applied sciences

Article

A Web-Based BIM–AR Quality Management System for Structural Elements

Mehrdad Mirshokraei, Carlo Iapige De Gaetani * and Federica Migliaccio

Politecnico di Milano, Dept. of Civil and Environmental Engineering, 20133 Milan, Italy; mehrdad.mirshokraei@mail.polimi.it (M.M.); federica.migliaccio@polimi.it (F.M.)
* Correspondence: carloiapige.degaetani@polimi.it

Received: 28 August 2019; Accepted: 18 September 2019; Published: 23 September 2019

Abstract: This paper investigates quality management (QM) during the execution phase of structural elements by proposing, developing, and testing a complete framework by integrating building information modeling (BIM) and augmented reality (AR) technology. QM during execution is boosted by BIM–AR integration through a dedicated web-based system aimed at reducing the occurrence of omissions and negligence. With such a system, efficiency is improved by allowing the entering of inspection data directly in a shared digital environment, where people involved in QM have permanent access to updated information and inspection results, clearly organized, and entered in real time. The system has been developed in the asp.net framework using C# language where, by generating a web-based checklist and establishing its link to AR, it can enhance the process of information extraction from industry foundation class (IFC) 4D BIM models and the recording of inspection data. A test has been performed on a real case study in Budapest, to assess the effectiveness of the system in the field. Results demonstrate the following benefits brought by such a type of QM system: improved understanding of the design, access to information, and overview of the quality status of the project, leading to reductions in defects and reworking, as well as improved and quicker response and decision-making.

Keywords: Building Information Modeling; process improvement; construction management; information and communication technologies; Augmented Reality

1. Introduction

Presently, due to customer demand and high competition in the market, there is pressure on construction enterprises to improve quality in their projects. The main way to achieve this goal and achieve a competitive edge in the market is by adopting a sound quality management (QM) system [1]. Although QM must be applied to all phases of the building process, from conceptual design to demolition, the main challenge of projects and construction managers is controlling the quality during the execution phase, which calls for more resources and time. Based on surveys conducted by Gottfried et al. [2] and Alpsten [3], it has been found that failures ascribed to the execution phase are more prevalent than errors in the design process, and the construction phase appears particularly prone to errors. On the other hand, structural elements are considered to be the most fundamental components of a building to be controlled for their quality, since they are directly responsible for structural integrity, strength, and safety, and any defects in them will cause fatal accidents, severe additional costs, or delay [4,5]. In many projects, structural elements have also proved to have defects after execution but directly related to the execution phase, such as incorrect positioning of the frame in relation to the foundation, or insufficient length of the reinforcement bars [6].

Since there may be differences in the perception of the quality of an object, quality must be defined in a clear way. The ISO standard [7] defines quality as "degree to which a set of inherent characteristics of an object fulfils requirements". Quality in construction projects refers not only to the quality of products and equipment used in the construction of a building or facility, but also to the adopted management approach. As Chung states [8], both the construction cost and time of delivery are also important quality characteristics. Construction project quality is managed through quality assurance (QA) and quality control (QC). Turner interprets QA as "preventive medicine" [9], which consists of steps taken to increase the likelihood of obtaining a good-quality product and management processes. The aim of QA is to ensure that the project scope, cost, and time functions are fully integrated. QC as part of QA is "curative medicine", which recognizes human fallibility and takes steps to ensure that any (hopefully small) variations from standards that do occur are eliminated. As such, QC is the specific implementation of the QA program and related activities. Effective QC reduces the possibility of changes, mistakes, and omissions, which in turn result in fewer conflicts and disputes, and reduced waste of project resources. Although the procedure of quality check during the execution phase is consolidated and seems to be well organized, it does not work out properly in practice, for instance, due to intensive manual data collection entailing frequent transcription or data entry errors. Supporting this statement, examples can be found in reports and surveys presented by Glagola et al. [10] and Meijer & Visscher [11]. However, the complexity of properly controlling the quality of execution of structural elements can be easily recognized by having in mind, e.g., the number of processes and stakeholders involved in the execution of the concrete structure.

Recently, information technology (IT) has gained much attention as a key driver of change in the architecture, engineering and construction (AEC) industry. Developments in IT have provided numerous opportunities for the AEC industry, one of which is building information modeling (BIM) [12]. BIM serves as a central data repository that can store information about a facility and is currently regarded as an essential tool in managing the lifecycle of a construction project from the initial design to its maintenance. BIM is not just a technology change, but also a process change. In fact, unlike the traditional approach, the BIM approach allows the project team and the stakeholders to share information and to be constantly aware about the project. BIM is considered to be a multi-dimensional digital representation of the physical and functional characteristics of a project. Every time a specific type of information is added to the model, a different dimension is set, and, for this reason, various dimensions have been defined. Three dimensions are generally sufficient for geometric purposes, but new descriptive modalities and quantities, such as time or costs, introduce a different type of information. According to BIM fundamentals there are seven recognized "dimensions". 3D (three-dimensional rendering of the artefact), 4D (time and duration analysis), 5D (cost), 6D (sustainability assessment), and 7D (management phase). Taking advantage of its potential, the BIM methodology can be exploited to manage all the QC data and the complex relationships between them, establishing an effective approach to realize improvements in construction quality management. Various researchers have already proposed to implement BIM concepts into a quality management [13]. As an example, the QC framework by Chen & Luo [14] consisted of a 4D model combined with a specific company's process, organization and product (POP) model. According to Turk [15]: "BIM refers to a combination or a set of technologies and organizational solutions that are expected to increase inter-organizational and disciplinary collaboration in the construction industry and to improve the productivity and quality of the design, construction, and maintenance of buildings". In this sense, several authors proposed the combination of BIM with other technologies aiming at exploiting their potential in the framework of quality management. There are many examples, involving different techniques and technologies, such as personal digital assistants [16], mobile devices to access design information and to capture work progress [17], radio frequency identification [18–20], laser-scan point clouds [21–25], and indoor positioning through magnetic fields and wi-fi signals [26].

