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Towards design tools for holistic assessment of indoor environmental quality

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SUMMARY
We present an approach for holistic indoor environmental quality (IEQ) assessment incorporating dynamic heat and moisture transport effects, indoor air flow and pollutant distribution. A common tool infrastructure provides interfaces to multidisciplinary models that are using product and material specific data stored in Building Information Models (BIM) for early design assessment. Hence, we present the results of a prototype tool development utilising integrated dynamic simulation models on the basis of the Modelica language. The sub-domain models for airflow and hygrothermal BPS are cross validated with state-of-the-art tools and experimental results. The properties of innovative multi-functional eco-materials and components are provided in a structured database to provide high quality predictions of IEQ under a broad range of boundary conditions and implementations. In an integrated design process (IDP) the procedures for simulations and results evaluation are automated and comparable figures for overall IEQ ratings are provided by a user friendly front-end.

KEYWORDS
Building Information Modeling, Indoor Environmental Quality, Eco Materials, Modelica, Holistic Performance Assessment

1 INTRODUCTION

Within the scope of the ECO-SEE Project[1] innovative, safe and energy efficient wall panels and materials for a healthier indoor environment are developed. In order to consider these in the design process, a common tool infrastructure is presented. The technology demonstrator integrates multi-domain models with BIM (Eastman *et al.*, 2011) to undertake holistic assessments of novel eco-efficient material applications.

In (Augenbroe, 2011) the performance of a building is defined as a quantifiable expression of how well a particular building function is achieved. So called key performance indicators (KPI) are individual target parameters that are defined in close cooperation with a client in order to individually emphasize such building functions, e.g. IEQ. One problem is that every part of a building contributes to multiple functions resulting in a complex system requiring an integrated design process (IDP), in which a collaborative multidisciplinary team prepares a system solution in a joint effort. According to (Negendahl, 2015) future attempts to provide

[1] www.eco-see.eu

BPS tool support to multidisciplinary collaboration during the early design stages should focus on integrated dynamic models that combine with programming languages and design tools. The contributing effect of this work resides in the presentation of a prototype of such a tool allowing holistic IEQ assessment of a room involving KPIs describing thermal, hygric as well as air quality aspects.

2 METHODS

In order to realize the setup of the multidisciplinary tool, a screen of available technologies was first conducted. The project team decided upon the technologies as illustrated in Figure 1 for the realization.

1. Modelica serves as the BPS environment. Its characteristic as dynamic systems modelling language for multi-physical problems serves as the basis for integrating the mentioned KPIs in a single model. (Modelica Association, 2012; Kim *et al.*, 2015; Reim *et al.*, 2015). Several model libraries facilitate the physical modelling of the prototype.
2. The Functional Mock-up Interface (FMI) for exporting stand-alone simulation modules (MODELISAR Consortium, 2014; Widl *et al.*, 2014) enables platform independent execution of a simulation model. Furthermore, modelling expertise is preserved.
3. Python as scripting language for automation tasks serves to mediate the communication between the tool technologies. (McKinney, 2012; Miller *et al.*, 2013)
4. SketchUp as design and construction tool supporting BIM standards and providing possibilities for user defined interfaces and extensions, (using the Ruby scripting language) allows for graphically interacting with the model geometry.
5. Excel serves as a database inheriting the properties of ECO-SEE materials as well as a post-processing environment for the simulation results.

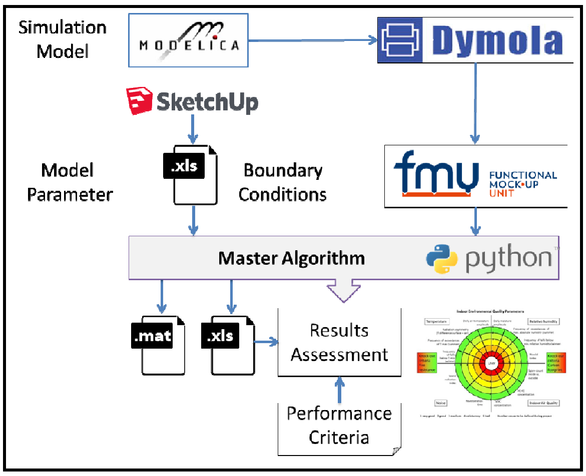

Figure 1. Involved technologies to realize the prototype of the holistic IEQ design tool.

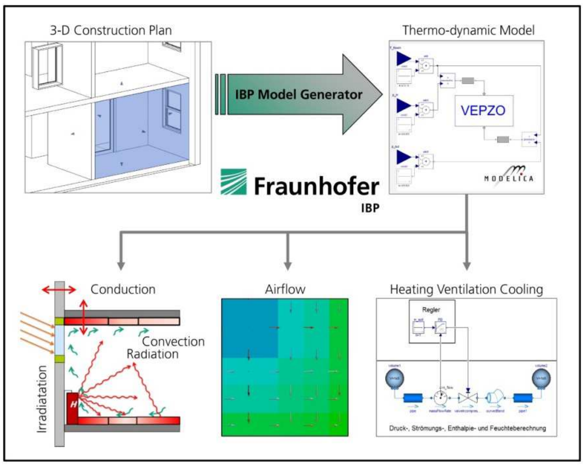

Figure 2. The IBP Model Generation Tool for automatic creation of Modelica simulation models from 3-D building or room designs (Pathak *et al.*, 2014).

The development of the design tool is supported by a prototype application of an ECO-SEE use case, i.e. comparing the performance of developed materials and resulting constructions.

