# Integration of Structural Health Control in BIM for Current and Future Residential Buildings

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**Abstract –**

**Currently the structural engineering and construction technologies go through substantial paradigm shift and development between energy conservation, health and living cost issues. Increasing energy consumption for e.g. heating and cooling and the constant effort to energy preservation in all forms promotes the manufacture of sustainable low-energy or near-zero energy houses, often with some independent energy production capability included.**

**As a subtheme in controlling the building performance and energy uses, there has been interest in applying Building Information Model (BIM) to building designs to store, optimize and use building-related information during its entire life-cycle. The BIM methodology is mostly limited for new buildings as the needed open access data on generic structures and materials is most often not available. Similarly, health considerations in current buildings are also poorly controlled and more detailed knowledge on the content and conditions of thermal transport, air exchange and moisture control would benefit the energy efficiency and sustainability of the buildings. Common issues with moisture entrapment leading to microbial growth and indoor air quality related respiratory illnesses are a practical, and extreme, example of insufficient understanding of structural design and control issues also in in public buildings.**

**Our study presents some of the recently discussed possibilities and efficiency of BIM utilization in the context of current and future residential buildings. In addition, hygro-thermal monitoring and modelling tools that have recently been made available to analyze the structural health of the buildings will be highlighted.**

**Keywords –**

**BIM; Building physics; Hygro-thermal analysis; Mould; Interoperability**

## 1 Introduction

Civil and structural engineering and the applied construction technologies go through substantial paradigm shift in many ways. Building speed, element pre-fabrication, 3D-prining, individualistic design features, energy and cost issues drive the development of large structures. Increasing energy costs and the constant effort of national and international institutions for lowering energy consumption [1,2] promote the building of sustainable passive, low-energy or near-zero energy houses and entire districts. Architects, engineers, constructors (AEC) and facility managers (FM) actively cooperate in managing resources efficiently in designs.

In the past decades, there has been interest in applying Building Information Model (BIM) to building designs. BIM represents a tool controlling building information during the entire life cycle of the structure, including 3D-design, construction material and layout selection and end-life considerations for recycling and reuse of materials. The BIM methodology is mostly established for new buildings; therefore the maintenance of existing buildings does not benefit of its centralised data archives, nor do the renovation or deconstruction projects base onto the BIM processes [3].

Sustainability and health considerations in current buildings are also poorly understood and controlled. More detailed knowledge on the content, conditions of building structures and their performance in e.g. extreme climate would be beneficial in promoting their energy efficiency. Householders of existing buildings often adapt their buildings to increase energy efficiency by installing additional insulation layers. However, additional insulation applied on the exterior or interior surface of the structure envelope may disable the designed moisture diffusion performance and lead to accumulating humidity inside the structural elements that may, in turn, enable conditions for mould growth [18].

Besides the structure itself, the living environment contributes a lot on the hygro-thermal conditions inside the structural elements. The interior conditions change according to actual use of the certain indoor location, as bathroom, kitchen, sauna, and so on, are characterized by higher humidity than other rooms such as bedroom, study and living room.

On the other hand, the major impacts on the hygro-thermal conditions inside the structure are provided by the exterior conditions. Exterior conditions, in turn, vary according the climate, structure's location, annual season, pertaining weather conditions, etc. For instance, climate effects on structures considering inland, coastal, northern and southern conditions were studied for example in [19], where the impact of climate on identical building envelope performance and moulding tendency were significantly different already between the few locations within Finland.

Taking solely the climate as a leading condition for exterior boundary designs will not suffice as structures are also significantly affected by the very local micro-climate. These conditions vary depending on the local building details and include perimeter locations such as attics, foundation, windows or doors, or those characterized by the presence of waterways, hills, trees or other buildings and related infrastructure in the immediate vicinity. Also details such as the location and orientation of the structure markedly affect its ambient conditions.

That is why monitoring the hygro-thermal conditions and simulation of building designs for the ambient and the inside conditions of the structure would be beneficial. Extensive humidity accumulation could lead to a certain damage caused by mould and following deterioration of structural material but such a risk can be significantly mitigated in advance with simulation tools.

