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BIM-QA/QC in the architectural design process

Vincenzo Donato [a], Massimiliano Lo Turco [b] and Maurizio Marco Bocconcino [a]

[a]DISEG – Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy; [b]DAD – Department of Architecture and Design, Politecnico di Torino, Torino, Italy

ABSTRACT

This paper describes a procedure for quality assessment in architectural design based on Building Information Modelling (BIM) technologies and investigates how the evaluations can affect the decision-making process. Based on techniques already defined in the literature, a method of evaluating the BIM processes and BIM model based on the definition of a BIM Quality Assurance (BIM-QA) that is applied through BIM Quality Control (BIM-QC) will be shown. The proposed method integrates into a general BIM methodology and its common procedures several tools and approaches. The method uses customised checklists and queries performed on a database management system that also perceives data from the use of model-checking software in order to achieve data that will be used for the evaluation of quality. The method was validated by applying the procedure to three projects in Italy, where quality issues play a fundamental role and influence the design solution on public building with health care functions. It was found that the procedure for integrating QA/QC into a design process based on BIM provided a range of possibilities for assessing quality during the design process.

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KEYWORDS
BIM (Building Information Modelling); design quality; validation of design solution; quality assurance; quality control

Introduction

The adoption of Building Information Modelling (BIM) is a paradigm shift in the Architectural, Engineering and Construction (AEC) industry. BIM represents a completely different way of approaching the building life cycle, enriching parametric elements with information from the early design phase up to the construction, and including the phase of maintenance and demolition. It is considered an efficient team-working technology because, if well governed, the system avoids the duplication of information. This may benefit all the participants involved in the building process: owners, buyers and managers have coherent data collection for management and maintenance, while designers and construction companies have coordinating tools to detect defects and intervene to correct the digital model. This process of exchanging information is part of the communicative issues that require correctness of the message emitted from the sources (designer), correctness of message transmission (type of support, media, digital files) and correctness of understanding by the receiver (based on sharing codes). This, in a BIM process, should generate a digital model without any misleading information in it. Usually, in design, the privileged communication media is the 'drawings', enriched by the alphanumerical information included in the parametric BIM elements. Therefore, the BIM quality refers to a complex process of information evaluations that will consider not only the correctness of the documents and the drawing produced but also the efficiency and effectiveness of the process evaluating the information included in the model. Ensuring an evaluation system is mandatory for those complex processes that involve so many participants,

CONTACT Vincenzo Donato vincenzo.donato@polito.it

especially in the case of large-scale design project realisation. Moreover, from the contracting authorities' perspective a system of evaluation that leads to a system of quality assessment that certifies the BIM model according to certain codified level of quality will be indispensable. Although there are a series of international standards and best practices about the implementation of the BIM, there is no reference for BIM quality assessment. This work, according to the different methods of code compliance and model checking already presented in the literature, proposes a semi-automatic procedure that will allow designers to overcome a recurring problem that often occurs in quality assurance systems that relates to additional costs and time-consuming effort.

The proposed process will consider two types of evaluation. The first is related to monitoring the process and giving feedback in real time, and the second is related to assessing the digital model and including information. As detected by the experimental phase, the process and model affect each other. Interesting results were highlighted during the application of the method especially regarding the detection of missing information that, if not detected, could undermine the entire project. The second part of the evaluation will consist of assessing the quality for the BIM model. The innovative part of the method will propose a semi-automatic procedure that will interrogate the presence of the parameters both in the BIM and in the Building Object Models (BOMs)[1] through interrogation on the database (DB). The parameter can be classified as indispensable, necessary and superficial. This parameter will be converted in a numerical form, transformed into a 'shared parameter' that will be added automatically to the BOMs and visualised through a graphical scale colour, for an immediate visualisation of possible missing information. Moreover, the research investigates how the quality assessment, both for the BIM process and for BIM model, can affect the decision-making process in architectural design. The experience has shown criticism relating to how information not considered at the beginning of the process could affect the architectural layout.

State of the art: taxonomy, methods and procedures

'Quality' is a complex concept that has been studied through different specialist authors' points of view and has undergone great evolution over time.[2] According to Juran (1988), quality can be defined in terms of (1) conformance to the agreed requirements of the customer and (2) a product or service free of deficiencies. In most cases, quality is associated to a product, a service, a project or a process and requires the setting up of a formalised system, *Quality Management* (QM)[3], that allows maximum results (effectiveness), using the best human resources, time and economic resources available (efficiency) (ISO, 9000, 2015).

We can argue about quality in the AEC industry**,** although 'quality' is used differently from industrial production due to the unique peculiarities influenced by local regions and the complexity of the building life cycle that is distinguished by different phases, such as design, construction and operation (Arditi, Gunaydin, David Arditi, & Murat Gunaydin, 1998). If we consider the literature and professionals' feedback, it is evident that the BIM is considered a helpful tool for: (1) improving design quality to support the reduction of design-related errors and reworks and (2) allowing the automatic detection of errors related to model elements (Woo, Oh, Kim, & Choi, 2015). Furthermore, it is a shared opinion that using BIM from the beginning of the design stages can be a fundamental tool to assist the designer during the entire building process and 'when adopted well, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration' (Eastman, Teicholz, Sacks, & Liston, 2011). In an industrial process, it is necessary to perform checks, tests and measurements necessary to eliminate or correct those products that do not meet the requirements set out in the specifications before the final delivery of a product (O'Brien, 1989). This is not possible in the construction industry because each variant or error in the construction phase entails a considerable cost. For that reason, it is possible to predict, in advance, the behaviour of the buildings realising a virtual prototype, and to perform an early evaluation of design alternatives using analysis/simulation tools that increase the overall quality of the building through BIM (Eastman et al., 2011). Quality can be also defined as the compliance with construction codes and specifications, and is required to a phase of validation often connected with a phase of control or inspection (Chen & Luo, 2014a). In spite of the massive widespread adoption of BIM, few research studies have been conducted that refer specifically to the BIM quality control and efficient information utilisation (Chen & Luo, 2014b).

Before going into depth to refer to a specific technical aspect of BIM's quality, it is necessary to start with some generic definition related to QM. During the process of quality assessment, we can refer mainly to two aspects: Quality Assurance (QA) and Quality Control (QC), which are often confused as one aspect. QA is a programme that covers the activities necessary to provide quality in the work to meet the project requirements (Arditi & Gunaydin, 1999), while QC is the specific implementation of the QA programme and its related activities (Ferguson & Clayton, 1988). The QA is a planned and systematic action necessary to provide adequate confidence that a structure, system or component will perform satisfactorily and conform to project requirements. On the other hand, the QC is a set of specific procedures involved in the QA process (these procedures include planning, coordinating, developing, checking, reviewing and scheduling the work). Moreover, for making quality measurable, it is necessary to set quantitative and qualitative 'indicators' to make the phase of evaluation objective. In general, the goals for measuring quality are: (1) to improve the satisfaction of the customers, (2) to reduce costs, (3) to make the performance of the organisation visible and recognisable on an objective level by everyone (collaborators, customers, etc.) and (4) to compare performance over time.

