HQM will be further enhanced by additionally integrating the economic perspective. Implementing the criteria of economic quality, as an integral part of the sustainability triple bottom line (TBL) concept, will complement the holistic quality assessment by providing cost–benefit estimations and will, therefore, add a new dimension to the decision-making process towards sustainable construction.

An elucidation of economic quality will be especially useful for analyzing novel building and production technologies, in comparison to established construction procedures. In the case of graded concrete component, for example, reduced labor costs and higher material efficiency could be expected. Consequently, higher productivity on site, as well as a shift in the construction value chain and, therefore, even microeconomic effects, could be suggested. This knowledge will add to the holistic quality assessment regarding the broad practical application and feasibility of graded concrete components and vice versa: results on the economic quality of novel building systems during the design phase will give important feedback, for example, on how to reduce initial costs, while simultaneously maintaining the same technical and environmental quality. All in all, the economic dimension will strengthen the foundation for the analysis of sustainable design and construction processes and the production of quality building components.

Author Contributions: Conceptualization, D.F., O.G. and R.D.B.; methodology, D.F., O.G., R.D.B., L.B. (Laura Balangé) and L.Z.; validation, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B., D.N., P.H., L.B. (Lucio Blandini), H.C.J., C.K., P.L., O.S. and V.S.; formal analysis, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B. and D.N.; investigation, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B., D.N. and P.H.; data curation, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B. and D.N.; writing—original draft preparation, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B., D.N. and P.H.; writing—review and editing, D.F., O.G., R.D.B., L.B. (Laura Balangé), L.Z., B.B., D.N., P.H., L.B. (Lucio Blandini), H.C.J., C.K., P.L., O.S. and V.S.; visualization, D.F., O.G. and R.D.B.; supervision, L.B. (Lucio Blandini), H.C.J., C.K., P.L., O.S., V.S. and W.S.; project administration, L.B. (Lucio Blandini), H.C.J., C.K., P.L., O.S., V.S. and W.S.; funding acquisition, L.B. (Lucio Blandini), C.K., P.L., O.S., V.S. and W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research and the APC were funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2120/1. Grant number 390831618.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy—EXC 2120/1-390831618.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

This appendix presents information for the environmental quality assessment of graded and massive concrete slabs. Table A1 reports construction layers and weights. Tables A2–A4 report the climate change total (according to [33]), primary energy non-renewable, and primary energy renewable. Such results are also presented in Figure A1.

Table A1. Construction layers and weights.

Construction Layers	Weight Unit	Graded Concrete—C_0/4	Massive Concrete—C45/55
Load-bearing layer	kg/m^2	243.50	431.94
Rebars (Steel)	kg/m^2	13.46	16.09
Hollow spheres d = 15 mm Ws = 2 mm	kg/m^2	14.22	0.00
Insulation: EPS	kg/m^2	0.02	0.02
Coating: cement screed	kg/m^2	0.16	0.16
Total (kg)	kg/m^2	271.38	448.22
Material savings	%	−44%	0
Non-renewable material savings	%	−44%	0
Recycling concrete	%	0	0

Table A2. LCIA results. Climate change total, according to EN 15804 + A2 [33].