## 2 BIM in current buildings

The BIM is a virtual IT-based information system where each element affects the design, the structure during its life cycle and deconstruction that are to be described in detail. The BIM method allows detailed visualization, code reviews, construction sequencing, cost estimation, conflicts and collision detection, forensic analyses and facility management. These lead to faster and more efficient processes, more accurate design, simplified production, (semi-)automated assembly, improved customer service and recording of designed life-cycle data for later uses [20].

Application of BIM as a part of new structure design is continuously increasing, but in the case of existing buildings, the BIM is still used rather rarely. One of the reasons is the very difficult access to detailed building information of all parties: owners, facility managers, suppliers, builders, subcontractors and architects. Other challenges observed in BIM research include updating, maintaining the data in BIM, modelling of indefinite objects, and related properties [3].

For instance, the BIM applied in the design of novel building consists of direct access to material properties and all required features of used objects provided by different manufacturers. On the contrary, current buildings were designed omitting the design details or not having them available in the required detail. In renovation stages, it is typical to notice that the former manufacturers do not exist anymore and/or the material properties used for construction are not available. Also the building designs can have inaccuracies and many prior renovations and changes have not been documented. This leads to higher cost at the beginning of the BIM model.

On the other hand, the BIM allows monitoring the actual conditions of the structure and in the case any problem is found, it can be solved quickly before large-scale damage occurs. The continuous monitoring assures healthy and sustainable building during the entire life cycle. The advantage of applying BIM in current and historic building is in elevated understanding of their structures behaviour as in many cases the energy consumption and detailed performance of the structure and materials is not known.

## 3 Hygro-thermal conditions

Essential part of the sustainable building design is played by building physics, where especially the hygro-thermal conditions inside the building and/or structural elements affect the structural behavior and biological contamination issues. The effort towards controlling the hygro-thermal conditions inside buildings and their structural elements is partially caused by the design of airtight, highly energy efficient buildings. The increasing demands on health indoor environments coupled with insufficient construction element insulation from the elements during the construction phase or accidental leakage of water into the structures later on may cause catastrophic issues.

Hygro-thermal conditions affect the properties of building material and if the favorable conditions persist for sufficient periods, they allow mold growth initiation. Reconstruction of such buildings or their parts usually requires removal of wetted and contaminated materials at high costs. The analysis options of the structural hygro-thermal conditions are threefold; laboratory tests, direct on-site measurement and numerical analysis. The laboratory tests with sampling work are usually time demanding and expensive. Continuous and automated measurements obtain data during the actual use of buildings, but observing the hygro-thermal conditions inside the structural elements demands permission from house owner and pre-installed sensors.

Numerical modeling as a third option often achieves good results in many engineering fields by simulating the features of any physical phenomenon. The combination of on-site measurements and numerical calculation seems to be an efficient method of hygro-thermal conditions analysis and control. Even though the numerical techniques are considered as efficient method of high accuracy, it is always beneficial to validate the method with on-site measured data.

The unexpected aspects significantly affecting the hygro-thermal conditions inside the structural elements include damaged construction material such as waterproof membrane and sudden water leakage from the exterior, extensive humidity and/or water absorbed in the structural elements during construction, accidental piping damage, house equipment accidents with extensive water outlet, and so on.

Installing online sensors to indicate temperature and humidity on surfaces of structural elements near locations where the accidents are most likely to occur, minimize the risk in numerical errors and unrealistic hygro-thermal conditions. In the case of higher humidity near the monitored location, the exact point of accident can be found and fixed before it causes major damage in the structure. The areas of interest for hygro-thermal monitoring are located in the ambient of details where high humidity can occur. It means in practical terms e.g. near the pipe junctions where is risk of water leaking accident is relevant and in the locations characterized by thermal bridge.