Considering the BIM process, the quality evaluation can involve two main aspects: (1) the BIM process management, through which it is necessary to detect the adherence of a predefined process approved by professionals, stakeholders and bidders (associated to define methods of collaborations and exchange information), (2) and the BIM models, in checking the coherence of digital model regarding the information enrichment into the parametric elements.

Regarding the first aspect, the BIM process management (1) during a construction procurement, the evaluation of the quality can affect the definition of the process which describes the method of exchange of information and responsibility, and sets a measuring indicator for the QA. International organisations and authorities, such as GSA (General Service Administration) and BuildingSmart, have established the 'best practices' that get quality results. In particular, in the Finnish documents COBIM2012 – Series 6: *Quality Assurance* (BuildingSmart Finland, 2012), the checklist and the rule compliance software for asset the models were suggested. But controlling the information, performing automatic rule and complying with the standards regulation are not the only factors that involve quality. The process management and the information exchanges are sensible parts that concur in the definition of quality. In literature, there is an interesting method proposed by the Computer Integrated Construction (CIC) Research Group, where a possible QA could validate the adherence to pre-established procedures that must be approved by all participants in the project process (The Computer Integrated Construction Research Group, 2009). This is defined as the *BIM Project Execution Plan (BIM PxP)*, which can be taken as a reference to define a contract stipulated at the beginning of the process and appointed to providing a global overview of the steps in which both the roles and the responsibilities of the members of the project are clear. Currently, several countries have decided to adopt mandatory BIM for public procurements; they have begun to request BEP (Building Execution Plan) that is a real contract stipulated by the people involved in it. Before working on the BEP, it is necessary that the administration or the owner establishes a list of design requirements that in technical terms are defined as the *Employer Information Requirements* (EIRs). The document specifies the *Level of Development* (LOD) (BIM forum, 2015) for the definition of the *Building Object Models* (BOMs), the parametric elements used in the BIM models. The LOD is defined by the *Level of Geometry* (LOG) and the *Level of Information* (LOI). In some samples, the checklist's criteria are based on the parameters of the 'yes/no' type, but in reality an evaluation scale can exist where the information can vary sensibility. In literature, although there are some process efficiency and efficiency detection schemes, there is no reference to BIM quality assessment.

Regarding the metrics on how to measure quality, we can highlight an accurate method that proposes to monitor the five components of the BIM performance measurements (Succar, Sher, & Williams, 2012). It includes: BIM capability stages, BIM maturity levels, BIM competency sets, Organisational Scales and Granularity Levels. These components are the result of some consideration that will bring BIM to increase the reliability, adaptability and usability from different stakeholders. In this work, the metrics (based on qualitative factors) that needs to be: accurate, applicable, attainable, consistent, cumulative, flexible, informative, neutral, specific, universal and usable has also been defined. In particular, it is interesting to note the second topic in the five components of BIM related to the maturity level, where the authors define a 'Maturity Matrix Level'. In this case, through the individuation of qualitative factors, the result of these analyses gives a performance level overview of the BIM implementation and gives awareness of the implementation to all the participants in the BIM process (Succar, 2010). Some of these parameters are mainly related to the visualisation aspect and the representation of the geometry, and it is demonstrated that a correct visual control can also increase the quality and efficiency. Although this work never directly mentions the concept of quality, it can be considered a part of a similar and well-known manufacturer model defined as the 'Continuous Improvement Model', where the participant can use it as a reference for improving their productivity and quality. The lack of this method is the 'subjectivity' on which the information and evidences are provided by the participant, which goes directly into the final definition of diagram. In this last case, there is no reference in how to assess quality for that information. Another interesting work (Zadeh, Staub-French, & Pottinger, 2015) refers to the BIM quality for Facility Management, and is defined as an analysis framework for the information quality (IQ). The author proposes to control the 'Information Incompleteness' and 'Value Inaccuracy' for asset and Mechanical, Electrical and Plumbing (MEP) system and the 'Spatial Inaccuracy' related to spaces and work areas. Moreover, the author also describes the 'Model Incompatibility' that is related to the model compliance with the BIM standards and contributes to the definition of IQ. This method is mainly based on the control of the data availability, but it does not interfere with any method that is able to evaluate the quality of the information given.

Regarding the specific quality control for the BIM models (2), different approaches have been depicted in the literature; they are subdivided into automatic or manual ones, which are aimed mainly at compliance checking. We can highlight several types of control, such as the checklist requirements (BuildingSmart Finland, 2012), the geometrical conflict highlight through the clash detection (Bhagwat & Shinde, 2016; Eastman et al., 2011), the automatic rules checking (Eastman, Lee, Jeong, & Lee, 2009; Zhang, Teizer, Lee, Eastman, & Venugopal, 2013), the standards consistency and the regulation compliance since the early design stages (Ciribini, Mastrolembo Ventura, & Paneroni, 2016; Eastman, 2009) and the ontology compliance (Fahad & Bus, 2016). All of these controls contribute to the definition of the 'Quality of BIM model', although not explicitly defined.

Proposal of a BIM-QA/QC: data management and graphic representation controls

In spite of the many 'best practices' regarding the implementation of the BIM, there are several criticisms that have emerged through the literature review on QA. First of all, there is a standard lack of, and no definition for, the quality systems or numerical factors in the BIM processes and model. Some method suggests measuring the adherence of the design process with a pre-established procedure and validating, through qualitative factors, the accuracy of the documents and the file produced. Moreover, implementing a quality system for an organisation presents additional costs and time, which are added to the already tight deadlines for project deliveries.

For that reason, our approach proposes an improvement to the traditional method of evaluation and to ease the quality evaluation implementation procedure in the design process through automated procedures. The aim is to reduce the time required to monitor the quality aspects.

