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Informative content validation is the key to success in a BIM-based project

DOI: 10.14609/Ti_2_15_1e

Key words: Building Information Modelling (BIM), Model Checking, Public Works.

Abstract The construction industry, particularly the public sector, started drawing attention towards containing costs and increasing performance. This is why several public entities worldwide are promoting new strategies and adopted innovating approaches such as the Building Information Modelling (BIM). Countries like the UK, Germany, France and Spain are working on it through investments in the industry digitalization. In Italy, despite the fact that the growing implementation of *information-based* technologies is not supported by a governmental strategy, public calls for tender requiring BIM have been set up. In addition, in order to benefit from a BIM-*based* approach, cooperating processes are being arranged to involve several parties from the very first stages of the project itself. This way flaws will be sorted out in advance and out of the construction site, and at the same time ideal solutions will be identified for the entire building lifecycle. Within the BIM methodology, a key role is played by Model Checking, which enables verification and validation of all projects, not only in the design phase, but also throughout the process phases. In order to guarantee reliable results, an initial *pre-check* should be carried out, the so called BIM Validation. This validates the data content of the Information Model and subsequently carries out analyses such as Clash Detection and Code Checking. The Information Model must come out of a meticulous modelling phase, in order to validate its geometric and alphanumeric content and ensure reliable results first, and then proceed with subsequent *BIM-based* analyses.

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INTRODUCTION

In the last few years the construction industry, and especially public constructions, started adopting innovating strategies to contain costs and, at the same time, to increase performance. The success of a project is strictly associated to the management of a huge amount of data, to be shared with the multiple parties involved, and to the different stages of the construction lifecycle. Accuracy and punctuality in data exchange are not constant factors in the standard design and construction proceedings, as these often feature interface data loss in different stages. This necessarily requires a new acquisition and processing, which is going to affect timeline, costs and quality of the final product. It is no wonder that the Building Information Modelling (BIM) is spreading more and more and certain countries such as the UK, Germany, France and Spain included it in a well defined government strategy. For instance, in the UK the BIM Task Group has been set up in 2011. This gathers competence in the construction industry, in the government, institutions and universities, in order to set standards and educate the oncoming 2016 construction industry, as in this year the government will require the implementation of a cooperating process of Information Modelling and Management for all public buildings of a certain financial threshold.

The Building Information Modelling is a process to manage information through programming, design, producing and managing a construction work. It is not just a mere tridimensional model, but rather the creation of a parametric information system designed to increase the data associated to the project via a direct connection of such information with the building elements, the BIM *object* making the model. The information conveyed through a parametric model is mainly of two types: geometric or alphanumeric data to digitally describe a certain artifact. The BIM application is based on a true revolution of the construction industry, which affects the approach (so far consequential) to the process stages: new key words are generated to regulate the relationships between the involved parties. By means of the BIM method, the process becomes interactive and the definition and management of the project requirements must develop along with the process itself. Rather than stopping at its preliminary stage, it should be able to adjust to the changes of the lifecyle of a construction work.[1] Of course such an approach does not guarantee a better architectural quality, but it makes it easier for the project to be developed through different options. Some key choices may be anticipated and the involved parties may be able to cooperate, collaborate and integrate even more, not just based on the constructability of the project, but also on its use, maintenance and management.[2] The goal is the mitigation of the risk of incosistency and failure to succeed. A key role within such a revolution is the client's, as they must be able to define their needs and requirements, including through binding contracts, such as the Employer's Information Requirements (EIR). This document is crucial, as the client uses it to define the informative requirements based on the BIM models, as well as the data management method.[3] Designers and companies must study their requirements in depth and respond to them through an actual virtual construction process where their hierarchic, functional and relational structure is directly allocated to each party in subsequent phases, hence guaranteeing clarity and role definition.

The Building Information Modelling is becoming more and more popular in our country. However, if we compare it to the other EU members, Italy does not have an effective BIM-*oriented* strategy to go along with *information-based* technologies. In the Italian market preliminary BIM implementation phase, there is not enough awareness about the entire changing process associated to it, and there seems to be a

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[1] Kiviniemi, 2005.

[2] Ciribini, 2015.

[3] PAS 1192-2:2013.

tendence to use new tools of Information Modelling/Management (IMM) exclusively to simulate standard processes and produce the required paper documentation. Such practice leads to the fragmentation of the information, and invalidates the potential innovating side of the IMM method.[4] Unfortunately the number of alleged “BIM Managers” and BIM experts is growing more and more. There is no consideration for the key factor of the effective responsibility (including at a professional and ensuring level) of such roles in the process implementation, which is strictly linked to Project Management and Design Management. This may lead to serious risks for the industry, because, with no in-depth understanding, there is higher risk of achieving lower results than the actual potential, including worse than the standard.

For instance, some calls for tender have been set up in Italy and required BIM. The majority of the tenders though, only required BIM-based software with no process modifications and without including specific requirements. Such a trend is quite dangerous as BIM requires a change in the management of the entire construction industry. In order to achieve positive results, a government based strategy is necessary to re-define the entire industry.

TENDERING AND CONTRACTS: TRADITION VS INNOVATION

Among the several methods to execute public construction work, the current[5] code allows to use tendering contracts and concession contracts. The main procurement methods are Design-Bid-Build (DBB), Design-Build (DB) and competitive bids.[6] In Italy, as well as in the majority of the world, the most popular procurement method for public construction work is DBB, for this reason also called “traditional”. The contracting authority develops the initial, definite and executive project, whereas the winning bidder is in charge of its execution. The involvement of the winning company is just in the executive phase and several parties are in charge of its design and construction. The executive project is normally available in the bid, for the bidders to be able to calculate quantities and evaluate costs. The awarding criteria are normally associated to the lowest price. In this type of tender the client has more control over the project and an accurate idea of the final cost is available based on an executive project prior to the bid. In addition, it is easier to check several offers as they are all associated to the same project. However, due to the separation between design and execution, the timeline is normally longer and the project, although executive, does not often contain a high level of details to initiate the construction work, or alternatively certain omissions may lead to controversies. In addition, during the bid malicious practices may occur. For instance, the winning bidder offers a lower price and subsequently attempts to recover the money by making changes or initiating legal claims.

In Design-Build (DB), the contracting company is in charge of developing the preliminary and detailed project, whereas the winning bidder is in charge of the executive project. This way, only one entity is in charge of work design and construction. There are several variants[7] and their main advantages are risk reduction for the contracting party and a better work quality thanks to the company’s contribution in the design phase which allows to sort out flaws in advance. However, it is not always easy to compare the offers and the contracting party has less control over project management.

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[4] Caratozzolo *et al.*, 2015.

[5] Legislative Decree n.163, 12th April 2006.

[6] Ibidem.

[7] Bolpagni, 2013.

In competitive bids, on the other hand, the contracting party only develops the preliminary project and a detailed project is defined throughout the bid. Once the winning bidder has been awarded, the company draws up an executive project based on the detailed project and executes the construction. In this case, unlike DB, the winning bidder may intervene in a previous phase. For this reason, the number of changes and flaws may be greatly reduced throughout the execution.