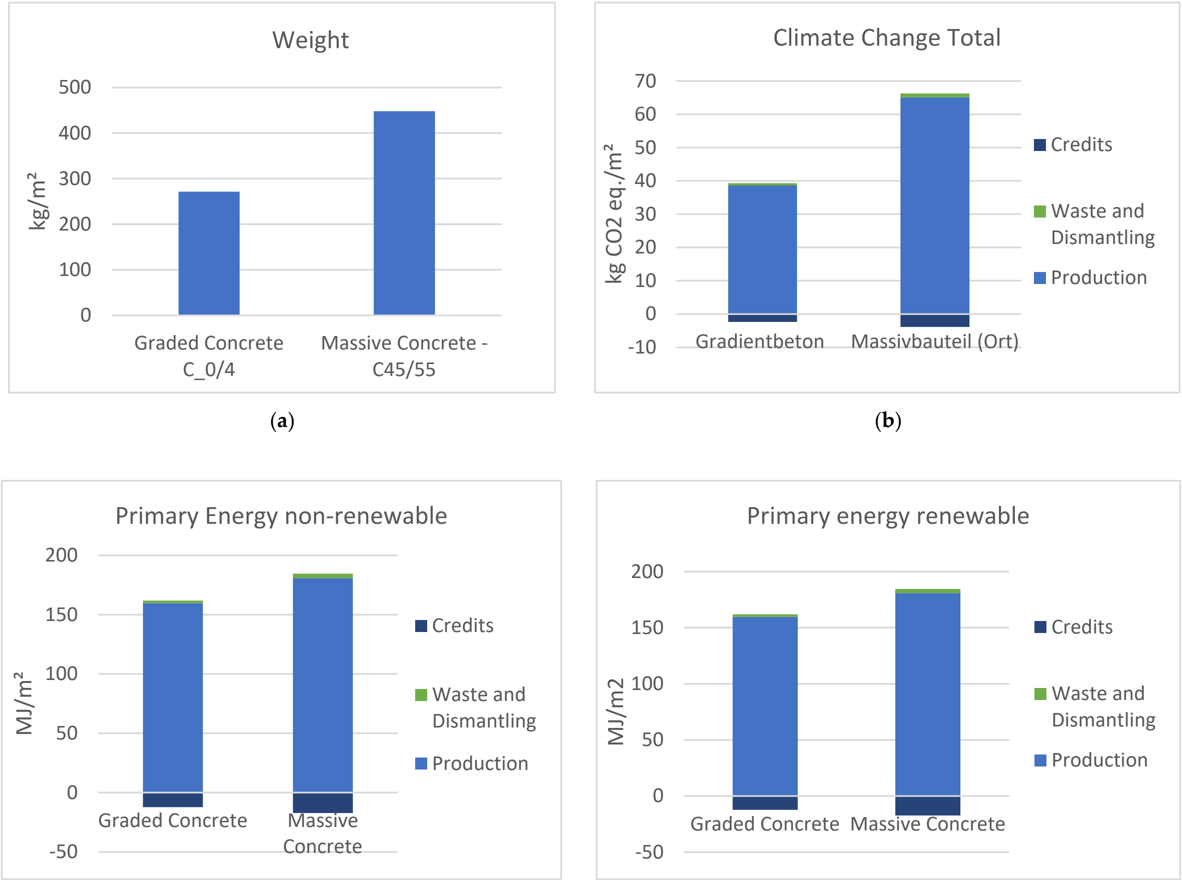
Life-Cycle Phase		CC tot Unit	Graded Concrete	Massive Concrete
A1–A3	Production	kg CO_2 eq.	38.60	65.08
C3	Waste and disposal	kg CO_2 eq.	0.70	1.16
D	Credits	kg CO_2 eq.	−2.38	−3.90
LC	Life cycle	kg CO_2 eq.	36.91	62.34
	Total savings	%	−41%	

Table A3. LCIA results. Primary energy non-renewable, according to EN 15804 + A2 [33].

Life-Cycle Phase		PENRT Unit	Graded Concrete	Massive Concrete
A1–A3	Production	MJ	176.88	248.91
C3	Waste and disposal	MJ	9.13	15.17
D	Credits	MJ	−31.49	−50.98
LC	Life cycle	MJ	154.51	213.10
	Total savings		−27%	

Table A4. LCIA results. Primary energy renewable, according to EN 15804 + A2 [33].

Life-Cycle Phase		PERT Unit	Graded Concrete	Massive Concrete
A1–A3	Production	MJ	159.66	180.78
C3	Waste and Disposal	MJ	2.26	3.74
D	Credits	MJ	−12.37	−17.35
LC	Life cycle	MJ	149.54	167.17
	Total savings		−11%	



(**a**) (**b**)

(**c**) (**d**)

Figure A1. Graphical results for the environmental quality assessment. (**a**) weight; (**b**) climate change total; (**c**) primary energy non-renewable; (**d**) primary energy renewable. According to [33].

Appendix B

We derived the values for GC from interviews with the developers of the GC technology and from observations. Some parameters could not be measured, due to missing information or due to their speculative character, e.g., the development of real wages of employees (DW_J4) with the use of advanced technology (GC) is difficult to predict, as this is subject to dynamics that go beyond the sociotechnical system under consideration and its characteristics, e.g., the level of qualification (which only explains 1.5% to 5% of the salary variance). For these, the value of the benchmark technology (MC) was used for better comparability (marked with [a]).