The thermal bridge is described by structural detail achieving different thermal resistance than the surrounding elements, such as wall-wall, wall-floor, wall-roof junctions, foundation attics, windows, doors and so on. As it can be seen in the Figure 1, the thermal bridge in the foundation structure is caused by rapid change in heat flow in the corner compared to the wall and floor structure that characterize the thermal bridge. These details indicate significant temperature difference inside the structure that considering certain conditions leads to a water condensation.

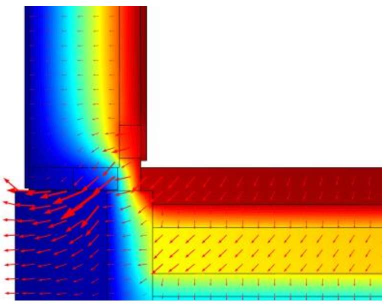

Figure 1. Heat transfer in foundation structure, thermal bridge.

## 4 Hygro-thermal Analysis and Mold Growth Risk

The International Passive House Association defines for passive houses the heat transfer coefficient (U-value) cannot exceed 0.15 W/(m$^2$K) and the space heating demand is limited by 15 kWh annually or 10 W/m$^2$ of usable living space [4]. Because of the high thermal resistance, especially in Nordic countries, the structures are these days quite airtight and the air exchange must be provided by ventilation systems [5]. The average air change rate in houses mostly built after 2000 in Finland at 50 Pa is 4.5 h$^{-1}$ in timber-framed houses constructed on site, 3.3 h$^{-1}$ in timber-framed prefabricated elements houses, 6.0 h$^{-1}$ in log houses, 2.8 h$^{-1}$ in brick houses and 2.6 h$^{-1}$ in houses built from concrete elements [6,7].

In the case of a high airtightness of a building, a suitable ventilation system can be installed to control the physical conditions indoor. The energy efficiency of the existing building may be increased by optimizing the house equipment usability and possibly by adapting the structural elements towards higher thermal resistance.

The indoor comfort level highly depends on suitable temperature and humidity. Specific combinations of temperature and humidity along with sufficient exposure time promote mould growth [8-13], which may lead to allergic reactions and other health issues for inhabitants [14], as well as influence the behavioural properties of structural elements [15].

The relationship between temperature and humidity in exposure time and favourable and unfavourable conditions for the initiation of mould growth can be expressed by a mathematical formula of critical relative humidity $RH_{crit}$ (Eq. 1), which is a function of temperature $T$ [9].

$$RH_{crit} = \begin{cases} -0.267T^3 + 0.160T^2 - 3.13T + 100.0 \; \textit{when} \; 0 < T \leq 20 \\ 80\% \; \textit{when} \; 50 \geq T > 20 \\ \textit{no growth assumed when} \; 0 > T > 50 \end{cases} \quad (1)$$

The equation (1) can be also expressed graphically as following (Figure 2).

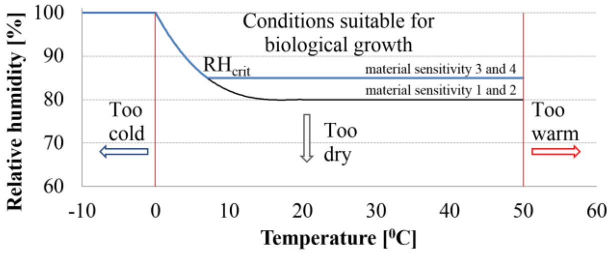


Figure 2. Favorable and unfavorable conditions for mold growth initiation.

The mould index indicating the amount of mould growth can be represented by equation (Eq. 2).

$$\frac{dMI}{dt} = \frac{k_1 k_2}{7\,exp\left(-0.68\,ln\,T - 13.9\,ln\,RH + 0.14W - 0.33SQ + 66.02\right)} \quad (2)$$

where $k_1$ is the mould growth intensity, $k_2$ is mould growth intensity moderating the mould index after approaching the maximum value, MI is the mould index, T is the temperature, RH is the relative humidity, t is the exposure time and SQ and W are the coefficients characterizing surface quality and timber species.