For considering the design process depicted by RIBA's Plan of Work (RIBA, 2013) in the definition of the BIM quality methodology, we will refer to the *Developed Design (DD)* Phase). This decision is related to the effort that must be taken for collecting data, and for the enriching of information that has to be included into a BIM model.[4] Along with the definition of process quality[5] (which contributes to an important part in defining the quality of the building), we can assume two main concepts that will be adapted for the BIM – Quality Assurance (BIM-QA) and subsequently the BIM – Quality Control (BIM-QC). BIM-QA has preventive purposes and aims to ensure that the production processes of the deliverables of a project meet the quality standards agreed upon by the end customer. In order to specifically implement BIM-QA, BIM-QC has the inspection purposes – it checks that the deliverables of a project conform to the specifications and the predefined requirements (QA criteria). So, BIM-QA is a part of the BIM-QA; and therefore, it is important to maintain a clear distinction between them. According to their definition, BIM-QA is a control component of the QC process; QA criteria instead are inputs (Figure 1). If we take into account the description of the BIM process provided by the *BIM Project Execution Planning Maps (BIM PxP) – Level 2: Design Authoring*, we can define two different BIM-QA: (1) one related to the process and (2) the other related to the model. The methodology that we propose defines a new process, criterion and metrics that will be described in detail in the text below.

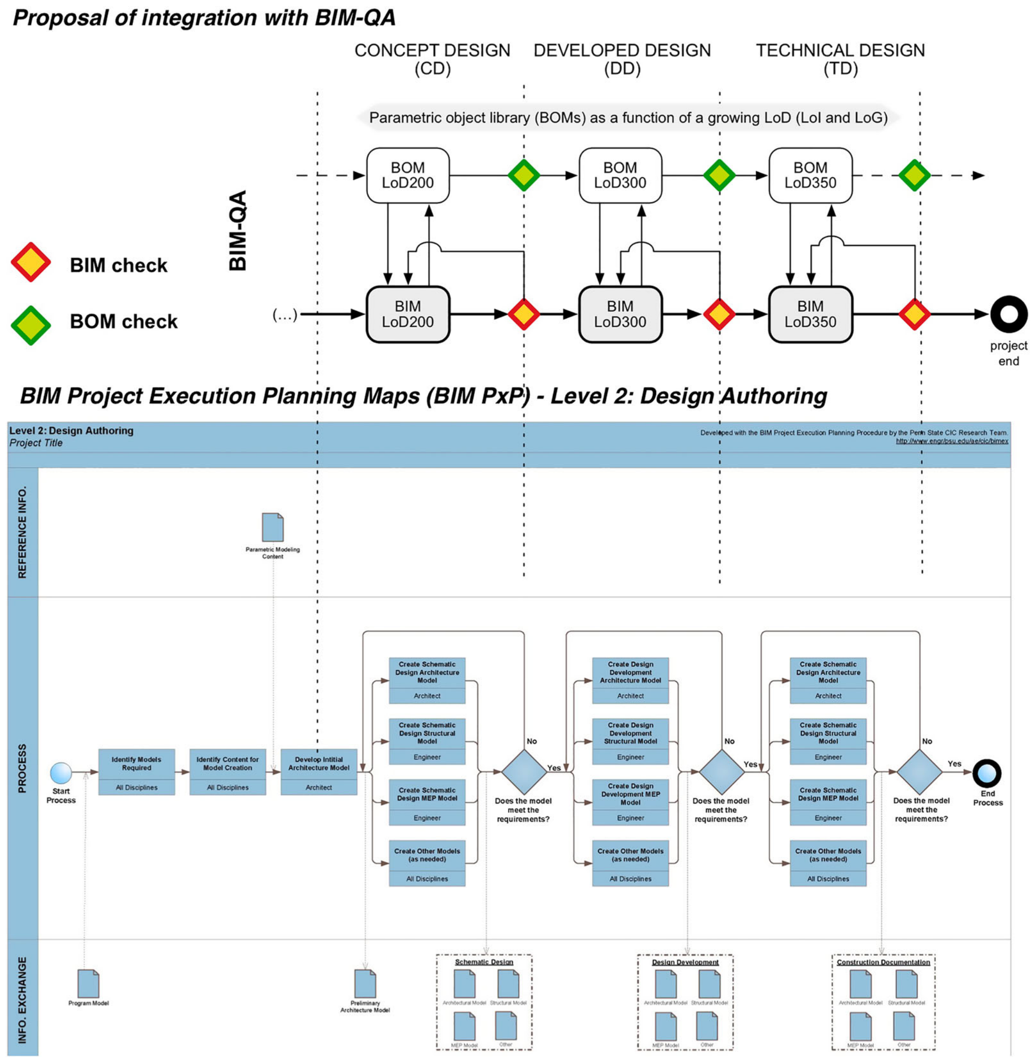

Figure 1. Integration proposal for BIMPxP through BIM-QA/QC: where the QA process intervene.

BIM-QA process

Regarding the BIM-QA process (1), taking inspiration from the method being successfully implemented and depicted briefly in the literature review, we will validate the adherence of the design process to a pre-established one, approved by all the actors involved via a preliminary contract (BEP). During this process, the information required (input) and information exchanged (output) are produced as the function of a specific phase. The suggested process takes inspiration from a well-known practice in the manufacture industry that is defined as 'Total Quality Management' (TQM), where a management approach to long-term success through customer satisfaction is described. The satisfaction is represented not only by the compliance with the initial requirements but also by the standards and regulations.

This method can be extended in a simplified way for a BIM process where all the operational phases can be monitored during the design stage, and evidences of the process can be gathered.[6] The quality is guarantee if all the criteria, action or process are satisfied[7]. For each criterion, the QA gives an evaluation in accordance with the matrix provided in the table, that is an equilibrium between efficiency and effectiveness of the process evaluated (Figure 2).

The criteria expresses a satisfaction in relation to a stage or a phase in the process and is expressed by a qualitative evaluation provided by the people in charge[8] for monitoring the process and can help in detecting some inefficiency during the design process. Only positive (upper to zero) values can pass the BIM-QA process. Moreover, the quality evaluation of the BIM process may be graphically supported using the 'IDEF0 Functional Modelling' method (Cerovsek, 2011). This method represents the structured information and also considers the decisions, actions and activities of the system organisation. As depicted in Figure 3 and coherently with the COBIM 2012, especially in reference to the volume 6 (BuildingSmart Finland, 2012), we propose four features that define the BIM-QA process, which are: Criteria (input data); Standards (control form); Method (control mechanism) and Team (subject involved and responsible for mechanism and co-operation).

The 'criteria' are used as input data to the quality model. They define the field of existence of the design to satisfy functional requirements, and a correct dataflow from documentation to construction and control phases.

The phase of 'Design Reviewing' and 'Approving Design' is based not only in gathering information related to the processual issue, but also in performing standards compliance checking (a typical issue of a BIM validation process specifically oriented to verify law and codes constraints) and physical and numerical simulation to assess the design solution. The process will involve the checking of documents; norms for technical drawings defining criteria such as readability, adequacy and completeness of information.