A contracting party may choose to execute a public construction by means of concession contracts. In this case, other than the mere execution, or the executive design and execution, or the final, executive design and execution, the winning bidder is in charge of the operational and financial management of the artifact. In this case, management is a key element as well as design and construction, since only effective management generates the required cash flows for credit institutions.

The company should pay more attention to the quality of the work and implement excellent solutions in the design phase in order to guarantee high levels of maintenance. The company has greater responsibilities and is urged to produce operational long-lasting artifacts.

Public clients often make use of the *leasing in construendo* (leasing while building) of public or public use construction work.[8] The public client sets up a tender notice for at least an initial project and the winning bidder is in charge of setting up subsequent design levels, its execution as well as its management for a certain period of time. The public administration either sets up a *leasing* contract with a funding party or a temporary company made of the funding party and the executing party. This way the *leasing* company takes on all financial risks associated to the investment, whereas the company deals with non-financial risks.[9] Thanks to *leasing in costruendo*, the contracting company relies on the financial resources of a private party, whereas the integration between the *leasing* company and the construction company supplies the required capital for the construction in line with the project development.[10] In addition, a certain price and the leasing quota is defined from the very beginning, thus stimulating the execution of the project within schedule. The leasing company will start charging the quotas once the work has been completed.[11] The *leasing in construendo* forces the company to pay great attention to the quality of the artifact and decrease maintenance costs as much as possible. At the same time, the company must follow the execution schedule to be able to receive the correspondent funding.

Another recently developed contract type are *performance-based contracting* (PBC). They are focused on the artifact lifecycle and its actual operation.[12] Payments are not made at the end of the work or upon completion of some of its parts, but they are associated to achieving previously defined performance standards.[13] This leads to a different level of responsibility by the involved parties, as they have to achieve certain results throughout time. In this case cooperation is required from the beginning in order to find excellent solutions. An example of PBC is e*nergy performance contracting.* The winning bidder is urged to supply the required energy to manage the artifact, receive payments based on savings as well as adopt innovating solutions.[14]

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[8] Legislative Decree n.163, 12th April, 2006.

[9] Bosetti&Gatti.

[10] Ibidem.

[11] Ibidem.

[12] Hughes and Kabiri, 2013.

[13] Ibidem.

[14] Ibidem.

You may find a greater attention is paid to the artifact lifecycle including within the new European Directive on public works.[15] For the first time, the concept of “life-cycle cost” has been introduced. Such an Anglo-saxon concept (*life-cycle costing*) draws the attention on the chronological factor, and considers the cost as set by subsquent expenses unrelated to the acquisition itself.[16] Such expenses are divided, but not limited to, two categories: a) “internal costs”, supported by the administration, such costs related to the acquisition, energy consumption, maintenance and end-of-cycle expenses; b) costs related to environmental external factors, such as emission costs and environmental mitigation.[17]

Another popular procurement method in the construction industry is the so-called *Construction Management,* where design and execution are carried out by two separate entities, however the public client appoints a Manager, called *Construction Manager*, who is in charge of the management of both phases. Unlike DBB, in this case the company is firstly involved in the design phase and may contribute to it. This way, the execution time is generally reduced. On the other hand, the public client takes on greater risks associated to the presence of a new role. Design and execution is developed by separate entities, hence collaboration is not fully exploited.

It is possible to implement a BIM approach in any tendering to improve the process as a whole.[18] Either during design or construction, there are clear benefits in using the BIM approach.[19] Despite the fact such a practice is not so popular in Italy, in some countries such as the US design and construction firms abandoned the traditionally bidimensional approach, to leave room to a daily use of BIM. It would be interesting to analyze the benefits of BIM throughout the bid, since such a practice is not popular yet, including in the most developed countries. A BIM-based approach can be actually used during DBB. In this case the contracting party may arrange a BIM model during the tendering in order to allow the bidders to fully understand the complexity of the project and extract quantities in a semi-automatic way (through *quantity take-off*).[20] The bidder may save time and money in drawing up their offers, and, at the same time, the public client may rely on more accurate offers and reduce the discrepancy between the price offered during the tendering and the final one.[21] In addition, the bidders may use the gathered quantities to draw up a work schedule.[22] Through a Building Information Model, you are guaranteed a higher level of documentation consistency within the contest, since the information comes from the same source hence it is more difficult to get mismatching information that may lead to controversies.[23] However, the use of BIM in this type of call for tender does not allow to fully benefit from a BIM approach due to the structure of the procurement method itself, as it involves the company later on.[24]

A BIM-based approach may be also integrated to DB. In this case, the bidders hand over a Building Information Model during the bid, which allows the jury to fully understand the offer thanks to a 3D

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15 European Parliament, 2014.

16 Lacava, 2014.

17 Lacava, 2014.

18 Bolpagni, 2013.

19 Dodge Data & Analytics, 2015.

20 Ibidem.

21 Ibidem.

22 Ibidem.

23 Ibidem.

24 Ibidem.

view.[25] In addition, the bidders are urged to work on the entire project, and not just to parts of it (*e.g.* plan drawings). This way, any possible flaw is highlighted in advance and can be sorted out. The public client also receives more accurate and reliable offers.[26] In addition, thanks to Model Checking (described in the following paragraph) you will be able to control the quality of the model in a semi-automatic way and verify compliance with the initial call for tender requirements.[27] [28]

Thanks to the collaboration and cooperation of the involved parties and the upfront involvement of all the different parties, innovative procurement methods have been developed in the last few years. For instance, Cost Led Procurement (CLP), Integrated Project Insurance (IPI), Two Stage Open Book, Integrated Project Delivery (IPD) and Project Alliancing (PA). CLP, IPI and Two Stage Open Book are procurement methods introduced by the British government for the first time in 2011.[29] The British government states that new tendering technologies "*embrace early contractor involvement, higher levels of integration and transparency and the option of independent assurance.They also emphasise the requirement for improved client capability.The client must know what they want, what it should cost and how best to go to market to achieve their objective.These are critical factors that will drive innovation, identify waste, secure knowledge transfer and corresponding growth opportunities.When considered alongside other existing and emerging approaches to construction procurement, encompassing both buildings and economic infrastructure, the new models offer considerable potential to reduce the cost of construction to the public sector, and therefore taxpayer.Alongside reduced costs, it is likely that the models will contribute to improved programme certainty, reduced risk and greater innovation, as well as improved relationships throughout the supply chain*".[30] It is clear how the public client plays a key role in setting the targets from the very beginning as well as the requirements of the project to achieve excellent results. The collaboration promoted by these innovative procurement methods would lose its effectiveness if the client was unable to manage the process itself.