In the last decade, augmented reality (AR) has received a considerable amount of attention from researchers in the AEC community [27]. According to Wang et al. [28] AR and BIM are complementary technologies. AR could represent the site extension of the BIM concept and approach, and maximize the potentials of BIM in the construction site. AR allows the overlaying of a virtual object into the real world and can present information on site where it is needed. Rankohi and Waugh [29] classified AR application areas in the AEC industry as follows: (1) visualization or simulation; (2) communication or collaboration; (3) information modeling; (4) information access or evaluation; (5) progress monitoring; (6) education or training; and (7) safety or inspection. Therefore, the benefits of bringing AR to the job site could be truly remarkable. In the framework of quality management, remarkable works can be found in the literature. Golparvar-Fard et al. [30] implemented the D4AR system for visualizing the deviation from the construction schedule by registering new daily site images and using a traffic light metaphor as feedback to represent discrepancies between the as-planned and the as-built. Wang et al. [28,31,32] developed a conceptual framework to investigate how BIM can be extended to the site via AR and investigated the use of BIM and AR for project control, procurement monitoring, visualization of design during construction, and linking virtual to physical objects. Park et al. [33] presented a conceptual system framework for construction defect management using AR and BIM technologies to enable the storage and retrieval of defect data visually. Following that study, Kwon et al. [34] proposed a defect management system for reinforced concrete work by integrating BIM, image-matching, and AR.

The aim of this paper is to propose a complete framework to integrate BIM and AR to improve the quality management of the execution of structural elements on site. Such a framework has been verified by implementing a prototype BIM–AR QM web-based system that is platform-independent and fully customizable, as well as able to be modified depending on the needs of the users. This prototype has been tested on a real-life test case to assess benefits, issues, and key points requiring further investigation.

2. The Proposed Framework for BIM–AR Integration for Quality Control

In this section, the developed framework integrating BIM and AR into the two pillars of quality management (QA and QC) will be described. The proposed procedure is illustrated in Figure 1. The QA starts by the customer defining his/her requirements, which are the basis for the design team to define the specifications. To be able to realize the constructed elements with a quality consistent with the specification, quality parameters and QC activities must be identified along with a schedule with the time when they need to be controlled. All this information will result in a QC plan which is the base for QC. After integrating quality information into a BIM, a quality model will be obtained to be shared between project participants, which will be the basis for inspection on site by AR technology. For the sake of simplicity, in this study the integration with a 4D BIM has been considered (i.e., including the project time schedule). Of course, with a 5D BIM model (hence including also cost information), a 5D quality model would be obtained, providing additional information, e.g., about the cost of possible required interventions.

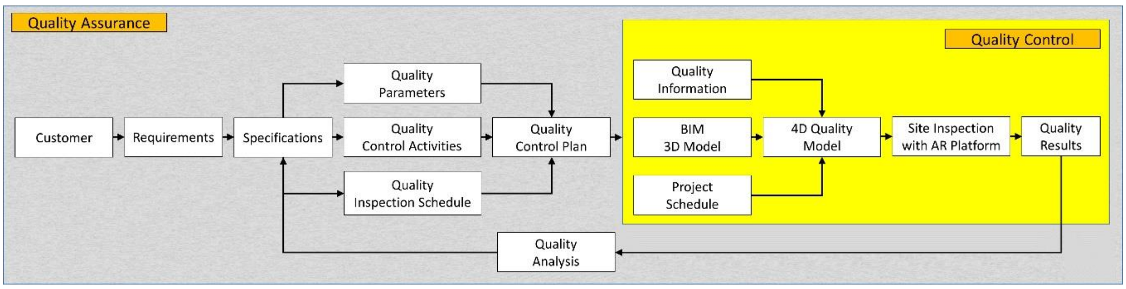

Figure 1. Framework of the proposed quality management (QM) procedure.

2.1. Quality Control Workflow

The QC workflow is represented in more detail in Figure 2. Using the 4D quality model as a reference, the supervisor can determine beforehand which parts need to be controlled; then, when entering the construction site, the position of the elements to be controlled can be identified with respect to the environment in the AR mobile application. On site, the required information can be extracted and visualized from the updated BIM model and, using a web-based checklist of all the quality parameters to be checked, a decision can be made on the quality conformance of each specific element. Once the evaluation is completed, a notification will be sent to the responsible contractor. The evaluation could result in a corrective action which needs to be taken—in this case, the BIM model will be modified based on the change. Further inspections could be required to determine if the corrective actions have been successfully performed. The project manager can also use the output from the inspection to have both an overall view of the project quality and an insight on current quality control processes and their effectiveness in limiting defects. This can help the manager to decide if any adjustment needs to be done in quality management, e.g., updating project scheduling techniques, adding/removing quality requirements, or modifying current checks/inspections.

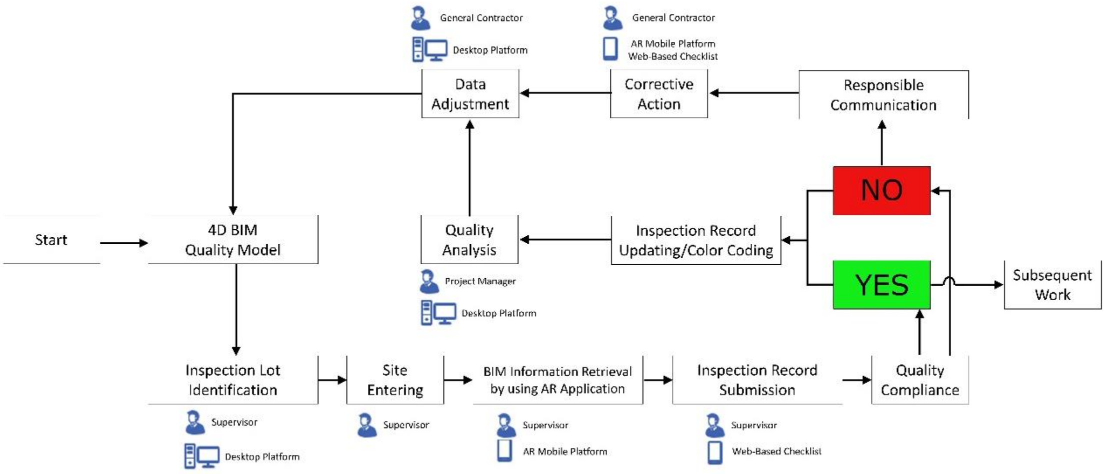

Figure 2. The proposed BIM–AR QC workflow.