BIM-QA model

Regarding the BIM-QA model (2), and referring to the already mentioned workflow of BIM PxP-Design Authoring, we can associate at the phase indicated as 'model meet requirements?' represented by a rhombus, two types of BIM-QC, which occur in two different moments: (a) 'BIM check', QC on the model, and (b) 'BOMs check' (see Figure 1).

The control performed on the model (a) is mainly related to generate a coherent Industry Foundation Classes format file (IFC). The validation will include the checking of design content and analyses[9]; standards and regulations compliance and technical information content (referred if the IFC file is correctly produced from the authoring software).

Along with these procedures, some inspective methods, which require visual control verifying the correspondence of the criterion reported into checklist or automated check on the internal DB, have been elaborated. The visual checks are carried out mainly 'by sight'; the operator checks the conformity of the elements (usually geometric) in relation to specific or previously approved conditions. Generally, this type of control is time consuming. Automatic checks take place by implementing

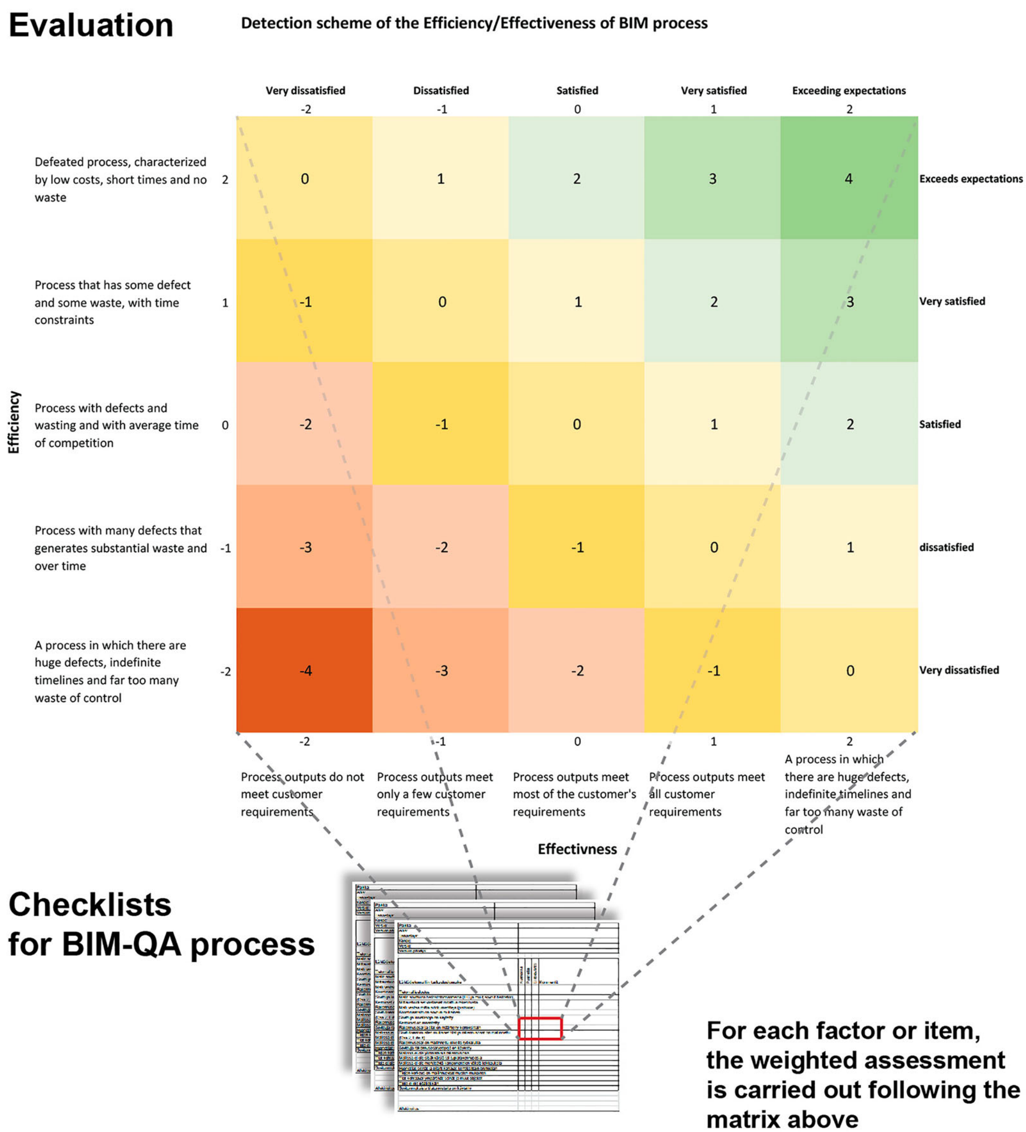

Figure 2. Detection scheme of the efficiency/effectiveness of BIM process.

precompiled rules in the model-checking software or through queries for the databases creating macros. The operator has the possibility to check the inconsistencies between models and to intervene to correct the data. Once the model has passed the tests and has been approved, the BIM model can be adopted as the basis for the next stage of the process.

The second type of control related to the BOM check (b), propose an information coherence control, and is based on two criteria: the former, is based on the 'yes/no' criteria as a function of checking the criteria (for instance, the operator will check the presence not only of parameters such as the transmittance, porosity or the elasticity module (if we are checking the composition of material) but also of parameters that can affect the design, such as the work volume, manoeuvring space and maintenance space). It is possible to generate an automatic procedure for controlling the presence of the parameters (control yes/no) via the DB. Moreover, through the generation of additional parameters[10] into the BOMs, it is possible to go back into the BIM software for visualising