The main goal of the Integrated Project Delivery (IPD) is similar to the previously listed procurement methods; IPD "*integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication and construction*".[31] The Integrated Project Delivery forces all the involved parties to sign a multilateral contract sharing all risks and benefits, and from the very beginning points out how collaboration is the way to find an excellent solution. It is important to stress out that, although you may use IPD with no BIM, BIM is relevant to effectively achieve the levels of collaboration required by IPD.[32] [33]

Another procurement method promoting a "*no fault, no blame*" approach, based on principles of openness and trust, is *Project Alliancing* (PA), also called *Alliance Contracting.*[34] This Australian

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[25] Dodge Data & Analytics, 2015.

[26] Ibidem.

[27] Bolpagni, 2013.

[28] Ciribini *et al.*, CEO 2015.

[29] Cabinet Office, 2012.

[30] Ibidem.

[31] AIA, 2007.

[32] Ibidem.

[33] Eastman *et al.*, 2011.

[34] Petäjäniemi e Lahdenperä, 2012.

developed procurement method includes the selection of the best offer based on the bidder's capacity to develop and carry out the work rather than based on its price.[35] Like in IPD, a multilateral contract is set up, and the client arranges to share responsibilities, risks and earnings with the other parties.[36] *Project Alliancing* could not be currently applied in Italy, since designers and constructors must have an insurance policy to protect the public client from potential risks coming from wrong design or execution.[37] This demostrates how the Italian Legislation is currently not promoting an environment of joint responsibilities, but rather tends to the comparison of the parties involved.

The Legislative Decree is currently being[38] updated to incorporate the European Directive.[39] For the first time the new European Directive[40] introduces the possibility of using a BIM approach: "EU members may request the use of specific electronic tools in public tendering and design competitive bids, such as electronic simulation tools for construction related information or similar".[41] In the English version, "*For public works contracts and design competitive bids, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar*",[42] the BIM term appears, hence this is a more effective version than the Italian.[43] However, the technology side associated to BIM "*tools*" is highlighted instead of its methodological side. The Italian legislator is carefully dealing with this issue in order to avoid for BIM to just be seen as a tool. As of now, we do not know whether the new Legislative Code will include procurement methods based on collaboration, upfront involvement of the counterparts and awarding to the most beneficial offer from the financial point of view or not. However, this is desirable in order to make a better use of the BIM-based approach.

Despite the fact that the previously described innovating procurement methods are very diverse, they all try to switch froma "everyone against everyone" to a "we are all on the same boat" approach. This is why the Building Information Modelling can be used to achieve such goals, because of its nature prone to cooperation and clarity.

As previously discussed, the Building Information Modelling can be integrated in several procurement methods, ranging from standard to innovating ones.[44]

However, when BIM is used in standard procurement methods, it loses quite a lot of its potential.[45] According to Dave *et al.*[46] standard procurement methods, such as DBB, can be the biggest barrieran appropriate use of Lean and BIM together (or even separately).

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[35] Petäjäniemi e Lahdenperä, 2012.

[36] Ibidem.

[37] Bolpagni, 2013.

[38] Legislative Decree n.163, 12th April, 2006.

[39] European Parliament, 2014.

[40] Ibidem.

[41] European Parliament, 2014.

[42] European Parliament, 2014.

[43] Bolpagni, 2014.

[44] Bolpagni, 2013.

[45] Salmon, 2012.

[46] Dave *et al.*, 2013.

The maximization of the value and the reduction to a minimum of money waste is difficult when the tender inhibits coordination, represses collaboration and innovation, and promotes individual targets against the counterpart.[47]

On the other hand, a "*partnering approach*", backed up by new contract types such as ConsensusDOCS, can promote those principles of collaboration and integration required by Lean as well as by a BIM-based approach.[48] These types of contract contribute to trade relations not only based on mutual respect, but they also make it easier to share knowledge and information by promoting innovation and creating value.[49] Thanks to this approach, you can manage time, cost and risks together and focus on achieving shared values or mutual goals such as meeting the client's requirements.[50] In addition, in case of good outcome, such contracts often include incentives or premiums for the entire working team, rather than for the single members only.[51] For this reason, compared to standard contracts, "relational" contracts are ideal to promote the co-location of working teams as well as the upfront involvement and joint development of the design.[52] Contract types suitable to a BIM approach are already available.[53] For instance, in the UK there is a long tradition of collaboration methods and the government is currently working in this direction.[54]

NEC3, PPC2000 and JCT Constructing Excellence contribute to a trust and cooperation based approach.[55] For this reason such contract types, although they have not been developed to support Building Information Modelling, are suitable to promote its implementation.[56] There are also other types coming from the US, such as Document E202 and ConsensusDOCS 301, designed to be included in BIM-based processes.[57] Generally speaking, the principles promoted by "relational" contracts are more difficult to be applied in the public rather than in the private sector due to several restrictions such as legal impediments, cultural barriers or lack of skills.[58] For this reason and to achieve the best results, attention should be drawn on its application in the public sector.

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[47] Mathews and Howell, 2005.

[48] Dave *et al.*, 2013.

[49] Colledge, 2005.

[50] Ibidem.

[51] Ibidem.

[52] Dave *et al.*, 2013.

[53] McAdam, 2011.

[54] Ibidem.

[55] Ibidem.

[56] Ibidem.

[57] Ibidem.

[58] Ke *et al.*, 2011.

THE ROLE OF MODEL CHECKING IN THE INFORMATION MODELLING AND MANAGEMENT PROCESS

The constant development and growing implementation of the BIM methodology and technology, as well as of neutral and interoperable formats such as IFC (Industry Foundation Classes) and BCF (BIM Collaboration Format), led to an increasing interest in Model Checking tools and to the development of a new generation of software for Quality Assurance and Quality Control (QA/QC) based on parametric rules (*rule-based*); Model Checking is now an integrating part, and key element in Information Modelling and Management. Since it is not just mere tridimensional geometric modelling, BIM is based on the exchange of information related to programming, design, execution and management of an asset, through the different stages of a construction lifecycle and by involving all the interested parties. The informative content of a parametric model must be validated to ensure reliable results in the following analysis stages. In addition, Building Information Modelling makes the client plays the role of the originator of the process and co-author of the work, hence it is paramount to verify that the means used to exchange data, *i.e.* the Building Information Model, actually contain the minimum informative level required by the Employer's Information Requirements (EIRs).[59] In this sense, the exchange of information becomes an integrating part of the Risk Management process.

The more the BIM method is being enforced, the clearer become the benefits and limits of this technology in exchanging information. On one side, the interoperability based on native models may increase production and efficiency, on the other, the use of a neutral format allows both open and side communication. It becomes clear how the most important aspect of this process is meeting the EIRs as well as data reliability, in order to avoid controversies. The formalization of information exchange procedures becomes the focal point, and Model Checking plays a key role in this sense. The digitalization of the construction industry cannot leave aside the client's capacity to define the conditions and contents of the interventions required in computational modelling. As a consequence, the validation of the parametric models must be a joint effort made by both the designers and the client in order to improve the quality of the project solutions, their consistency with the client's needs and their support to cost analysis and the construction phase. This way the number of project modifications required during the work execution is reduced, a functional and quality building is guaranteed at the end, and, at the same time, process transparency has been increased.[60]

In standard design processes, just the 5-10% of the project informative content is sistematically checked.[61] Model Checking leads to an automated validation of 40-60% of the design,[62] by following specific checks rather than sample checks. Checking the informative context of the model is required in many phases, the so called *checkpoints.* This way the potential flaws are detected in advance and a reliable performance on the following applications is guaranteed through an Information Model achieving fully coordinated Information Management. The Quality Assurance (QA) process of a model, (hence, of a project) will be used by the client to verify the presence of all the alphanumeric attributes required in the EIRs and developed in the BIM Execution Plan. At the same time it is an essential tool for the designer alone, as well as for the entire design team, to carry out a regular self-assessment.