2.2. *Data Needed for Quality Control*

In the proposed BIM–AR QC procedure, the information needed for the quality management of structural elements is represented by three types of data that must be collected, exchanged, and synchronized to have a 4D BIM quality model:

- model of physical objects involved in the construction processes such as column and beam components and equipment employed, including the geometric data and the data on materials and other specifications; an example of generic physical objects that can be modeled is presented in Figure 3, in the case of a steel and cast-on-site reinforced concrete structure;
- work schedule data based on the project tasks, their relationship, and their time schedule, where inspection lots and their parameters can be related to these tasks to give them a time dimension;
- QC data, including definition of inspection lots and relevant quality parameters serving as a checklist to be controlled for each element, acceptance criteria, decisions, and instructions to the persons in charge in case of rework.

All these data can be divided into three categories, based on when they need to be used, namely: (a) before, (b) during, and (c) after execution. The aforementioned categorization of the data for QC purposes is quite basic to apply in real-life projects, but structured enough to comprise the most relevant aspects and verify the proposed framework.

According to European standard 13670:2009 [35] on the execution of concrete structures, quality parameters must be controlled for material, process, and geometry. The used material must be consistent with the required specification as well as the compliance of the finished element. The related activities and preventive measures must follow specific guidelines, and defined tolerances are admitted in terms of geometry of both simple and composite structural elements. As an example, Figure 4 shows how activities for the execution of a concrete structure are divided into the three phases; in each phase, quality parameters are controlled for material, process, and geometry. In Table A1 of

Appendix A, all the quality parameters for the control of the material of a concrete structure are listed, with the corresponding inspection lots, related activity, relevant standards, and execution phase.

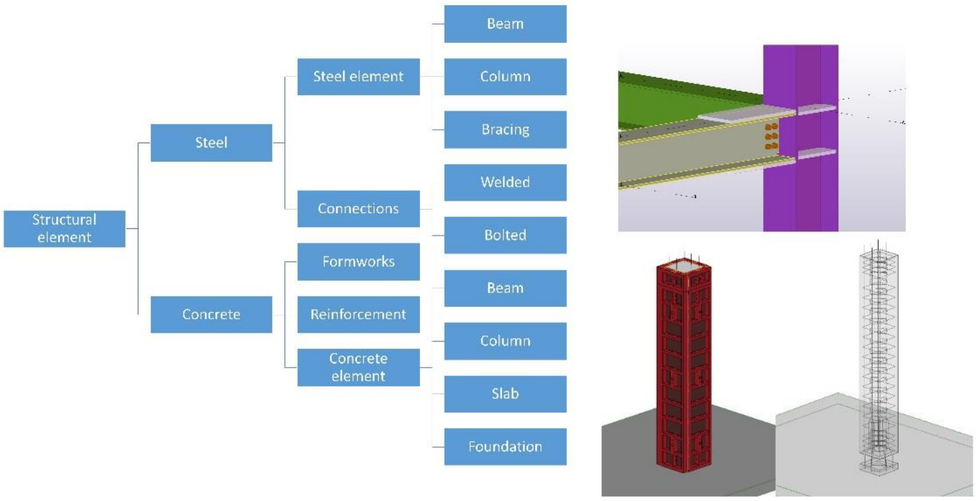

Figure 3. Example of generic physical object elements.

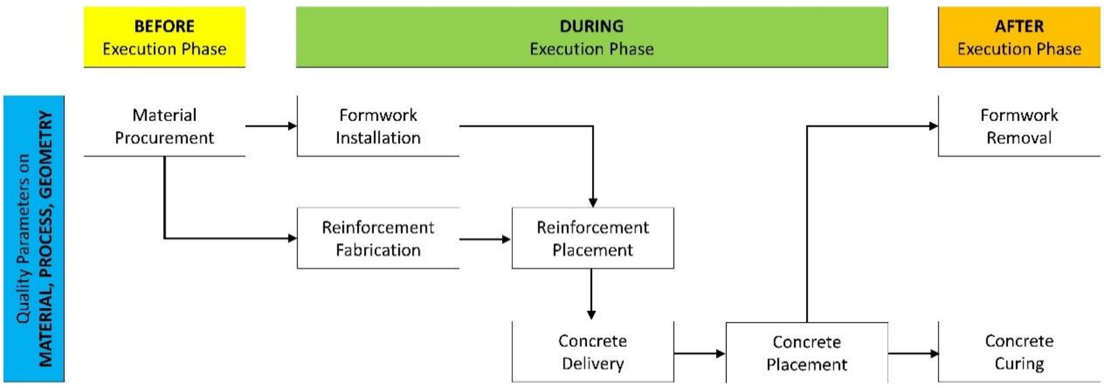

Figure 4. Quality control phases for a concrete structure execution.

3. Quality Control System Development

The proposed workflow needs a suitable system for it to be realized. Such a system has been developed based on a stepwise procedure. Ideally, the starting point is the 3D BIM model of the structure in industry foundation class (IFC) format. IFC is one of the open standards in the buildingSMART portfolio; it is a neutral data format to describe, exchange, and share all building information including geometry, spatial relationships, attributes, and quantity [36]. With such a format, the model can be then imported in suitable software to prepare the time schedule of the project, define the actors involved, and assign the physical elements to the work schedule, obtaining the 4D BIM model. The developed QC system synchronizes the 4D model and the quality information, generating a web-based checklist, storing all the inspection results and generating the link in the 4D IFC model to the AR application. By importing the synchronized 4D IFC model into the AR application, it is possible to visualize the BIM model on site, while the checklist is also accessible and can be updated.

The QC system was developed using the asp.net framework based on C# programming language to synchronize all information needed. Since the system is platform-independent and it can be accessed through any type of web browser, it can be accessed through either desktop or mobile devices and there are no requirements on the type of operating system. The input/output scheme of the system is represented in Figure 5.

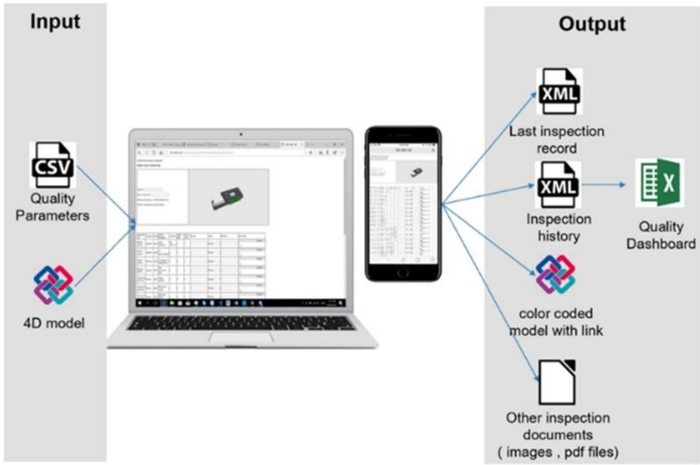

Figure 5. Input/output scheme of the proposed QC system.