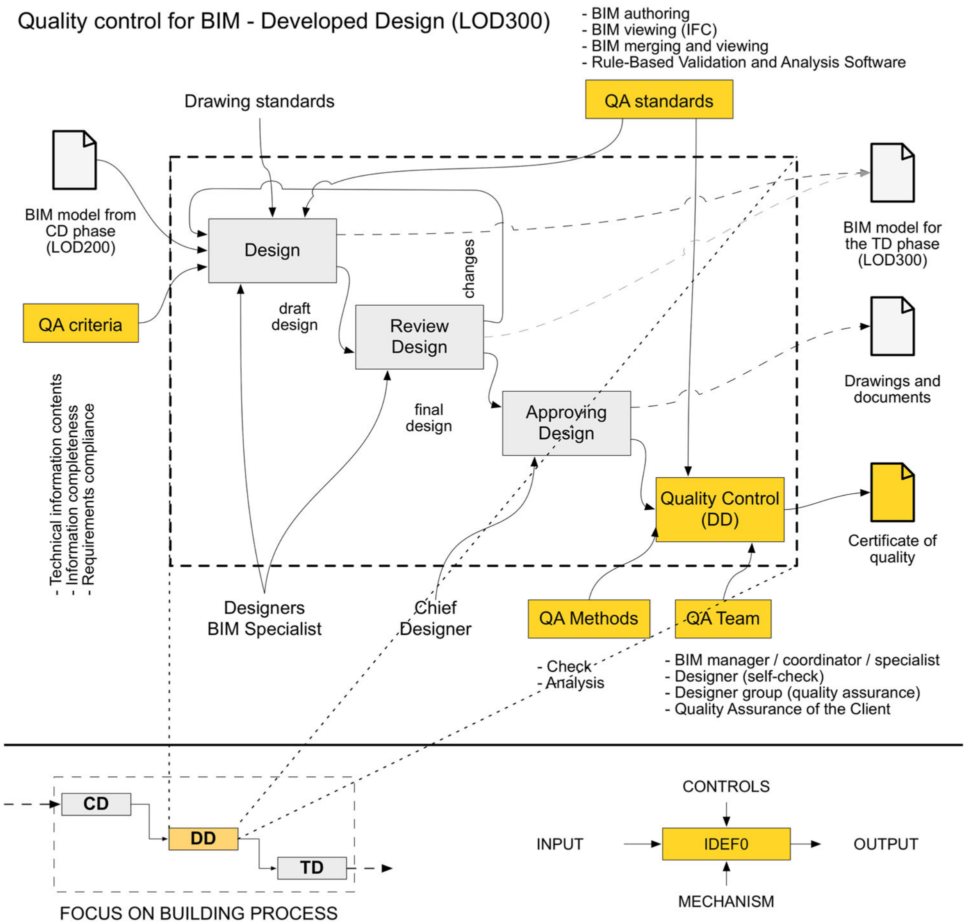

Figure 3. Quality control for Developed Design Phase.

the result of the evaluation through a scale colour. Generally, the control on BOMs must consider: dimension of the file (large BOMs, in terms of Mb, can effect negatively the BIM central model), the presence of simplified geometry (that describes work spaces and volume useful for designing), the presence of detailed information (in accordance with the specific LoD), physical and mechanical parameters, and many other factors.

If we are focusing on the DD Phase, it is possible to associate a precise LOI that is equal to LoD350, to international standards, such as PAS 1102-2 (BSI, 2013). An LoD350 has no clear definition because it is declared that an element (BOM) 'is graphically represented within the Model' (BIM Model) 'as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element' (BIM forum, 2015). In our opinion, a BOM can have two sides of the same coin: a *low LOG* (expressed by the 3D geometry and upgradable with time and the growing number of specifications) and a *high LOI* (a) or a *low informative level* but a *high LOG* (b). This particular equilibrium must be decided and signed into the BEP. In general, a good criterion could be implemented and use BIMs as lean as possible[11] (an example is provided in Figure 4).

The evaluation of a BOM consists of detecting a correspondence of LoD as a function of the information required on the EIR. Moreover, the validation must consider the capability to generate a coherent IFC file from which information can be easily transported towards another software. The evaluation of a BOM, overcoming the stage of 'yes/no' criterion, can reach an index that can be

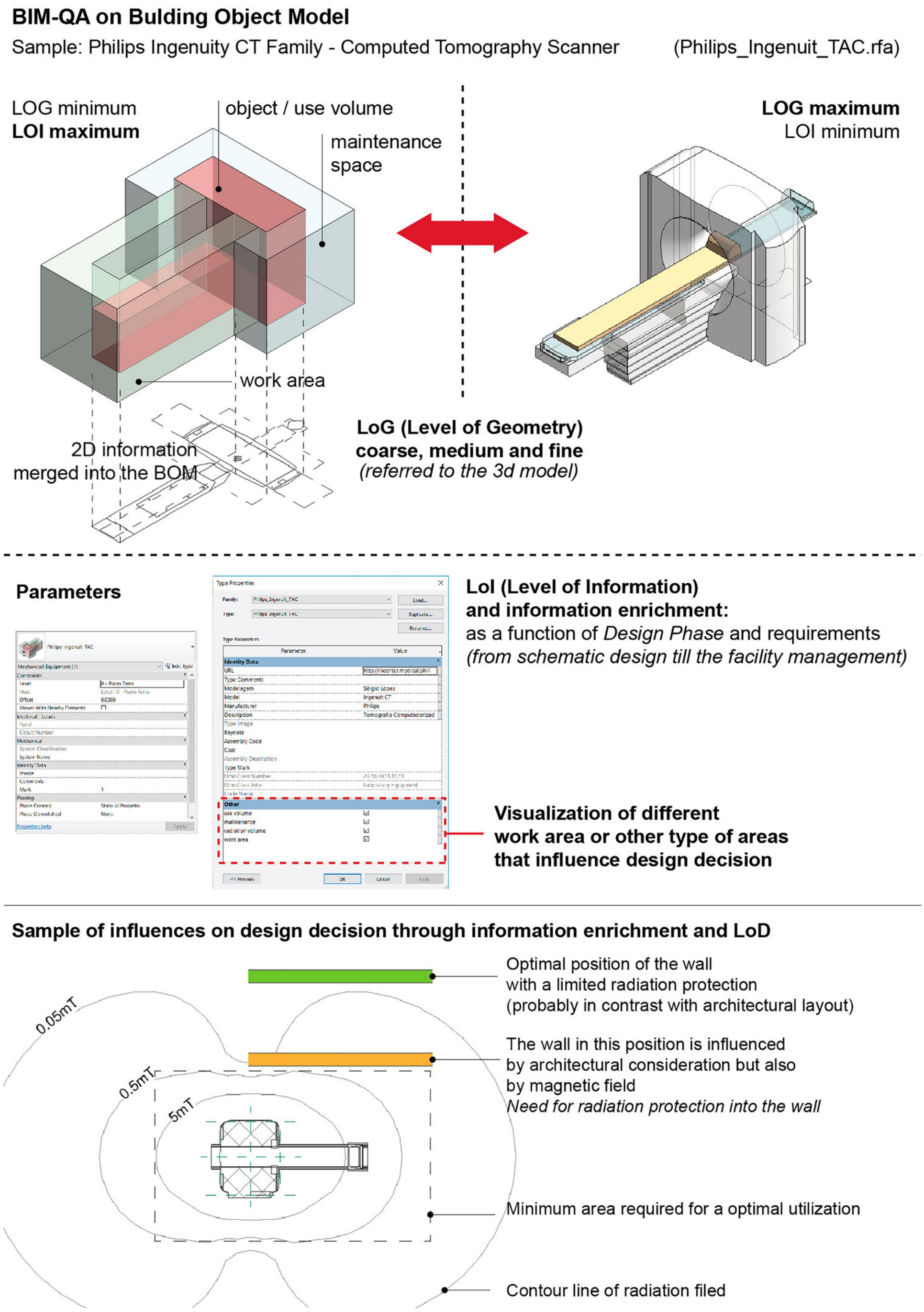

Figure 4. LoG and LoI for the quality assessment: two different ways of managing information.