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[59] PAS 1192:2-2013.

[60] COBIM 2012, Series 6.

[61] Ibidem.

[62] Ibidem.

The model verification and the analysis of the results should be included in the standard routine and sufficient time should be allocated for it, including the time required to make any adjustment.[63]
During the Model Checking phase, the parameters implemented in the informative models, whether geometric or not, are analysed and validated by testing the Building Information Model through various validation domains. Generally speaking, the *rule-set* to check the model is organized in three phases of consequential verification: BIM Validation, checking modelling attributes and procedures, Clash Detection, *i.e.* interference check, and Code Checking, verifying compliance with the correspondent regulation.

BIM VALIDATION

The proper implementation of the BIM methodology cannot be irrespective of consistency checks and quality of the data conveyed through a Building Information Model, provided that such model is structured to supply an effective tool to support the Information Management decision making process. Firstly, in order to ensure the communication between the Information Modelling BIM platform and the Model Checking BIM tool, the check rules and the model must contain the same semantics, that is to say, the parametric items included in the Information Model must necessarily be mapped and recognized by some Model Checking tool features; for this type of interoperability, the most commonly used are Name and Type. Before moving on to advanced analyses, a pre-check of the model informative content is required through a *rule-set*, in order to validate its accuracy: this is called BIM Validation phase. The BIM Validation analyses and defines the internal level of quality and consistency of a Building Information Model through the management of a proper set of parametric rules and based on logical and semantic analyses, thus ensuring reliable results for the following phases of BIM-based analyses;[64] it also checks that all the elements have been properly named and classified. Such a Quality Assurance process ensures that the model contains all the required information to carry out an advanced check, including all those alphanumeric attributes which, in properly structured Information Management, are included in the BIM Requirements established when drawing up the BIM Execution Plan (BEP). These are paramount to exchange information between the parties, as well as to ensure the accuracy and reliability of the documents coming from the Building Information Model. This is a key and preliminary stage to other Rule-based Model Checking phases, as it verifies the compliance of the model with the specific design requirements, according to the BIM Uses defined by the client and the set goals.
As previously explained, a BIM tool of Rule-based Model Checking allows to establish a predefined set of rules for the BIM Validation phase: customizable by the user, it should be applied to the single discipline models first, and then to the federated model, or Merged Model, integrating different disciplines. Once the first validation is complete, the model may be subject to more specific analyses such as the *quantity take-off* among others, for computing purposes, the energy analysis (Building Energy Modelling) and the design compliance with the correspondent regulation (Code Checking). The issues that may be detected in the BIM Validation can be related to the alphanumeric content, *i.e.* the attributes of the parametric model, or merely to the geometric aspect of it, featuring two error types: modelling related or design related.[65] Checking the accuracy of tridimensional modelling is crucial. For instance, in the *quantity take-off* and computing phase a (not so infrequent) error in modelling two

[63] COBIM 2012, Series 6.

[64] Ciribini *et al.*, ISARC 2015.

[65] Ciribini *et al.*, ISARC 2015.

overlapping floors may lead to double counting the materials used in the associated stratigraphic package. Other issues may be attributed to design errors and are detected through the logical analysis potential of the construction elements of some of the Model Checking tools. This may allow the identification of a possible lack of design consistency, such as the proper dimensioning of a fixture compared to the height of a false ceiling (Figure 1).

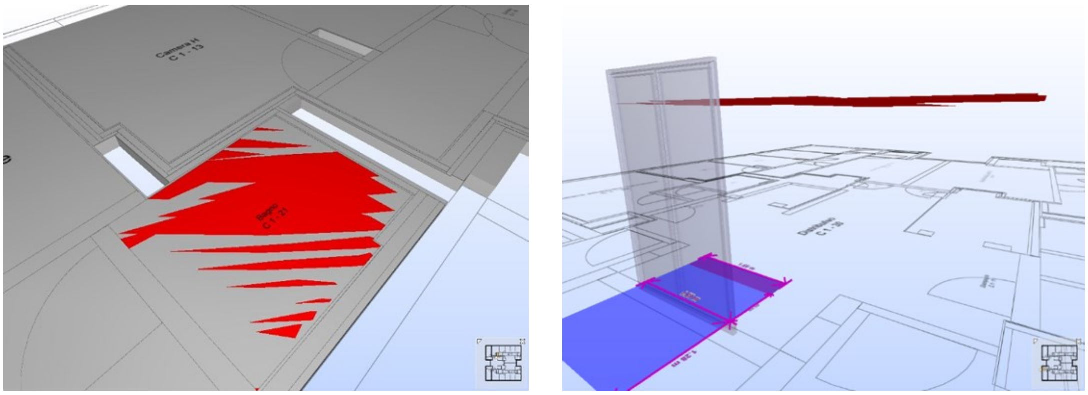

Figure 1 Examples of geometric results of the BIM Validation *rule-set* executed with Solibri Model Checker v.9. A preliminary check allows verification of the absence of overlapping elements and consistency of the building elements. In the left hand side figure two floors are compenetrating; this would lead to an error in computing materials. On the right hand side a mismatch between the dimensioning of a fixture and the height of a false ceiling has been detected

Eventually, BIM Validation allows the analysis of the whole of the informative content associated to a parametric item, hence allows the validation of the correspondent Level of Development (LOD) through proper classification systems, as well as on the basis of what detailed in BEP. Several attributes are associated to each LOD, which must necessarily be defined and compiled for each item. Consider a “Door” element for example: a specific LOD matches with several attributes such as “Fire rating”, “Fire Exit” and “Door Operation”.[66] The validation of the informative content verifies the actual presence and proper compilation of such parameters, in order to allow the comparison between declared content and modelled content, hence supporting an adequate flow of information between the involved parties.

CLASH DETECTION

Model Checking validates two types of data: geometric data and alphanumeric data. Clash Detection is a geometric and spatial consistence analysis, and is nowadays one of the most common applications of the Building Information Modelling. There are numerous benefits associated to such an analysis, which is performed in a short period of time and with minimal effort involved. Advanced Clash Detection occurs when the logical analysis skills of the Model Checking tool are able to distingush and classify the detected interferences. These will be classified according to several degrees of severity, previously defined in the BIM Execution Plan. Interferences between MEP and structural elements rather than between MEP and architectural elements, including the same design phase would require to be dealt with through a different approach.[67]

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[66] Solibri, Inc.