The main packages/modules used to generate the quality system are the xBIM Toolkit which is a NET open-source software development BIM toolkit that supports IFC: it allows reading, creating, and viewing BIM Models in the IFC format. Two core libraries of the xBIM toolkit are xBIM Essentials and xBIM Geometry which are written in C# and C++. To allow addition of the BIM model to the checklist, WeXplorer was used; it is the visualization part of xBIM toolkit and uses WebGL technology giving 3D viewing control.

There are no specific entities for quality information in the IFC standard, therefore new entities describing the quality management process and their relationships with other information have been created [37]. The entity IfcQuality has been defined as an entity connected to other different entities describing the quality of an element. One of them is IfcInspectionLot and its subset IfcQualityParameters. The latter is categorized with respect to the epoch (IfcQualityPhase) and the type (IfcQualityCategory) of the control. IfcQualityAcceptance and its subset IfcQualityDoc describe the information regarding the inspection results and the related uploaded documentation. IfcInspectionPlan describes the assignments of activities and their schedule information in the framework of QC. These new entities are related to other entities already defined in the IFC standard Version 4 such as IfcProduct and its inherited entities describing the designed products, or IfcWorkSchedule describing the timing of the activities. Figure 6 shows the IFC-based process model and the relevant entities.

As an example, in the case of a wall that should be under inspection after concreting, the geometrical data and its properties are represented by IfcWall as a type of IfcProduct and it has one assigned IfcQuality entity. This entity is defined by three IfcInspectionLot, specifically cross-sectional geometry, surface control, and hardened concrete quality. Regarding the cross-sectional geometry of IfcInspectionLot, three parameters (dimensions, skewness, orthogonality) are related to geometry (IfcQualityCategory) and execution phase (IfcQualityPhase) with their own upper and lower deviation limits. In IfcQuality, the related quality parameter activities (the concrete placement in the case of wall geometrical quality parameters) are recorded in IfcInspectionplan, while the results of the inspection are recorded in IfcQualityAcceptance.

The 4D BIM model in IFC format, inspection lots, their corresponding quality parameters and related activities in comma-separated values format (CSV) are prerequisites as input for the system. The application initially parses the CSV file and stores the data in a dictionary which will be used to determine the value of quality classes, their subtypes, and their attributes. Loading the IFC model, the system parses all the IfcBuildingElements that are in the model and retrieves their globally unique identifier (GUID) and type. For concrete structures, the type of IfcBuildingElement could be IfcColumn, IfcBeam, IfcWall, IfcFooting, IfcSlab, IfcReinforcementRebar, and IfcBuidlingElementProxy. Based on such types, the associated quality classes will be dynamically loaded, also containing the GUID of the specific elements. Since each element has its own unique GUID, for each element a specific webpage address will be generated and this web address will be added as a user-defined property (IfcPropertySet) in the 4D IFC model, creating the link between this system and the web-based QC checklist. Opening this webpage will direct to the checklist of the related quality parameters, where the inspector can enter and record all the requested information. The results will be saved in IfcQualityAcceptance class and stored as two XML files. One of them is used to save the results of the latest inspection performed and the other to save all the inspection results and the documents related to each quality parameter. Whenever the checklist opens, the results of the latest inspection are shown. The other file can be imported into a spreadsheet for data queries, filtering, and quantification. Results can then be summarized to generate a quality dashboard of the project. Another output of the system is a color-coded IFC model, which provides the construction team with direct visual feedback on the contents of the inspection results. This reduces the time needed to analyze data and allows for a faster corrective action of quality defects to take place on site. The color coding is based on the legend reported in Figure 7.

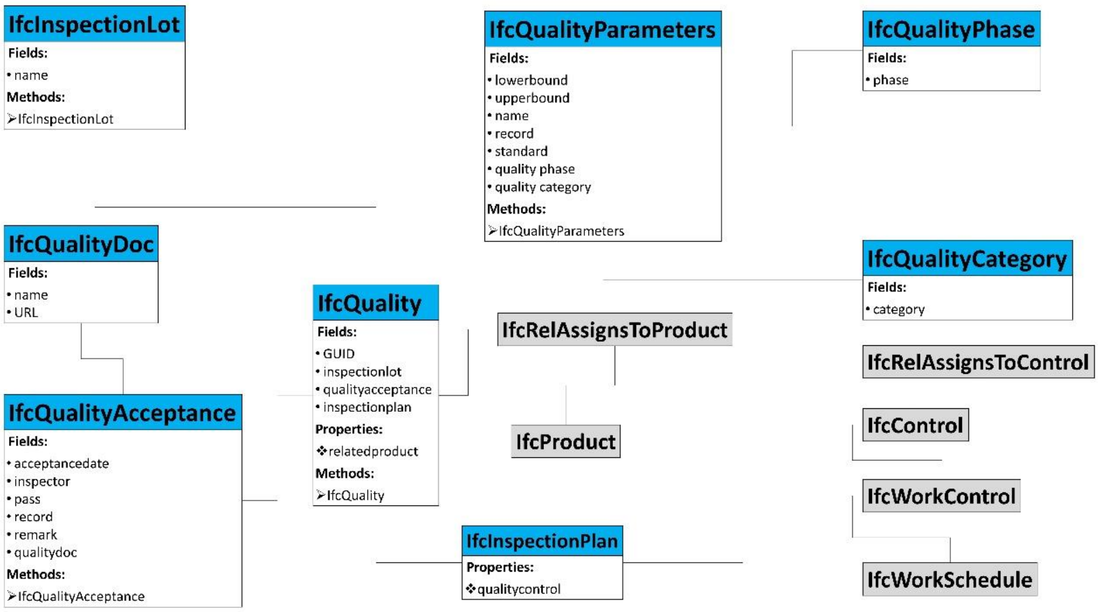

Figure 6. IFC-based process model. New entities are highlighted in blue.

The on-site visualization of the color-coded model with a mobile device exploiting the integration with AR can be useful for both the inspector and the people responsible for rework. In the former case it will make up the basis for subsequent inspections, while in the latter case it can be used to access the inspection checklist to identify the element, its problem, and the inspector's comments. Through a central interface, projects are managed and IFC models are uploaded and visualized on site. Figure 8 shows the interface of the AR application and the steps needed to visualize the model on site and to access the web-based checklist; as an example, the figure reports the inspection of a column element.