The values for MC were derived from reports [60] and the literature [61]. There are some values, which evaluate the feature without providing information for the individual underlying parameters (marked with [b]). In these cases, the aggregated value [b] was taken for all parameters of this characteristic (marked with *).

Table A5. Social quality results for graded concrete and massive concrete.

Parameter	Criteria/Description	Scale	GC	MC
Decent Work: Control			**0.63**	**1 [b]**
DW_C1: Influence Amount of Work	Employees should be able to influence the amount of work.	0 (no)—0.5—1 (partly)—1.5–2 (yes)	0.5	1 *
DW_C2: Influence Working Time	Employees should be able to influence the organization of their working time.	0 (no)—0.5—1 (partly)—1.5–2 (yes)	0.5	1 *
DW_C3: Influence Work Planning	Employees should be able to plan their work independently.	0 (no)—0.5—1 (partly)—1.5–2 (yes)	0.5	1 *
DW_C4: Influence Work Station	Employees should have the possibility to set up their own work station.	0 (no)—0.5—1 (partly)—1.5–2 (yes)	1 [a]	1 *
Decent Work: Safety			**0.97**	**0.5 [b]**
DW_S1: Awkward postures	Employees should not work in awkward postures.	Ranking: 2 standing—1.5 sitting—1 stooping—0.5 kneeling—0 overhead	1.8	0.5 *
DW_S2: Weather protection	Weather protection should be given (Roof, enclosed space, climate/heating (constant 20 °C), humidity (40–60%), protection from spray/dirt).	0 (none)—0.4 (one)—0.8 (two)—1.2 (three)—1.6 (four)—2 (five)	0.5 [a]	0.5 *
DW_S3: Physically hard work	Work should be as little physically demanding as possible.	Ranking: 2 standing—1.33 working with hands (much skill, fast, great strength))—0.67 lifting heavy loads (m: >20 kg; f: >10 kg)—0 forced postures (stooped, squatting, kneeling, overhead).	2	0.5 *
DW_S4a: Noise exposure 8 h	Daily noise exposure level should be less than 8 h of 85 dB.	0 No; 2 Yes	0.5 [a]	0.5 *
DW_S4b: Noise exposure peak	Peak sound pressure level peak should be less than 137 dB.	0 No; 2 Yes	0.5 [a]	0.5 *
SW_S5: Labor inspection	Occupational health and safety officer should be available on site.	0 No; 2 Yes	0.5 [a]	0.5 *
Decent Work: Work Intensity			**1.08**	**1 [b]**
DW_I1: Rush to work	There should be no rush to work.	Production system (0), top down (0.5), cooperation with colleagues (1), employees relatively autonomy (1.5), or employees themselves (2) dictate the working speed?	0.5	**1 ***
DW_I2: Requirements to reconcile	There should be no requirements to reconcile. indicated by working on several workstations?	0 not met; 2 met	1 [a]	1 *
DW_I3: Relevant information	There should be all work-related information available.	*tbd*	1 [a]	1 *
DW_I4: Interruptions of work flow	There should be no interruptions in the work flow.	Embedding of work step in overall process	2	1 *
DW_I5: Worktime	Should be typical (700–1900).	0 alternating shifts—0.5 three shift system; 3 two shift system (atypical); 4 two shift (typical); 5 typical no shift	1 [a]	1 *
DW_I5: Overtime	No overtime.	0 unpaid; 1 compensated; 2 none	1 [a]	1 *