[67] Ciribini *et al.*, ISARC 2015.

In this case, in order for the results gathered through a Clash Detection *rule-set* to be reliable and effectively supporting the decision making process, several manual checks must be carried out at first, and the BIM requirements of the geometric modelling should be clearly defined. First of all, the interference check includes the manual management of the verification process of the design versions of the informative models and their positioning in an appropriate Cartesian coordinate system. Then it validates the single discipline models and the Merged Model. In order to detect inconsistencies, *e.g.* between the MEP and the structural designs, the MEP systems must be modelled with great geometric accuracy. This is the only way to detect and fix any issues, which otherwise would be arising during the MEP installation phase. Being Finland one of the leaders in the implementation of the Information Modelling, the Finnish BIM *guidelines* [68] stress out how the geometric accuracy of the network to support the installation phase in the building to be carried out according of the Building Information Model.[69] The goal of the geometric modelling in this case is to be able to create a model with no intersections. Such an approach is inevitably mirrored on the responsibilities the designer is subjected to within the entire construction process. Such responsibility grows as soon as a higher multi-discipline coordination is required for the implementation of the BIM methodology.

The Clash Detection phase is developed through subsequent *steps*. First of all, the designer should be detecting any interference to his/her competence in the BIM Authoring platform:[70] nowadays, the majority of parametric modelling software feature such applications or *plug-ins* in order to perform a preliminary check of the interferences or a partial BIM Validation of geometric aspects. BIM Viewer and BIM Coordination tools, such as Tekla BIMsight, Solibri Model Viewer, Autodesk Navisworks and Autodesk BIM 360 Glue can be used in the following multi-discipline coordination phase. Some of these are also available on mobile devices. In order to perform more advanced checks based in customizable *rule-set*, dedicated BIM tools are required, such as Solibri Model Checker, leader in the industry, which promotes an Open BIM access through an interoperable IFC format. In addition, some new rule-based software are arising on the market, such as BIM Assure. After defining the desired *rule-set*, this should be applied to the single discipline models at first, then any coordination issued in the Merged Model should be detected (Figure 2).[71] In addition, the identified clashes and issues are not just exclusively associated to physical interferences. Thanks to a Rule-based Model Checking tool, you may verify the distance between objects and determine, for instance, the minimum tolerance for the installation or maintenance of different building components.

An ongoing interference check may also effectively support the construction of a facility, as it allows verification of its constructability based on the suggested design documentation. Periodic checks of the federated model highlight possible multi-discipline clashes and interferences and become the basis of coordination meetings. In such meetings, all parties suggest solutions that can be verified and discussed a second time, thus guaranteeing knowledge integration and the sharing of the process (Figure 3) (Figure 4).

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[68] COBIM 2012.

[69] COBIM 2012, Series 4.

[70] COBIM 2012, Series 6.

[71] Ibidem.

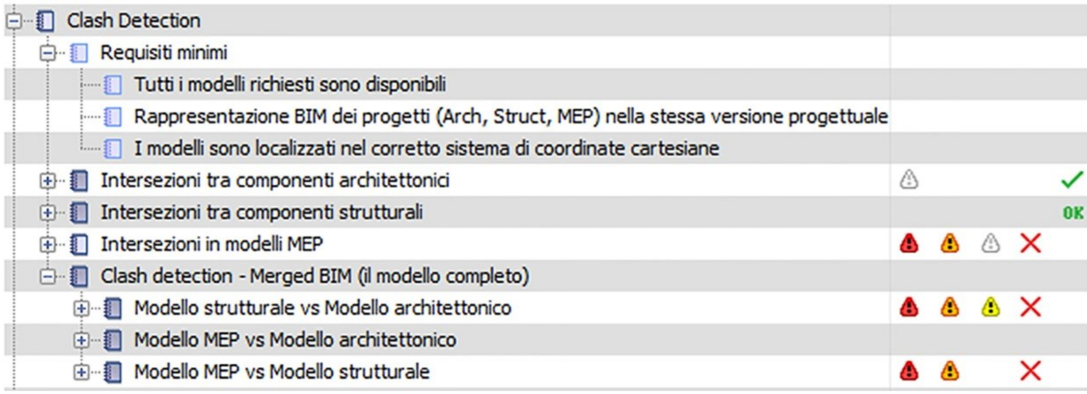

Figure 2 Development of a *rule-set* for Clash Detection using Solibri Model Checker v.9. The *rule-set* was created for an Italian public owner. First, manual checks should be performed on minimum requirements (all required models must be available, presence of Building Information Models for different disciplines at the same design stage, right coordinate system). Later, the checking process deals with the control of Models of each discipline (*e.g.* clashes between architectural elements, clashes between structural elements, clashes within MEP models). Finally, clash detections should be performed on the Merged Model (Structural vs Architectural Models, MEP vs Architectural Models, MEP vs Structural Models).

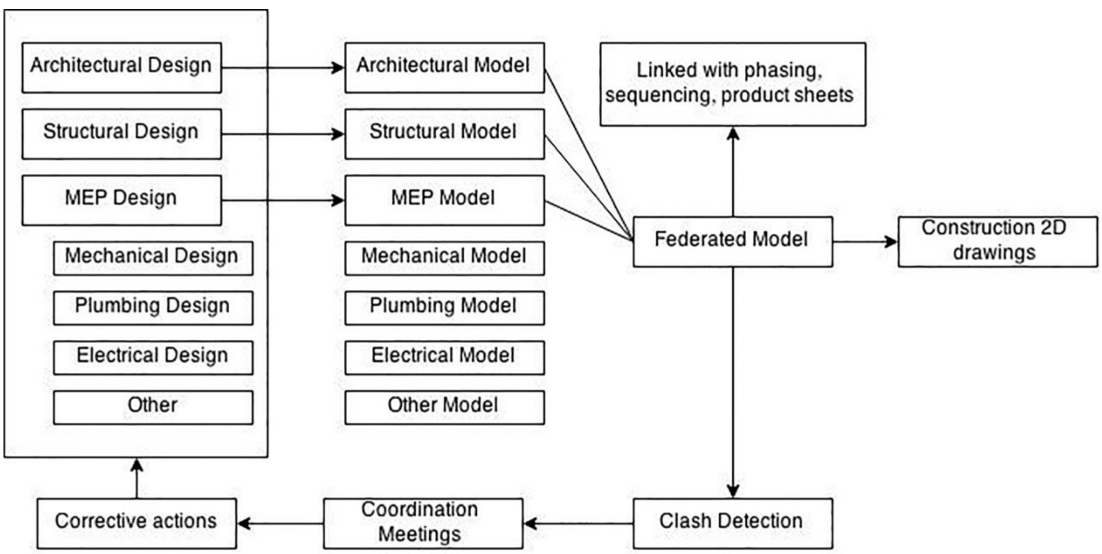

Figure 3 Ongoing discipline and multi-discipline Clash Detection to support the decision making process and verification of the facility constructability. Operating flow readjusted by *The Contractor's Guide to BIM - 2nd edition* (The Associated General Contractors AGC of America)