expressed as a percentage (0–100% QA). The percentage is also associated to a scale colour for an immediate understanding through visual representation of the values. The parameters in the BOM can be subdivided into three categories: *fundamental* (indispensable requirement without which you cannot pass the quality check), *necessary* or *non-necessary* (those that still influence the general evaluation). The last two, necessary and non-necessary parameters, influence the QC value when expressed as a percentage. In order to evaluate this kind of information, it is possible to apply BIM-QC through the semi-automatic DB consistency control on BOMs. In order to verify the correct settings of parameters inside each BOM, we check for three conditions starting from the alphanumerical list extracted by the IFC or authoring software file. The whole automatic process produces a value that we call the 'QA state of the parameter'. This can assume three values: inexistence of the parameters (−1), existence but misses compilation (0) and existence and it is compiled (1). This validation finally activates a return flow inside the BIM model within the authoring software environment, in order to graphically visualise the results through the scale colour before being defined. Each instance in the BIM model assumes a value (−1, 0 or 1) that produces a different colour behaviour (red, yellow or green) so, we can visually locate the missed parameters. Having assumed a relational DB approach, we can also count the percentage of instances that satisfy the LoD criteria (1 value) with respect to instances that do not; the percentage total value is finally assigned to a specific part of the design (room or area), so that we can graphically visualise the synthetic result.

Case studies in hospital design: a graphical approach and conceptual evaluation

The methodology previously shown was applied to some large public procurement tenders for hospital facilities (Table 1 and Figure 5), which are driven by some of the biggest Italian construction companies. The BIM-QA procedure has been applied to all the projects that are presented in this paper, although in some cases, a partial application was performed due to timing reasons, to satisfy tight delivery deadlines.[12] The aim of this experimental phase was gathering feedback from the professional experiences and finding parameters that give a feedback on applicability, flexibility and usability of the whole process through the professional application. The evaluation phase required an enormous effort, both in terms of resources and in terms of the time necessary for performing the check of the models for validations.

All of the projects used a BIM-based approach, and different models were developed (architectural, structural and MEP). The federated models used the Autodesk platform (i.e. Revit Autodesk) and then exported as IFC files for managing the clash detection and for using DB queries. The constructed BIM models using Autodesk Revit, up to the LoD350, are depicted in Figure 5. In general, all the designs propose new design solutions for improving the functional distribution on the basis of a preliminary project, which was provided by the contracting authority. Moreover, the BIM models were used to produce the tendering documentation, and to conduct the analyses.

Table 1. Case studies: summary statement of the characteristics of the building.

Case study	Udine Hospital	Sulmona Hospital	Modena Hospital
Type of intervention:	*New design*	*New design*	*Renovation*
Value (approximately):	60 Million Euros	16 Million Euros	8 Million Euros
Dimensions (total gross floor area):	12.300 m^2	7.420 m^2	2.300 m^2
Composition of team and corresponding models:	ARC STR MEP	ARC STR	ARC STR MEP
BIM documents produced	General drawings Construction drawing Shop drawings	General drawings Construction drawings Specification Estimation	General drawings Estimation
Documents produced through traditional approaches:	Landscape Specification Estimation	Landscape MEP documentation	Landscape structure specification
Dimension of federated file:	250 Mb	80 Mb	42 Mb
Approx. time of realisation of models:	ARC: 12 weeks STR: 6 weeks MEP: 8 weeks	ARC: 8 weeks STR: 4 weeks MEP: 6 weeks	ARC: 3 weeks STR: 2 weeks MEP: 2 weeks
Time for performing the evaluation:	2 days	3 days	1 days

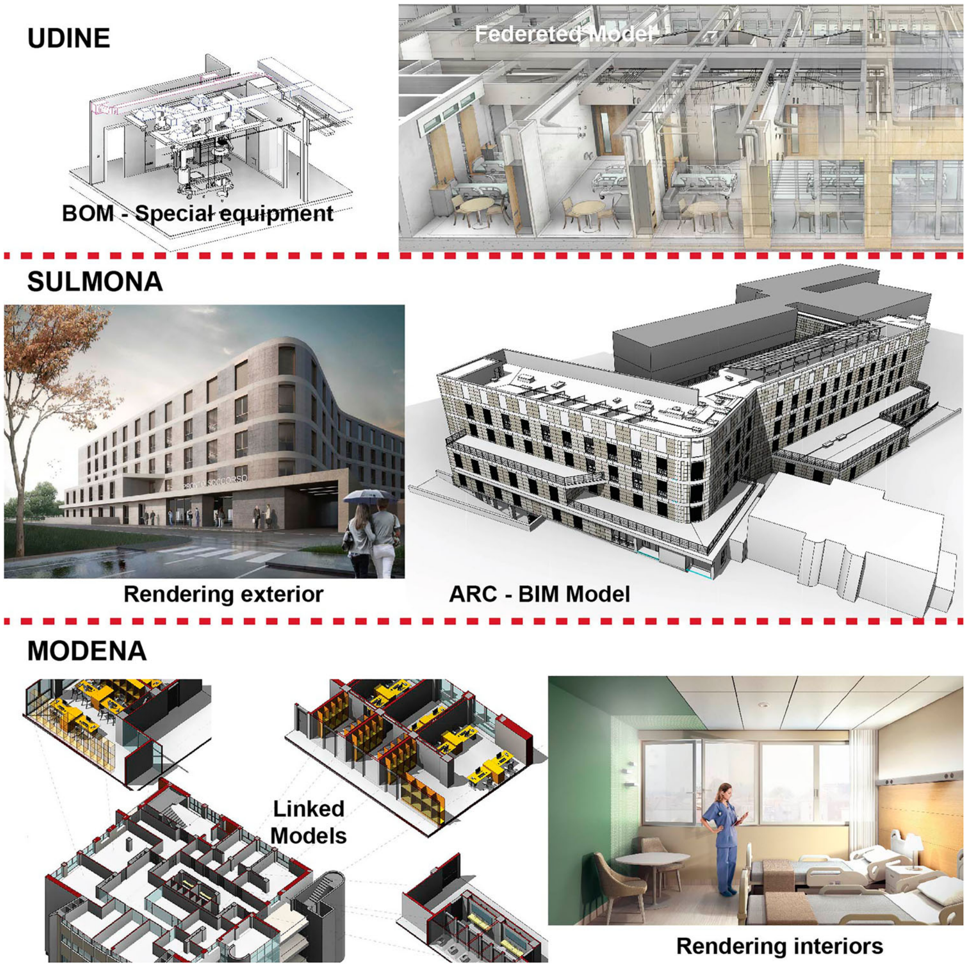

Figure 5. The case studies.