The mould index allows qualitative evaluation of mould growth by seven levels; 0 for no growth present, 1 represents small microscopic trace amounts of mould on the surface, 2 indicates appearance of several microscopic locally identified mould growth colonies, 3 is for the first visual mould, 4 for clear visual appearance with 10-50% coverage, 5 indicates more than 50% coverage and 6 indicates heavy and full mould growth coverage [9]. Significant role is reserved also material sensitivity in the location of mould index evaluation. There are 4 defined material sensitivity levels; very sensitive such as pine sapwood, sensitive such as glued wooden boards, medium resistant such as mineral wool, and resistant such as metals.

As the mould index mathematical model requires continuous data of the temperature, relative humidity and exposure time the hygro-thermal simulation can be performed numerically. Numerical simulation using for instance the Finite Element Analysis based tools achieve results with high accuracy can be applied for the hygro-thermal simulation and evaluation of mould growth risk within a structure. However, it is always beneficial to provide on-site monitoring as organic residues typically accumulate in structures on building sites via dust or rain, which may contain microbial spores, predisposed to mould growth initiation.

## 5 BIM and hygro-thermal simulation interoperability

The effort towards economic and energy efficient building designs support invention and development of new technologies for quicker and more efficient designs, constructions and life-cycle control [16].

One of the most important information management systems of construction industry is represented by Building Information Modelling (BIM). It allows detailed information about all objects implemented in a project and controls their interaction and behavior while they are in use. The aim of the BIM is to connect teams and experts involved in the project allowing their collaboration and sharing ideas while minimizing errors caused by e.g. misunderstanding of cooperators and incompatibility of individual objects [17].

Traditionally, the information is exchanged between project participants through drawings and other printed documents such as cost plans. The BIM represents digital virtual model where each elements that affects the structural design and/or its life cycle is described in detail. The BIM is an IT-based information system recently operated by an increasing amount of Architecture, Engineering and Construction (AEC) companies.

Although there have been number of BIM projects applied in practice especially within large commercial projects there are still challenges that limit its use [3]. One of them is possibility of creating system that includes the entire package of involved parties that must be included or those that can improve the building performance [16]. There is a potential risk that the number of hygro-thermal based problems increase when the authorities, designers, builders and inhabitants do not have sufficient real time information about the performance of the buildings and structures.

By integrating the hygro-thermal simulation in BIM, the simulation can be extended by implementing mould growth risk methodology and energy control to express the hygro-thermal behaviour of the building in detail. Hence, the energy and structural health is invariably controlled and possible risks can be solved at their origin. The complex process of integration the hygro-thermal numerical application considering validation with measured data and BIM can be illustrated as in the Figure 3. The procedure consists in simplification of the complex digital model into a model determined by elements directly affecting the hygro-thermal conditions. Then, the BIM simplified model is parameterized into a mathematical model prescribed by dimensions needed for accurate mapping the hygro-thermal conditions. For instance, two-dimensional numeral model are applied in details where the heat flow and mass movement happens in two directions only, such as wall-floor, wall-wall junctions and the foundation. If the conditions are required for corners joining three directions elements, then the three-dimensional numerical model is required. When the geometry and physical properties of the numerical model are defined the numerical simulation is performed. At the same time, the on-site measured data is taken for verification of the numerical model and possible contradictions are corrected to meet the real hygro-thermal behaviour. The verified numerical results obtained are preceded into evaluation of the mould growth risk and compared with energetically requirements to meet the sufficient performance of the structure. In the case, the obtained performance satisfies both energetically and structural health requirements, the model is adapted back to the BIM format. Otherwise the procedure is repeated and the design and/or conditions are adapted to meet the requirements.