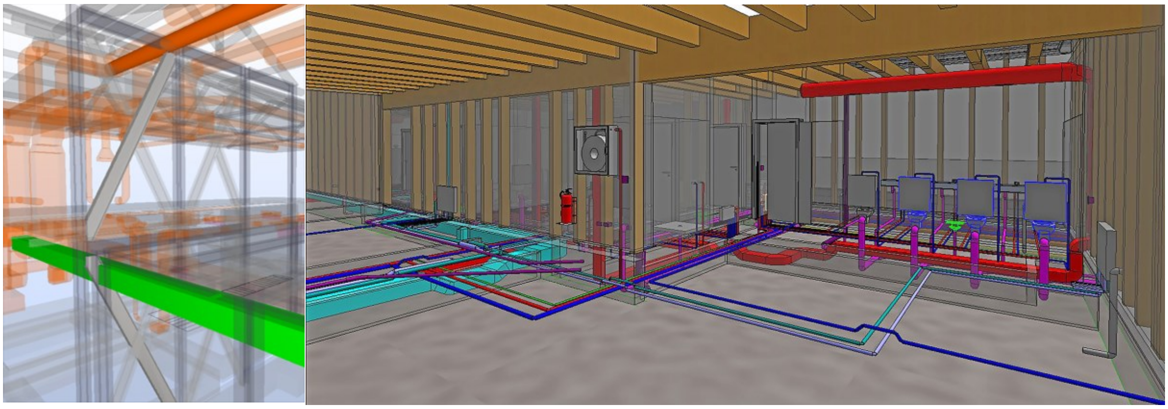

Figure 4 Example of Clash Detection performed with Solibri Model Checker v.9 and highly accurate geometric MEP modelling with Autodesk Revit 2014. The goal is to detect any possible flaw in the digital construction of the building. Such flaw would otherwise only be detected in the construction phase, when the effectiveness of any modification is considerably reduced and the costs are much higher

CODE CHECKING

Code Checking is a declination of Model Checking by means of which the design may be validated[72] by comparing the parameters included in the model with reference regulations and codes. The construction process is regulated by several rules at a local, national and international level,[73] and the relevant information included in such documents can be translated into parametric rules through the support of a semantic reading and interpretation system. The same procedure applies to the client's requirements or to good design and construction practices, since, once they have been translated into parametric language, they may be implemented as actual rules. Through a rule-based control system, the user is able to perform a *check*, whose results may be *"pass"*, *"fail"*, *"warning"*, and *"unknown"* (in case of incomplete or missing data). In order to support a mainly computerized process, the Building Information Model must be enriched with alphanumeric information, that is, data that are not always automatically generated by BIM Authoring platforms, as occurs for geometric information and dimensional data.[74]

Through traditional design methods, the verification of the compliance with regulation based on bidimensional graphic representation is carried out manually, through samples, and requires several meetings and comparisons.[75] In addition, a specific process phase cannot not validated until all designs have been completed. Such an approach often includes mismatches, ambiguities and subjectiveness in the interpretation of the documents, as well as an increase in costs and time.[76] For these reasons, the possibility of partially computerize the verification process should be one of the priorities of the digitalization process in the building sector. However, such innovations are only available through the modification of the work method, from the definition of a project as the sum of multiple documents, to the implementation of a unique and consistent Building Information Model to

72 Hjelseth and Nisbet, 2010.

73 Hjelseth and Nisbet, 2011.

74 Niemeijer *et al.*, 2009.

75 Nguyen and Kim, 2011.

76 Greenwood *et al.*, 2012.

support the decision making process through the entire lifecycle of a construction project, and from which the necessary documentation and information may be gathered.

Several researches at an international level have been focusing on the transition of those provisions included in the codes to rules applicable to rule-based Model Checking on one side, as well as on the development of a parametric model featuring the required alphanumeric attributes to evaluate compliance with the rules on the other.[77] Thanks to the *rule-set* and since requests are univocal, the evaluation process becomes more objective.[78] This way the margin of personal interpretation of the regulations (often generic and lacking details) is reduced. In addition, once a code or regulation has been analysed and parameterized, the same set of rules may be used to verify the Building Information Model of the same design environment. This is even more obvious if school, hospital and accommodation facilities are considered, where the standardization of the functional, relational and qualitative verification allows the comparison between different models (hence design solutions) in a faster and clearer way.[79]

The Rule-based Model Checking process is divided into four phases: Rule Interpretation, Building Model Preparation, Rule Execution and Rule Reporting.[80]

Rule Interpretation

In the Rule Interpretation phase, the regulatory code is analysed and structured through parameters, in order to develop checking rules to be implemented in Rule Checking tools. Codes and regulations are normally easily translatable into a formal notation, *i.e.* into parametric language. An interpretation based on four control semantic operators ensures reliable rules and results. The reference semantic operators are:

- **R**equirements
- **A**pplicability
- **S**election
- **E**xception

These tags are the tools of the so called RASE Methodology,[81] a logical and semantic analysis method supporting the interpretation of regulation codes and their translation into a unique and defined rule, that can be easily implemented in a Rule-based Model Checking tool. The majority of the regulation codes can be parametrized through this approach; however, some exceptions may occur in case of human judgement related requests. For instance, a requirement such as "the solution should be environmentally friendly" can be implemented as a parametric rule, however, it cannot be automatically verified until it is clearly defined through objective parameters. Such restrictions may also be included in the *rule-set* in a text format and considered as a checklist supporting the design phase, hence ensuring a thorough analysis in all its aspects. Since it sometimes requires human judgement, it is then called "semi-automatic" validation.

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[77] Sanguinetti *et al.*, 2012.

[78] Ciribini *et al.*, CEO 2015.

[79] Ibidem.

[80] Eastman *et al.*, 2009.

[81] Hjelseth, Nisbet, 2011.

Building Model Preparation

In this second phase, the parametric model is enriched with informative content in order to be compared to the set of rules for validation purposes. The Building Information Model is integrated with the information attributes required for the rule checking execution based on the topic and the defined validation domains. In order to support a mainly computerized process, BIM Models must include data that are not always automatically generated by the modelling platforms, as occurs in merely geometric information.[82] In this case, not only the model must include a proper classification by subject that allows Clash Detection for instance, but it must also be enriched with the required information to verify compliance with the reference regulation.[83] Based on the aspects to be verified, whether it is fire prevention, architectural barrier removal or energy efficiency requirements, the necessary informative content is so different that it sometimes leads to the generation of several versions of the same model.[84] Eventually the Building Model Preparation phase must be developing along with the implementation of the Rule Checking Execution one. The rule set must be able to "communicate" with the model, interpret its informative content and look for the required attributes for its validation. In addition to the definition of BIM Requirements to create a model based on the intended use (hence based on the checks to be carried out), it is good practice for the designers to hand over the Model Specification[85] document, detailing the model and its compliance with the requirements. Such integrating document also supports the validator during the Model Checking phase.