Table A5. *Cont.*

Parameter	Criteria/Description	Scale	GC	MC
Decent Work: Job Security			**1.25**	**1.5 [b]**
DW_J1: Creation of jobs for high- and low-skilled workers	Same ratio of low- and high-skilled workers as status quo.	0 less unskilled; 0.5; 1 same; 1.5; 2 more unskilled	0.5	1.5 *
DW_J2: Length of job contracts	Ratio temporary/permanent employment.	0%—2 . . . 100%—0	1.5 [a]	1.5 *
DW_J3: Time workers	Ratio time workers.	0%—2 . . . 100%—0	1.5 [a]	1.5 *
DW_J4: Real earnings of casual workers	Average salary of workers compared to industry average.	0 (<EUR 24.768 minimum wage DE)—0.5 (EUR 29.306)—1 (benchmark: EUR 33.845.23 GAI mean precast concrete worker)—1.5 (EUR 38.383)—2 (>42.922)	1.5 [a]	1.5 *
Sociotechnical Robustness: Competences			**1.1**	**1.25 [b]**
STR_C1: Competence reconfiguration	Vocational training opportunities should be available.	*tbd*	1.25 [a]	1.25 *
STR_C2: Competences ideas	Internal innovations management should be given.	*tbd*	1.25 [a]	1.25 *
STR_C3: Competences rewards	Rewards should be given.	*tbd*	1.25 [a]	1.25 *
STR_C4: Tacit knowledge	Basic education instead of specialized/selective training is given.	*tbd*	1.25 [a]	1.25 *
STR_C5: Manual takeover	Technical systems should be able to be bypassed/taken over manually.	0 impossible; 0.5 mostly not; 1 partly; 1.5 mostly; 2 possible	0.5	1.25 *
Sociotechnical Robustness: Digital Accessibility			**1.25**	**1.38**
STR_A1: Keyboard access	Keyboard equivalents for mouse actions, documentation for keyboard functions, and logical tabbing order.	0 (none)—0.67; (one)—1.33; (two)—2 (three)	1 [a]	1
STR_A2: Screen elements	Descriptions and labels for elements. placed nearby to the elements.	Given for 0%—0 . . . 100%—2	1.5	1
STR_A3: Display and Color	Color is not the only way used to differentiate items or navigation, and display allows for removal of patterns or flashing elements.		1.5 [a]	1.5
STR_A4: Documentation	Manuals and documentation are available in electronic format as well as ASCII text file. To what depth?	0 (none)—0.5 (instruction)—1 (explanation of elements)—1.5 (explanation of computation)—2 (Explanation of embedding in overall system)	1	2
Sociotechnical Robustness: Transparency			**1**	**1.63**
STR_T1: Transparency of algorithmic decision-making	Access to all relevant information should be given.	STR_A4	1	2
STR_T2: Competences	Competences to understand relevant information.	STR_C	1	1.25

Table A5. *Cont.*

Parameter	Criteria/Description	Scale	GC	MC
Socio-technical Robustness: Human Agency			**0.93**	**1.45 [b]**
STR_H1: Competences	Empowerment through compentences	STR_C	1 [a]	1.25 *
STR_H2: Human acitivity niveau	Human acitivity niveau should be as high as possible	0 (passive)—0.5 (semi-active)—1 (re-active)—1.5 (pro-active)—2 (cooperative) (Rammert 2012: 97)	1	1.5 *
STR_H3: Human agency	Human agency be as high as possible	0 (Low causality)—0.4 (high causality)—0.8 (low contingency)—1.2 (high contingency)—1.6 (low intentionality)—2 (high intentionality) (Rammert 2012: 99)	0.8	1.6 *
Wellbeing: Building Physics Characteristics			**1**	**1 [c]**
BP_C1: Thermal comfort	Building component should contribute to Thermal comfort	0 none; 1 meets mandatory requirements; 2 exaggerated mandatory requirements	1 [a]	1 [c]
BP_C2: Indoor air quality	Building component should contribute to Indoor Air quality		1	1 [c]
BP_C3: Acoustic comfort	Building component should contribute to Acoustic comfort		1 [a]	1 [c]
BP_C4: Visual Comfort	Building component should contribute to Visual Comfort		1 [a]	1 [c]
Process Quality: Design			**1.33**	**0.5**
PQ_D1: Software	Compatibility should be given (open source; freeware compatibility; open data standard)	0 (none)—0.67; (one)—1.33; (two)—2 (all)	0	0.67
PQ_D2: Quality assurance	For elective requirements should be implemented from beginning (LCA; technical; social)		2	0
PQ_D3: Co-design 1	Integration of different disciplines from beginning of design (LCA; structural engineering; building physics)		2	0
PQ_D4: Co-design 2	Feedback loops between design and fabrication should be given	0 no; 0.67 requirements; 1.33 feedback loop; 2 coop	1.33	1.33

[a] Missing values—values could not be measured. For better comparability of graded and massive concrete. the values of massive concrete were used for graded concrete. [b] Aggregated value for characteristic according to the DGB Good Work Index (XY). Parameters values derived from aggregated characteristic value marked with *. [c] such as technical quality—mandatory requirements met.

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