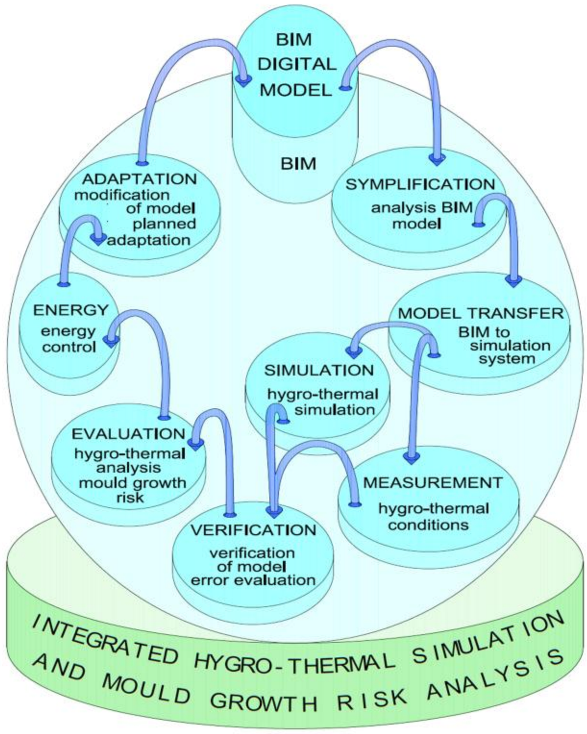


Figure 3. Scheme for interoperability between BIM and hygro-thermal analysis.

The interoperability of BIM and hygro-thermal analysis allows higher understanding of the structural and material behaviour and overall sustainability aspect from material origins and sourcing to recyclability criteria assessment of materials used. The boundary conditions represent critical data for achieving accurate simulation and further analyses.

BIM and numerical simulation integration consists of creating geometric model including boundary conditions in BIM, transferring the model to numerical application, such as a FEA based computing tool, computing procedure and evaluation of the obtained results. In the case the results are accepted following the defined requirements, the numerical model is not transferred back to the BIM, but the current BIM digital model is used. Otherwise, the numerical model is modified until the goal is achieved and then transferred back to BIM. The numerical techniques considering the physical behaviour, such as the hygro-thermal conditions and the structural design or control can be optimized with the obtained results. Hence, the BIM digital model improves the structural design and sustainability of the building during its entire life span.

The difficulties appear especially once detailed and special analysis, such as airflow, harmonic, seismic or hygro-thermal analyses are required. These are usually time consuming and have high requirements for computing performance, hence certain simplifications are common. These usually consist of removing objects or minor geometrical details that do not affect the analyses and performance of physical phenomena.

The detailed hygro-thermal numerical simulation is numerically demanding, thus 1- or 2-dimensional geometry representing the structural details is often analysed. In some cases, 3-dimensional numerical model is required, for instance 2-wall-ceiling corner or 2-wall-foundation corner.

The numerical models exclude elements with no effect on the hygro-thermal performance, often they are also presented in BIM. From this point of view, the detailed hygro-thermal analyses should be considered as individual processes requiring detailed professional attention. The hygro-thermal simulation requires detailed information about the structure and applied materials as well as the exact conditions in the ambient.

Even though, the current development and research indicate the possibility of creating the entire building model to control energy consumption and building physics properties control, the hygro-thermal analyses leading to realistic monitoring are remarkably demanding. Therefore, the 1- or 2-dimensional detailed models are recommended to monitor the hygro-thermal conditions inside the structural elements.

## 6 Conclusions

The effort of national and international authorities for lowering energy and environmental impact of buildings creates new demands for building designs and joint data management that have been neglected so far. The full digital archive of existing building can enable advanced use of BIM as well as simplify the deconstruction phase and end-of-life use of the materials. Promoting a few specialized areas of expertise, such as hygro-thermal control, mold growth risk analyses and BIM interoperability can provide sustainable building practices and optimized energy efficiency of novel and existing building.

## 7 Motivation and future significance

The goal in the BIM application of simulation input is to develop the datasets of conform with Industry Foundation Class (IFC) standards that represents neutral platform for the object-based building data model and its understanding. Only then can the integrated systems and the level of detail be involved in the building designs so that its entire life-cycle is covered and understood. Implementing the hygro-thermal control together with the mold growth risk analysis provides additional tool to be developed into future BIM systems to promote and balance the health control and energy efficiency requirements.

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