The BIM technology supports a certain level of automatism in the design evaluation, however, such innovations are usually facing problems associated to conventions and semantics. These acquire importance when they detect key elements in Rule Checking practices, such as IfcSpace.[86]

Currently, the main software for BIM modelling openly represents *spaces* as three-dimensional objects to be associated with certain shapes and properties. In order to arrange the "semantics" of a model several key data may be gathered: a *space* is not just defined by its 3D geometry and its spacial relations, but mostly through important properties, such as "space name" and "space group" binary name sets, the "space number", the area, the volume, the intended use and possibly Space Programming requirements, which can be externally managed through their correspondent *plug-ins*. A meticulous classification of the premises and a systematic arrangement of the name usage are crucial, as the current bidimensional CAD design practices are often used with no precise conventions, through abbreviations or different synonyms, including within the same project. In order to deal with this problem, an external database mirroring space arrangement and specifying the requirements may be set up. Once it has been structured, it would play have a key role and would be used in several designing phases as well as in different projects.

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[82] Niemeijer *et al.*, 2009.

[83] Eastman *et al.*, 2009.

[84] Sanguinetti *et al.*, 2012.

[85] Bolpagni, 2013.

[86] Lee *et al.*, 2012.

Rule Execution

Rule Execution is the verification phase applying the rule set to the model, which is imported in the Quality Assurance software in an interoperable format, normally Industry Foundation Classes (IFC). Once the rules have been analysed at a semantic level by the regulatory codes and translated into implementable parameters, they can be arranged in a single set of rules, thus representing the validation domain the model should be subjected to. In addition, by combining different sets of rules, several domains may be automatically validated.[87]

Rule Reporting

The last phase of this iterative Rule Checking process is Rule Reporting, an automated result phase to be shared and analysed by other members of the design team, the client and other parties of the construction process.

Code Checking may include geometric aspects first, and verify, for example, minimum allowed heights and areas, window-to-floor area ration or the special positioning of certain functional areas (Figure 5) and spaces. From geometric aspects also comes Code Checking applied to the analysis of accessibility. The evaluation of the accessibility is a current issue in design and an articulate mix of non-easily interpreted factors. As of today, certain rules for the verification of geometric requirements (Figure 6) have been implemented, such as areas for manoeuvres and side positioning of wheelchairs. However, in the future it may be possible to go beyond that, and include sensorial aspects, such as the presence of tactile signs or the effort required to open windows and doors, the use of colours, as well as light or sound conditions.[88] Such aspects are more difficult to shape and may require a highly detailed Building Model Preparation phase, featuring adequate BIM requirements to be defined since the preliminary phase. The application of the Code Checking at an international level is also working in this direction.[89]

In addition, it is possible to translate tender requirements in a parametric *rule-set* in order to use Code Checking during the awarding phase and to verify compliance of the presented models to the initial Contracting company requirements.[90]

Another example of Code Checking is the implementation of parametric rules for fire prevention as well as to check compartmentation and emergency exits. To this purpose, you may refer to one of the key concepts of the BIM: “Begin with the end in mind”.[91] Every project may theoretically be represented through a multiple set of parametric models based on the BIM Use. Fire prevention also requires alphanumeric BIM Requirements to be met, such as including the attributes of fire resistance and the swing direction of doors. Introducing such parameters in the modelling phase is even more important, and including them during the creation of the parametric model allows the Code Checking tool to read them directly from the IFC files, as well as to read the geometric and dimensional attributes of the items themselves, thus ensuring a certain level of automation in the analysis.[92]

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[87] Hjelseth and Nisbet, 2010.

[88] Bellomo, 2012.

[89] Ciribini *et al.*, ISARC 2015.

[90] Ciribini *et al.*, CEO 2015.

[91] Eastman, 2011.

[92] Ciribini *et al.*, ISARC 2015.

It is worth mentioning that the results of the rules included in the parametric *rule-set* are based on the available information within the BIM method. Such data may be inaccurate or wrong, and some of the most important ones may be missing, hence generating unrealiable results. The preliminary check of the BIM Validation becomes crucial in order to verify the implemented or non-implemented parameters during the modelling phase.[93]

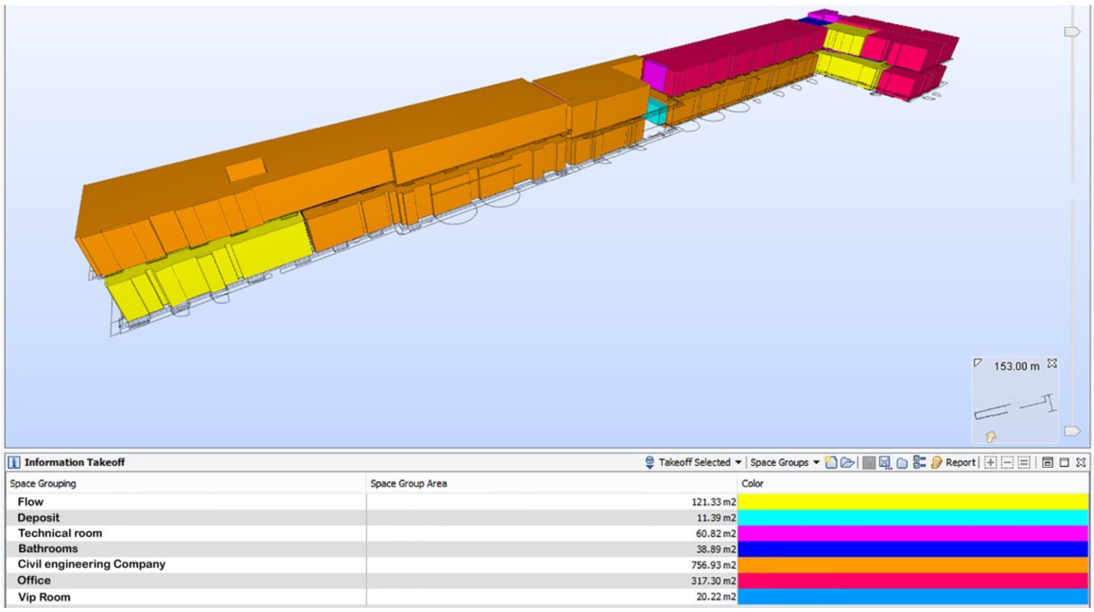

Figure 5 Result of the distribution control of functional areas in an office and exhibition building with Solibri Model Checker v.9