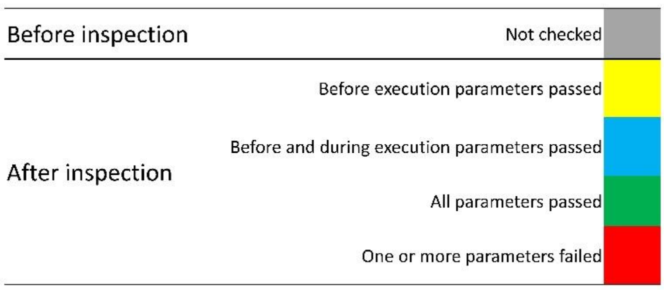

Figure 7. Color coding legend for the visual feedback on the inspection results.

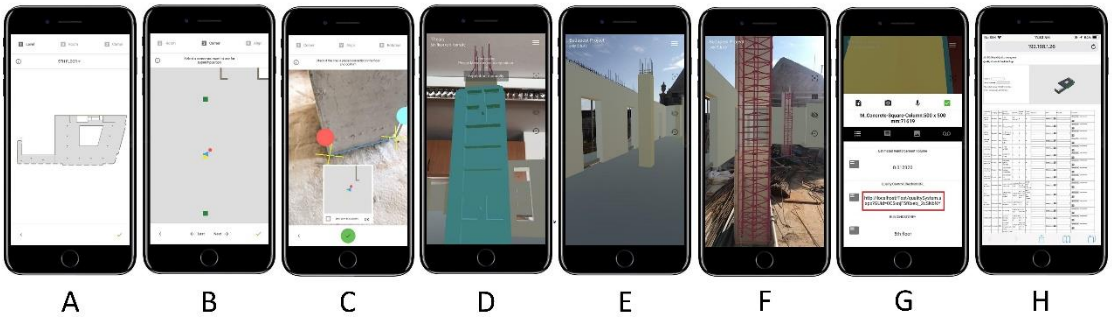

Figure 8. AR application user interface. (**A**) Opening the file and choosing the level. (**B**) Choosing an element for positioning. (**C**) Positioning by superimposing two corners of the element. (**D**) Augmented column with formwork. (**E**) Hiding formwork. (**F**) Column reinforcement. (**G**) Retrieving element properties and linking the checklist web address. (**H**) Accessing the selected element quality checklist.

4. On-Site Test of the Proposed BIM–AR QM System and Results

The proposed system has been tested in the case study of a reinforced concrete building under construction in Budapest, Hungary. Trial inspections have been performed on one level of the building to check the quality of structures and test the developed system. The test followed a stepwise procedure. First, the 3D model of the building was created in Autodesk Revit®and exported to IFC format. Secondly, the model was imported in Synchro Pro®establishing the connection between schedule information and the building elements and then exported again in IFC format. Such an IFC 4D model was finally imported into the developed system to synchronize the quality information with the physical and schedule information of the building and to generate the web-based checklist and the link for accessing the AR application. The Gamma AR Pro®application was used as the AR platform to visualize the BIM model on site. Such application directly uses the IFC format and gives the possibility of accessing information regarding the elements by just clicking on the object. This application positioning system is marker-less, and uses depth-sensing as the tracking system to overlay the BIM model to the reality on site. For positioning, the inspector needs to choose the floor and room and then select two corners of a wall or column in the model to superimpose it to the reality. An Apple iPhone 7®was used as the mobile device for the AR application.

The project used for the test is an office building with reinforced concrete structure which is being reconstructed after demolishing the old one, to match the architecture of the building next to it. Considering the building is being used as offices, based on EN1990-2002 Annex B [38], the consequence class CC2 has been chosen. Moreover, based on EN13670 [35], Execution Class 2 has been considered for assigning the range of admissible tolerances and the severity of the inspection. A total of 36 elements were inspected and the results were recorded. At the time that the test was done, most of the structural elements had been constructed and the activities related to the architectural part of the project were ongoing. Therefore, the inspection lots related to the "after-execution" phase of QC and were added as an input to the web-based checklist. In this phase there are no inspection lots related to formwork and rebar elements; however they were modeled in Revit®and then exported in IFC to examine how the inspection could have been performed on site using AR. In this way, it was also possible to assign and then retrieve their corresponding quality parameters. In Figure 9, the model of a column is shown, together with its on-site visualization using the AR application.

Inspection records were saved as XML and visualized using the color-coded model of the quality system; in this way it is also possible to find the location of the defects (see Figure 10). Furthermore, the dashboard of the quality status of the projects shows the results of the inspection (see Figure 11). During the inspection test, the response was negative in three cases (8% of the items checked); all of them concerned the concrete placement, two were related to walls, and one was related to a slab. Two of the failed inspection lots concerned the geometry and one concerned the material. These cases are represented in Figure 12.

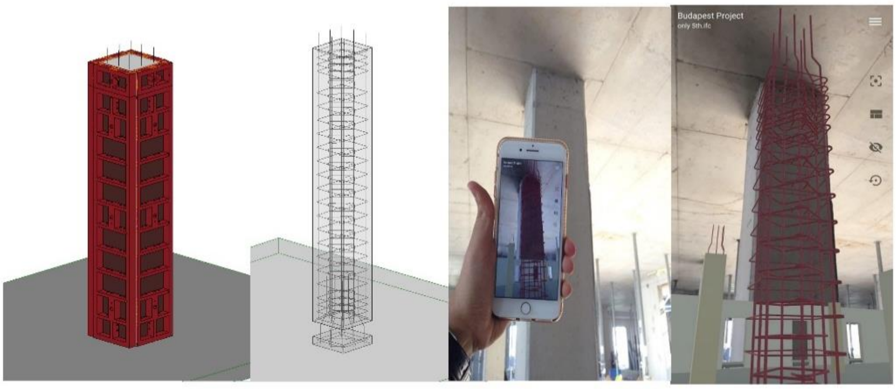

Figure 9. Model of a reinforced concrete column with its formwork, and how it is visualized on site.