To automatically check both the BIM models and the BOMs, a series of queries in Microsoft Access were performed. A graphic evaluation based on an automatic procedure made explicit through scale colours has been used. In the picture below, it is depicted as an example of the results of evaluations (Figure 6).

The evaluation phase of the BIM model analyses several design aspects (i.e. traditional controllers based on professional practices such as the control of environmental, energy, sustainability, structural and functional aspects); in addition to new controls that arise from the need to automatically control data for all of the BOMs present in the project.

BIM-QA model was applied for assets:

(1) Warning of geometrical coherence to be solved (usually detected automatically by the authoring software);
(2) Clash detection[13] of the federated models avoiding any interference between architectural (ARC), structural (STR) and plant (MEP) models. The MEP model was further subdivided into HVAC sub-disciplines.[14] The result of the interference check is reliable only if the input data can achieve a good quality, according to a correct LoD (Figure 7);

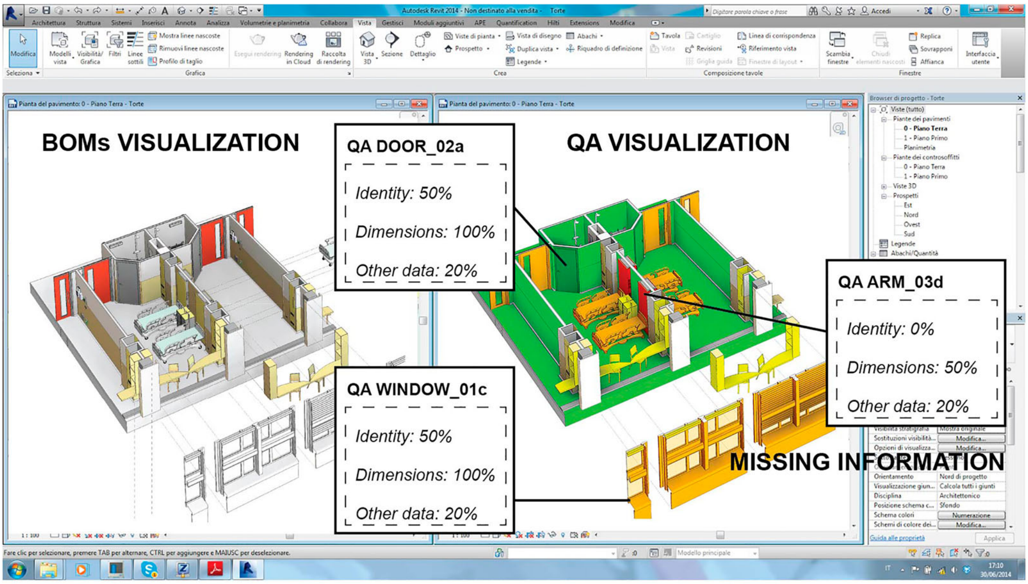

Figure 6. Graphical evaluation of level of information included into BOMs.

(3) Document control and visual checking for the correctness and the aesthetic appearance of the drawings (readability, adequacy, completeness of the information included into the BIM model and into the output drawing);
(4) Aesthetic checking performed with augmented and virtual reality.[15]

Taking into account the interoperability issue, within the specific domain of each designer, two outputs can be achieved: the first is the native file format of the software used by the designer; the second one has been generated on the basis of the previous one and then exported in the IFC extension file. In this broad panorama of digital models, the IFC file plays a critical role in BIM-QC as it can be considered independent from the specific BIM software used. During the design phase, to move from one phase to another, the model must obtain a 'certificate of quality', which ensures that the file is compliant. The BIM-QA has included additional analyses that have modified the sensibility of the architectural distribution design, such as optimising the internal-distance flows, minimising the movement of the workers between the various spaces (highlighting the preferable locations for nurses and doctors), creating visibility diagrams for introspection of the interior spaces, calculating the windows/floor surface ratio, calculating a daylight factor and comparing with the minimum required. A possible additional analysis that could easily be automatised into a BIM software is the check for visibility. The visibility diagrams most sensibly influenced the design phase; these diagrams lead to the change of the original design solution to a more optimised solution. Due to the visibility diagrams deriving from the space syntax approach (Al Sayed, Turner, Hillier, Iida, & Penn, 2014), the distribution of the access door into the inpatient department was changed. In this case, the door was oriented to permit the nurse (i.e. the person in charge of the patient) to control four positions rather than only two. A similar reasoning was used for the intensive and sub-intensive care units. To control and manage information during the process, an approach for separating the file that contains the BOMs, and for transferring the information into the project, was used. This step is fundamental not only to control the information for each category and element but also because the file, which we named 'Abacus of Elements', is subjected to cost control. This cost control is connected to the list prices provided by the manufacturer and approved by the construction company.