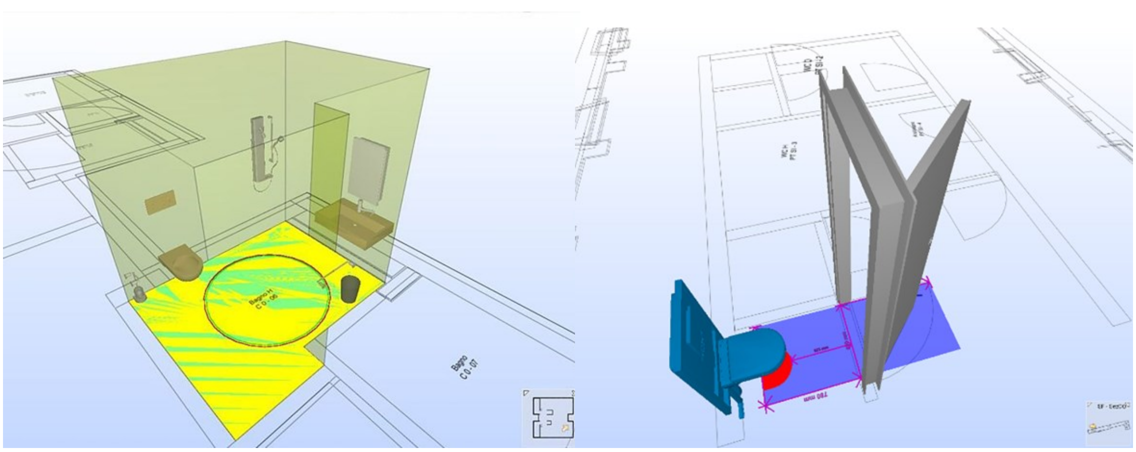

Figure 6 Results of the Code Checking phase with Solibri Model Checker v.9. Dimension to verify design compliance to regulation on accessibility of residential buildings (left) and minimum requirements for spaces to be used as public toilets (right)

[93] Ciribini *et al.*, ISARC 2015.

MODEL CHECKING AND VIRTUAL PROTOTYPING

The Building Information Model can be seen as a virtual prototype, as it anticipates a product that is not yet ready, but appears and acts as if it was. Thanks to Model Checking advantages may be greater than in a traditional process. However, the client's or final user's involvement is still restricted. For this reason Virtual Prototyping (VP) associated techniques (such as Virtual Reality or VR and Augmented Reality or AR) are becoming more and more popular in order to assess the design before the construction phase. Thanks to VP, the client has a better idea of the final product and, if needed, he/she may work along with the designers to meet his/her own requirements. In addition, the upfront involvement of the final user is a key stage of the Validation process, and contributes to fixing errors and optimizing ergonomic aspects as well as space utilization. More users are able to validate the same project and better analyse its components, hence promoting a design that meets everyone's needs ("design for all"). For instance, the same plan may be validated by a child, an adult in good health, a pregnant woman and a disabled person to better understand everyone's needs.

Both immersive and non-immersive Virtual Reality techniques can be used to navigate within the Building Information Model. Non-immersive techniques allow users to interact with the virtual environment through conventional tools such as the keyboard, the mouse and the monitor. However, immersive techniques allow a more realistic experience.[94] In this case, the user is surrounded by curved screens, either *cave automatic virtual environments* (CAVE) or *head-mounted displays* (HMD).

One of the most common devices is the Rift© by Oculus© (generally called "Oculus Rift"). It may be connected to different devices tracing hand movement (*e.g.* Leap Motion©) thus allowing a closer experience to reality.[95]

Although it is possible to navigate within the Building information Model, a game engine software (*e.g.* Unity©) is generally preferred to recreate a more interactive experience. A virtual environment can be created within such software, however, when a BIM model is available, it can be transferred from BIM Authoring software to the game engines through the interoperable IFC format.[96]

It is important to highlight that the interaction between a final product and the user is not just available in one direction but it is a rather multi-sensory experience.[97] For this reason, an effective Validation process should not just involve sight, but also hearing, touch and smell. For instance, a disabled person may find useful to validate spaces by considering the physical properties of the floor surfaces. Thanks to a game engine, you can simulate a wheelchair behaviour (*e.g.* mass centre, acceleration and deceleration) (Figure 7).[98]

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[94] Hilfert and König, 2015.

[95] Ibidem.

[96] Ibidem.

[97] Rizzi and Bordegoni, 2011.

[98] Hilfert and König, 2015.

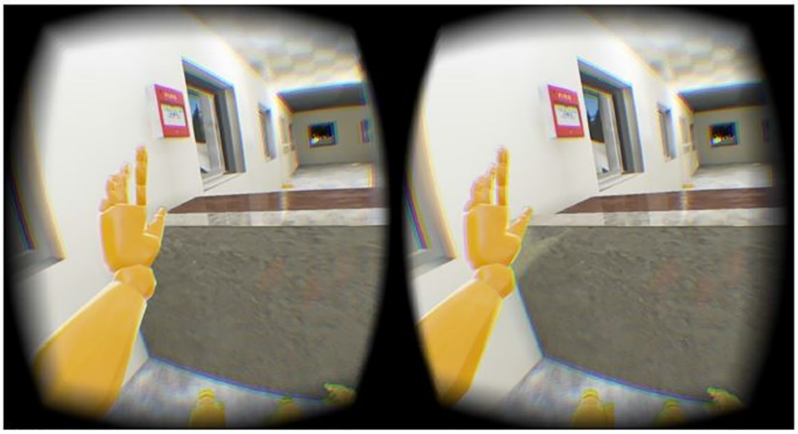

Figure 7 Simulation of the space assessment made by a person in a wheelchair (Hilfert and König, 2015)

In addition, touch simulation may also faciltate the Validation process. For instance, a technology simulating the sense of touch (*haptic*) can be used to recreate an emergency situation, such as a fire, in order to check whether the surface temperature allows safe evacuation or not. It may also be useful for the final user to understand the insulating properties of certain materials (*e.g.* walls). Virtual Prototyping techniques, in this case, may replicate an appropriate sound level (*e.g* traffic or conversations), and allow the final user to understand space acoustic quality. In addition, the simulation of smells may also be very effective to validate space positioning based on different activities, if you need to choose between different types of vegetation throughout the year.

Thanks to this approach, the Validation process may be much more effective and Model Checking may benefit from Virtual Prototyping techniques. Eventually, by promoting such a validation, you may promote remote checks, decrease the number of trips and set up more effective meetings, drawing the attention towards the critical aspects of the project.

CONCLUSION AND FUTURE DEVELOPMENT

The use of Building Information Modelling is developing more and more, and several countries are promoting a government based strategy in this direction. BIM is not just a mere technology twist, but rather a revolution of the process as a whole, which necessarily requires a different cultural approach. For this reason attention must be drawn to the type of tendering to be chosen, and promote collaborative tenders having their parties share both risks and earnings. In addition, the Validation process through the Model Checking should be a key practice in order to validate the content of the Building Information Model in a partially automated way. Virtual Prototyping techniques allow recreating multi-sensory interactions in a realistic way by involving clients and final users in the Validation process. This way, possible issues can be detected in advance and the entire process may be optimized by working along with the designers. Currently, there is good visual and movement replication technology, however, more work is needed to integrate hearing, smell and touch. In order to facilitate the Validation process, designers must eventually work along with human science experts from the very beginning (*e.g.* neuroscience, cognitive psychology) in order to promote design techniques meeting different users' requirements (*user-centric*).

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