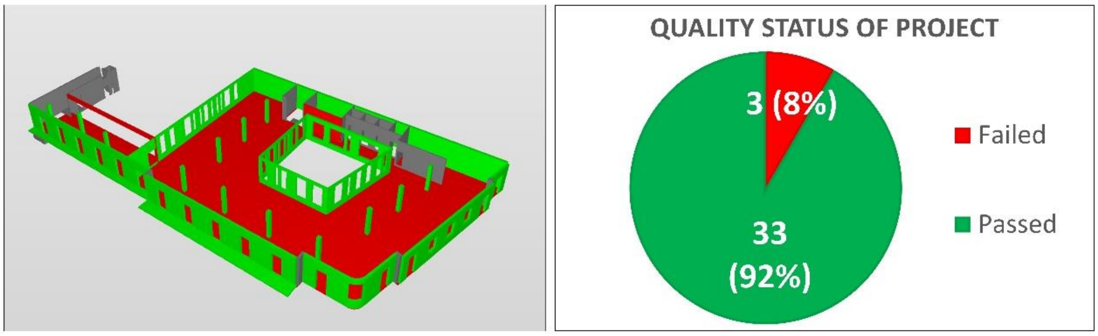

Figure 10. Case study, screenshots of the produced quality dashboard: visualization of the color-coded model (**left**) and report on the quality status of the project (**right**).

Figure 11. Case study, screenshots of the produced quality dashboard and summary of the defects: three defects in the concrete placement have been reported (**top-left**), a slab and two walls are involved (**top-right**), two defects regard the geometry of the objects, the remaining regard the material (**bottom**).

Figure 12. Case study, shots of the failed inspection lots: wall concrete surface with honeycombing (**left**), wall cross-sectional geometry (**center**), hole in a slab (**right**).

5. Discussion

The results showed that the main weaknesses of the current QM practice (namely: poor management, poor understanding of the scope of quality, and poor communication between stakeholders) can be overcome, while the practice itself can be made more efficient and effective by exploiting the integrated use of BIM and AR technologies in a web-based collaborative system. The case study allowed identification of benefits in adopting the proposed framework. Figure 13 maps the possible outcomes of the proposed system while pursuing the objectives of budget, time, and quality of the construction project.

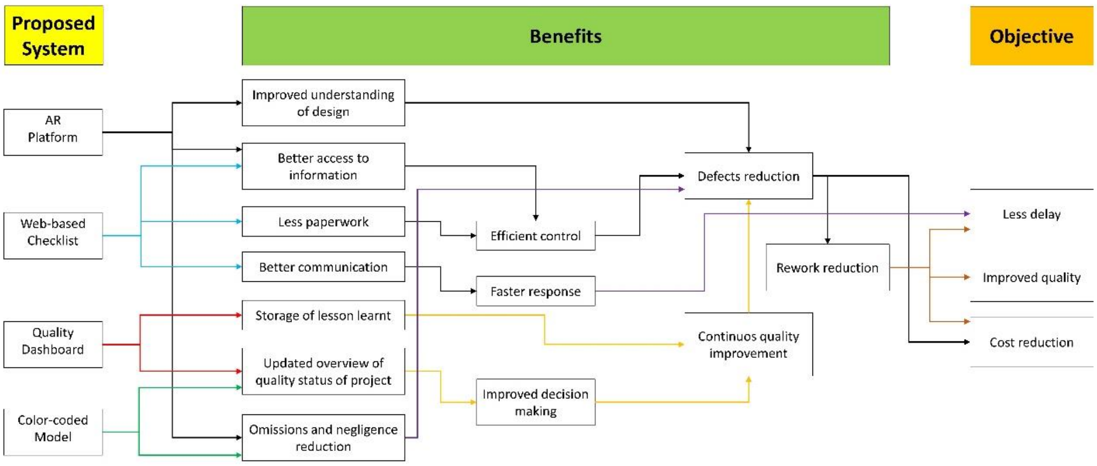

Figure 13. Benefit map of the proposed system.

On the other hand, during the development and testing of the proposed system, some limitations and barriers have been identified. One of the most important is the problem related to the correct positioning of the virtual model on the real environment. In fact, the accuracy of the positioning is not sufficient to rely on this system as a tool for the measurement of geometry, and therefore geometric measurements should still be done using traditional approaches. Furthermore, due to the nature of the construction sites and the dependency of the AR system on depth sensors, it could be difficult to superimpose the pins in the correct positions to achieve an AR experience with acceptable accuracy during the first tries. A possible solution could be the integration of both marker-based and marker-less tracking systems in the AR platform. With a proper enhancement of the software, the indoor positioning could exploit, e.g., near-real-time photogrammetric techniques to guide the procedure.

Occlusions create difficulties, as well. In AR, an object closer to the viewer obscures the view of objects further away along the line of sight, affecting the interpretation of the environment by the AR application in the case of complex models with lots of elements and details. Again, it the opinion of the authors that this could be managed by the AR platform at software level so that, on the basis of a more accurate positioning of the device, it could recognize the relative distance of objects and manage the overlaps between superimposed elements. Examples of these problems are shown in Figure 14.

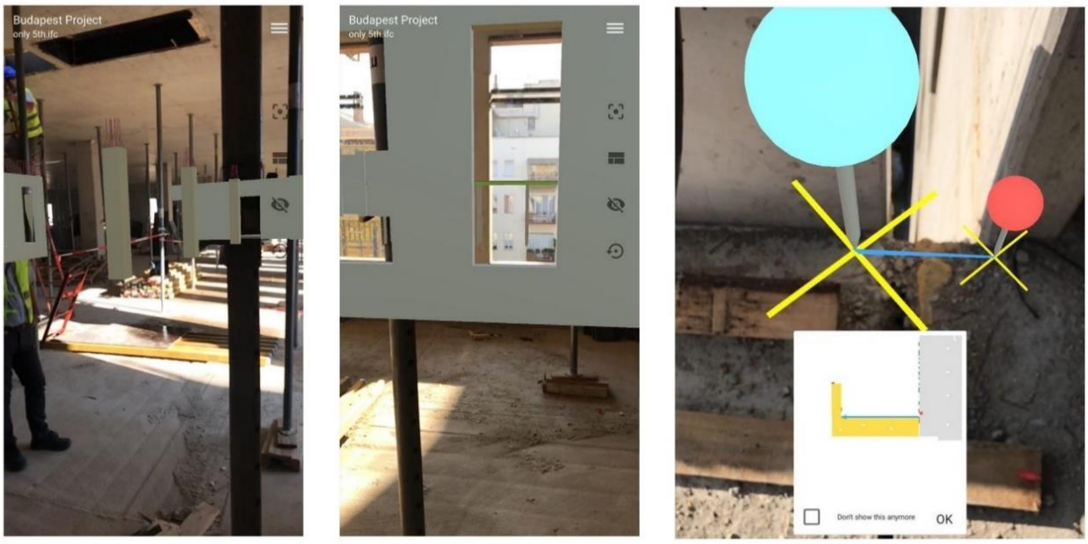

Figure 14. Examples of problematic behaviors: occlusion of the real objects by the wall model (**left and middle**) and positioning accuracy problems (**right**).