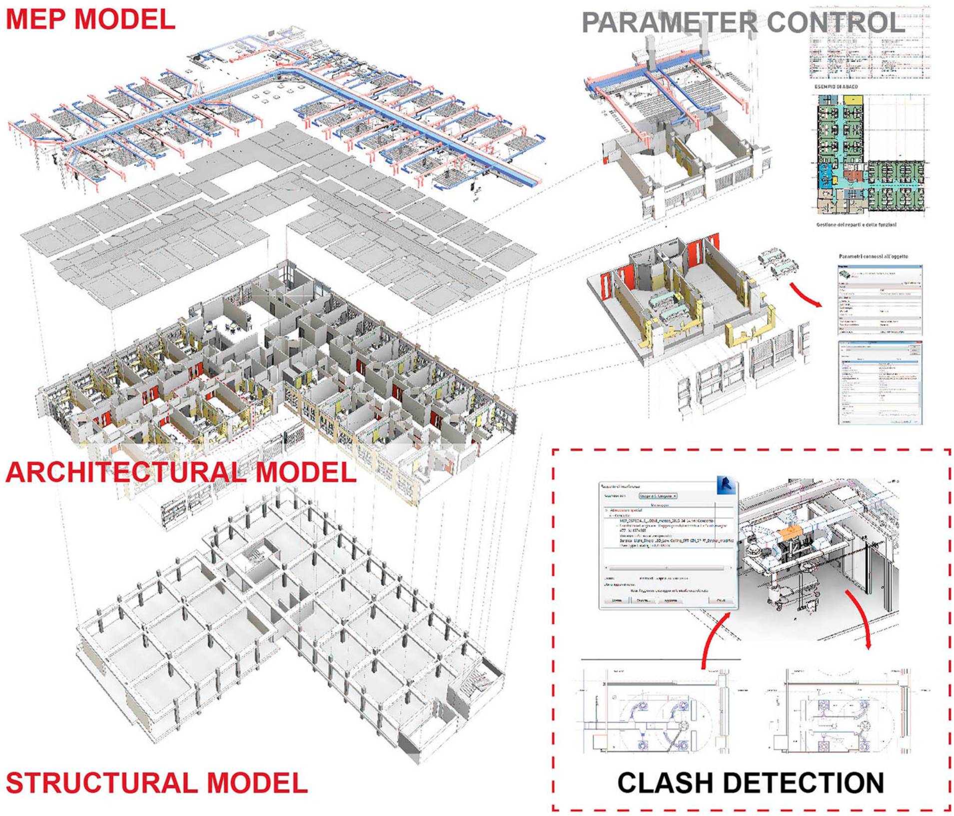

Figure 7. Clash detection as quality main indicator.

Conclusions and further development

The procedure proposing the integration of the QA/QC into a design process based on BIM provides a range of possibilities for assessing quality during the design process. The procedure was elaborate to guarantee: applicability of the method depending on the time available, flexibility due to the possible extension of the procedures to other design phases (such as Concept Design and Technical Design) and neutrality, by not using a particular software produced by only one vendor but instead using the IFC file. The aim of a BIM-QA is to improve the quality of the design solutions intervened by monitoring the process that will consider the conformance to the client's needs, and the predictability of the construction schedule and costs. Moreover, the 'quality' is also guaranteed by ensuring the continuity of the information flow at all stages of the BIM process, which were evaluated through the definition of the matrix of efficiency/effectiveness, mentioned along the methodology.

The analyses conducted through case studies have shown the application of QA/QC during the transition between two subsequent design phases CD and DD, especially moving from LoD200 to LoD350. These procedures have shown advantages in terms of the time spent in conducting the analysis but at the same time, limitations are that, even after the attempt to make the evaluative factors measurable, some aspects of the evaluation (especially in relation to the process) are based on qualitative factors, and some of them are also based on subjective evaluation. The opportunity to make them more objective would require a detailed report of the time scheduling with a precise completion of a particular phase (i.e. monitoring the time that it takes to complete a task, the resources used and many others). The main criticism of the entire process proposed is expressed also by the definition of the requirements because the result of the QA is the consequences of the comparison between the requirements included in the EIR and the items performed during the process under evaluations. The quality of the EIR was not addressed in this work, but requires further insights and discussions. A further development of this procedure will be to extend and incorporate other types of automated analyses such as functional and documental controls that was not implemented in this work.

Further investigation, in relation to a purely informatics problem and playing a role of strategic importance for BIM implementation in the future years as well, should be conducted for investigating how the information added now can also be accessible at a future date. This is not a trivial issue and is not the first time it reappears dramatically when a software is withdrawn from the market. A possibility, if shown by using the IFC file that currently represents the best support for sharing information through a platform neutral, opens file format specification that is not controlled by a single vendor or group of vendors. Although IFC represents the best open file for BIM, not all the information can be exchanged through this type of file; for instance, for energetic analysis, it is suggested to use other formats (such as the gbXML) to export and import correctly other types of data and consider correctly the analysis. Although there were great improvements in terms of software interoperability since 2010, the case studies have shown limitations related to the communication between different platforms, even in the early initial stages.

The latest topic that needs an international discussion is speaking about a 'quality certificate' for the BOMs. On the internet, there are several resources included in libraries provided by specialised operators, but all of them are not at acceptable levels of quality (for example, the geometry is not a parametric but realised by importing inside the BOM a 3D mesh model that makes the object unusable and many other types of issues that must be solved). In our opinion, the best way will be to consider adopting a 'chart of quality' or a 'certificate of BIM/BOMs quality' that must be respected in order to guarantee a correct BIM process.

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Notes

1. If we refer to a BIM software (i.e. Revit Autodesk) BOMs refer to 'families'.
2. The concept of quality was studied during the 1940s and 1950s when there was a wave of enthusiasm for the use of statistical methods in quality control; in the 1960s and 1970s, various terms such as 'total quality control', 'zero defects' and 'product assurance' emerged as alternatives to the use of quality control as an all-inclusive term for the regulatory process (Juran, 1988; Juran & Godfrey, 1998). During the mid-1980s, there emerged a revival of keen interest in statistical methodology under the name 'statistical process control' (O'Brien, 1989) and only in late 1990s (Bubshait & Al-Atiq, 1999) was it introduced for the quality for buildings with the introduction of the standard ISO 9000.
3. ISO 9004:2008 – The standards quality management system.
4. In fact, usually the design effort also for producing the necessary documents between the Concept Design Phase (CD) and DD is bigger than the one from DD towards the Technical Design (TD).
5. Already provided in the state of the arts and which contribute to an important part in defining the quality of the building, we can assume valid the process that consists in monitoring how the input and output information are constantly produced.

6. Evidences are gathered through the observation of certain efficiency and effectiveness criteria that is reported into checklists.
7. For instance, a possible check criterion could be if the information is exchanged through native format file and IFC file, if all the parameters are correctly generated into an IFC file, if the BIM model has the correct number of technical sheet, and so on.
8. Unusually, this evaluation could be demanded to the BIM manager.
9. Analyse the model comparing components of the model against each other (i.e. consistency and clash detection) or against known requirements (i.e. spatial requirements, deficiency detection, building code checking).
10. Shared parameter into Revit Autodesk.
11. So, in this case, it is always preferable to implement a type (a) process.
12. The BIM Quality Assurance (BIM-QA) was elaborated for research purposes and has not been expressly required neither by the client nor by the construction companies. The process was experimented for the first time by the architectural firm that also has the role of project coordination.
13. Model checking software such as the Solibri Model Checking.
14. Electrical, mechanical and special hospital equipment i.e. the MEP model included ducts for nitrogen and oxygen in accordance with the location of the operating rooms.
15. Using Enscape (a Revit plug-in), it was possible to realize real-time rendering and utilize the Oculus Rift to design the space. Through the classic controls in the work area (e.g. “move”, “copy”, “wheel”, “stretch” and “add family”), the user can design and view the space at the same time as the change is made in the BIM model.

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No potential conflict of interest was reported by the authors.

ORCID

Vincenzo Donato http://orcid.org/0000-0002-3947-8402
Massimiliano Lo Turco http://orcid.org/0000-0003-1440-3911
Maurizio Marco Bocconcino http://orcid.org/0000-0002-2926-817X

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