From this point of view, several different techniques aiming at improving the accuracy of the positioning during the AR experience are under investigation by the scientific community [39], due to the huge potential that such technology has in various fields of application.

Another shortcoming of the proposed system for quality inspection is represented by the dependency on Internet access, which may cause problems when the signal is poor. Finally, there is the need to train people to use the system properly for safety reasons: in fact, working with mobile AR applications may cause the user to lose attention to the surrounding area, which could be very dangerous in a construction site and cause safety issues [40].

6. Conclusions and Future Work

In this paper, a comprehensive approach for QM has been proposed by integrating BIM and AR technology. Exploiting advantages and help from the potentials of BIM and AR and their integration, a system has been developed for acquiring inspection data, processing the results, and facilitating collaboration among the actors involved in QM, through the web. The approach has been implemented and a preliminary test has been carried out on a real building project to study the efficiency and effectiveness of the system.

The results confirm that objectives such as delay reduction, quality improvement, and cost optimization can be pursued through the proposed quality management system. The produced web-based checklist makes the access to updated information easier, by improving the communication between the involved parties. Moreover, the quality dashboard summarizing the results, combined with the color-coded model, gives an overview of the current quality status of the project both in qualitative and quantitative terms.

In the frame of the experimental approach followed for the proposed methodology check, difficulties also encountered during the testing phase can be considered to be positive outcomes, and the seeds for further considerations and research work.

Regarding possible future developments to optimize the proposed approach for integrating BIM and AR for QM purposes, a more stable and accurate positioning of the AR platform would improve the experience, offering the possibility to add tools to measure and record the as-built situation for real-time comparisons with the designed plan and make the control of geometric quality parameters more efficient. Furthermore, other improvements could be represented by a priority index for each defect, ranking its influence on the others, and by a feature allowing superimposition of the model onto the appropriate LOD (Level Of Detail), to avoid visualizing too many details, and to make the AR experience better.

Author Contributions: Conceptualization, M.M. and C.I.D.G.; Methodology, M.M. and C.I.D.G.; Software, M.M.; Validation, M.M. and C.I.D.G.; Formal analysis, M.M. and C.I.D.G.; Investigation, M.M.; Writing—original draft preparation, M.M., C.I.D.G. and F.M.; Writing—review and editing, C.I.D.G. and F.M.; Visualization, M.M. and C.I.D.G.; Supervision, C.I.D.G. and F.M.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of quality parameters for the control of the material of a concrete structure.

Project Item	Related Activity	Inspection Lot	Quality Parameter	Standard	Execution Phase
formwork	material procurement	mechanical properties	adequate stiffness	EN12812 EN12813	Before
		surface condition	clearness of surface		
		release agents	no unintended effect on the color and surface quality no detrimental effect on permanent structures		
reinforcing steel		mechanical properties	steel class tensile test	EN10080	
		surface condition	free from loose rust and deleterious substances no cracks and other damage		
		spacers	protection against corrosion		
concrete	concrete delivery	concrete ingredients	cement	EN197-1	
			aggregates	EN1260 EN13055	
			mixing water	EN1008	
			admixtures	EN934-2	
			mixed design		
concrete	concrete delivery	visual inspection of delivered concrete	no aggregates segregation no concrete bleeding no paste loss		During
		fresh concrete tests	cube/cylinder strength test	EN12350-1	
			slump test	EN12350-2	
			temperature test		
			air content test	EN12350-7	
concrete	concrete delivery	hard concrete test	non-destructive tests		After
	concrete placement	surface control	crack formation no honeycombing no damage or disfiguration		

References

1. Building in Quality Working Group. Building in Quality Initiative: A Guide to Achieve Quality and Transparency in Design and Construction. Available online: https://www.architecture.com/working-with-an-architect/building-in-quality-tracker (accessed on 3 September 2019).

2. Gottfried, A.; Di Giuda, G.; Villa, V.; Piantanida, P. Controls on Structure execution: Acceptance condition and Types of inspection for cast on site reinforced concrete. In *New Developments in Structural Engineering and Construction, Proceedings of the 7th International Structural Engineering and Construction Conference, Honolulu, HI, USA, 18–23 June 2013*; Research Publishing Services: Singapore, 2013; pp. 461–466. [CrossRef]
3. Alpsten, G. Causes of Structural Failures with Steel Structures. In *IABSE Symposium Report*; International Association for Bridge and Structural Engineering: Zurich, Switzerland, 2017; Volume 107, pp. 1–9.
4. Gorse, C.; Sturges, J. Not what anyone wanted: Observations on regulations, standards, quality and experience in the wake of Grenfell. *Constr. Res. Innov.* **2017**, *8*, 72–75. [CrossRef]
5. Knyziak, P. The impact of construction quality on the safety of prefabricated multi-family dwellings. *Eng. Fail. Anal.* **2019**, *100*, 37–48. [CrossRef]
6. Forcada, N.; Macarulla, M.; Gangolells, M.; Casals, M. Assessment of construction defects in residential buildings in Spain. *Build. Res. Inf.* **2014**, *42*, 629–640. [CrossRef]
7. International Organization for Standardization. ISO Standard No. 9000: Principles of Quality Management. Available online: https://www.iso.org/publication/PUB100080.html (accessed on 27 August 2019).
8. Chung, H.W. *Understanding Quality Assurance in Construction: A Practical Guide to ISO 9000 for Contractors*, 1st ed.; Routledge: London, UK, 2002.
9. Turner, J.R. *The Handbook of Project-Based Management: Leading Strategic Change in Organizations*, 3rd ed.; McGraw-Hill: New York, NY, USA, 2008.
10. Glagola, C.R.; Ledbetter, W.B.; Stevens, J.D. *Quality Performance Measurements of the EPC Process: Current Practices*; Construction Industry Institute, University of Texas at Austin: Austin, TX, USA, 1992.
11. Meijer, F.; Visscher, H. Quality control of constructions: European trends and developments. *Int. J. Law Built Environ.* **2017**, *9*, 143–161. [CrossRef]
12. Morgan, B. Organizing for digitalization through mutual constitution: The case of a design firm. *Constr. Manag. Econ.* **2019**, *37*, 400–417. [CrossRef]
13. Chen, K.; Lu, W. Bridging BIM and building (BBB) for information management in construction: The underlying mechanism and implementation. *Eng. Constr. Archit. Manag.* **2019**, *26*, 1518–1532. [CrossRef]
14. Chen, L.; Luo, H. A BIM-based construction quality management model and its applications. *Autom. Constr.* **2014**, *46*, 64–73. [CrossRef]
15. Turk, Ž. Ten questions concerning building information modelling. *Build. Environ.* **2016**, *107*, 274–284. [CrossRef]
16. Kimoto, K.; Endo, K.; Iwashita, S.; Fujiwara, M. The application of PDA as mobile computing system on construction management. *Autom. Constr.* **2005**, *14*, 500–511. [CrossRef]
17. Davies, R.; Harty, C. Implementing 'Site BIM': A case study of ICT innovation on a large hospital project. *Autom. Constr.* **2013**, *30*, 15–24. [CrossRef]
18. Jaselskis, E.J.; Anderson, M.R.; Jahren, C.T.; Rodriguez, Y.; Njos, S. Radio-frequency identification applications in construction industry. *J. Constr. Eng. Manag.* **1995**, *121*, 189–196. [CrossRef]
19. Wang, L.C. Enhancing construction quality inspection and management using RFID technology. *Autom. Constr.* **2008**, *17*, 467–479. [CrossRef]
20. Moon, S.; Yang, B. Effective monitoring of the concrete pouring operation in an RFID-based environment. *J. Comput. Civ. Eng.* **2009**, *24*, 108–116. [CrossRef]
21. Akinci, B.; Boukamp, F.; Gordon, C.; Huber, D.; Lyons, C.; Park, K. A formalism for utilization of sensor systems and integrated project models for active construction quality control. *Autom. Constr.* **2006**, *15*, 124–138. [CrossRef]
22. Tang, P.; Akinci, B.; Huber, D. Quantification of edge loss of laser scanned data at spatial discontinuities. *Autom. Constr.* **2009**, *18*, 1070–1083. [CrossRef]
23. Tang, P.; Anil, E.B.; Akinci, B.; Huber, D. Efficient and effective quality assessment of as-is building information models and 3D laser-scanned data. In Proceedings of the International Workshop on Computing in Civil Engineering 2011, Miami, FL, USA, 19–22 June 2011; pp. 486–493. [CrossRef]
24. Anil, E.B.; Tang, P.; Akinci, B.; Huber, D. Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data. *Autom. Constr.* **2013**, *35*, 507–516. [CrossRef]
25. Bosché, F.; Ahmed, M.; Turkan, Y.; Haas, C.T.; Haas, R. The value of integrating Scan-to-BIM and Scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: The case of cylindrical MEP components. *Autom. Constr.* **2015**, *49*, 201–213. [CrossRef]

26. Ma, Z.; Cai, S.; Mao, N.; Yang, Q.; Feng, J.; Wang, P. Construction quality management based on a collaborative system using BIM and indoor positioning. *Autom. Constr.* **2018**, *92*, 35–45. [CrossRef]
27. Wang, K.C.; Wang, S.H.; Kung, C.J.; Weng, S.W.; Wang, W.C. Applying BIM and visualization techniques to support construction quality management for soil and water conservation construction projects. In Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC 2018), Berlin, Germany, 20–25 July 2018; Volume 35, pp. 1–8. [CrossRef]
28. Wang, X.; Love, P.E.; Davis, P.R. BIM+AR: A framework of bringing BIM to construction site. In Proceedings of the Construction Challenges in a Flat World 2012, West Lafayette, IN, USA, 21–23 May 2012; Cai, H., Kandil, A., Hastak, M., Dunston, P.S., Eds.; ASCE: Reston, VA, USA, 2012; pp. 1175–1181. [CrossRef]
29. Rankohi, S.; Waugh, L. Review and analysis of augmented reality literature for construction industry. *Vis. Eng.* **2013**, *1*, 9. [CrossRef]
30. Golparvar-Fard, M.; Peña-Mora, F.; Savarese, S. Integrated sequential as-built and as-planned representation with D4AR tools in support of decision-making tasks in the AEC/FM industry. *J. Constr. Eng. Manag.* **2011**, *137*, 1099–1116. [CrossRef]
31. Wang, X.; Kim, M.J.; Love, P.E.; Kang, S.C. Augmented Reality in built environment: Classification and implications for future research. *Autom. Constr.* **2013**, *32*, 1–13. [CrossRef]
32. Wang, X.; Truijens, M.; Hou, L.; Wang, Y.; Zhou, Y. Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry. *Autom. Constr.* **2014**, *40*, 96–105. [CrossRef]
33. Park, C.S.; Lee, D.Y.; Kwon, O.S.; Wang, X. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Autom. Constr.* **2013**, *33*, 61–71. [CrossRef]
34. Kwon, O.S.; Park, C.S.; Lim, C.R. A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. *Autom. Constr.* **2014**, *46*, 74–81. [CrossRef]
35. European Committee for Standardization. EN Standard No. 13670:2009. Eurocode—Execution of Concrete Structures. Available online: https://standards.cen.eu (accessed on 27 August 2019).
36. BuildingSmart. Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries. Available online: https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/eu (accessed on 27 August 2019).
37. Ding, L.; Li, K.; Zhou, Y.; Love, P.E. An IFC-inspection process model for infrastructure projects: Enabling real-time quality monitoring and control. *Autom. Constr.* **2017**, *84*, 96–110. [CrossRef]
38. European Committee for Standardization. EN Standard No. 1990(2002). Eurocode—Basis of Structural Design. Available online: https://eurocodes.jrc.ec.europa.eu (accessed on 27 August 2019).
39. Joshi, R.; Hiwale, A.; Birajdar, S.; Gound, R. Indoor Navigation with Augmented Reality. In *Lecture Notes in Electrical Engineering*; Kumar, A., Mozar, S., Eds.; Springer: Singapore, 2019; Volume 570.
40. Sabelman, E.; Lam, R. The real-life dangers of augmented reality. *IEEE Spectr.* **2015**, *52*, 48–53. [CrossRef]