3 RESULTS

Similar to (Reim *et al.*, 2015) we defined an overall workflow for generating and managing results from the integrated simulation model. The workflow relies upon an already existing model generator (Pathak *et al.*, 2014) that is capable to create a Modelica simulation model from a 3-D construction plan. The so called IBP Model Generation Tool (MGT) is a vital part of the described workflow since it automatically generates a first model framework (see Figure 2) for the subsequent integration of further sub-domain models.

The IBP Model Generation Tool sets up a geometrically correct indoor environment model that allows predicting the KPIs after invoking the following sub-models:

- Airflow Model: i.e. indoor spaces are divided into multiple control volumes
- Radiation Model: long-wave radiation model and solar model
- Convection Model: convective heat exchange between walls and adjacent zone
- Conduction Model : conduction through monolayer as well as multilayer walls
- Linear Langmuir Model: the model is used to evaluate an adsorption and desorption process of the Volatile Organic Compounds (VOCs) over the material surface (Tichenor *et al.*, 1991). The model assumes a monolayer adsorption over a homogeneous surface. It is expressed by the following equation:

  dM/dt = k_a*C_a - k_d*M

  where

  k_a = adsorption rate coefficient (m/h)

  k_d = desorption rate coefficient (1/h)

  dM/dt = Net mass rate of change of VOC adsorbed on the material surface (μg/m^2 /h)

  C_a = VOC concentrations in the zone (μg/m^3)

  M = VOC concentrations on the wall surface (μg /m^2)
- Indoor Air Quality Model: simulates concentration of VOC, CO_2 and other pollutants in each zone
- Hygric Model: moisture transfer model coupled with airflow model and heat exchanging models; simulates the absolute humidity in each zone

The development of the Functional Mock-up Interface (FMI) and above all its revision in 2014 created new possibilities for working with simulation models. Supporting tools are able to export stand-alone simulation units, called FMUs, which can be simulated without the presence of the source tool (Widl *et al.*, 2014). Other tools or script languages like Python may serve as an executing instrument. The exported FMU embodies a dynamic link library providing the simulation algorithm as well as a XML file containing information about inputs, outputs and parameters of the model. In this state, the process to solve the equation system arising from the simulation model cannot be changed anymore. However, input variables or parameters can be set. To realize the integrated design tool an FMU is created representing the generated Modelica model described above. The FMU can be equipped with various construction elements, tested under different boundary conditions and, to a limited extend be adapted in its geometry. In this case, a box-shaped room as originally used for the generation of the model can be changed in length, width and height. Incorporating the FMU technology finally allows a user to execute the model without having additional software installed. Before executing the model the user can graphically change the simulated setup in SketchUp by determining boundary conditions such as weather data or parameters, like geometry, window size and position. Furthermore, the ECO-SEE materials to be tested need to be chosen. The simulation is finally started via a plug-in that triggers a Python script. The script applies the defined boundary conditions and populates the model with the relevant characteristics, like thermal and hygric properties as provided in the material database. Figure 3 presents an overview of the tool generation and application process.

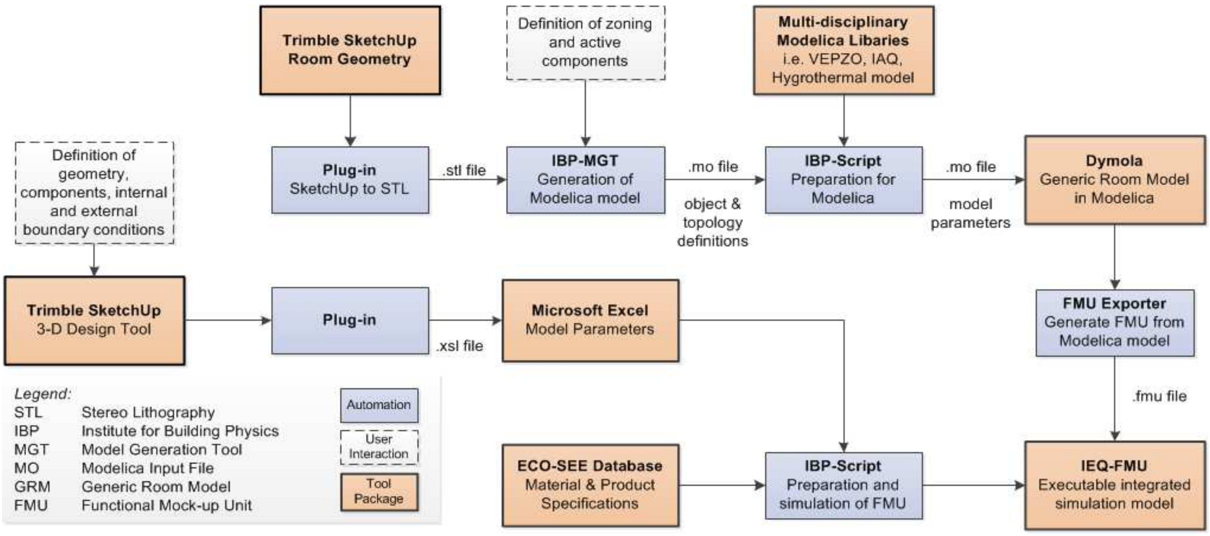

Figure 3. Process overview for the creation of the multidisciplinary IEQ design tool showing used exchange formats and tools.

Relevant results of the simulation are exported to an XSL file that inherits post-processing capabilities in order to automatically generate an evaluating diagram based on several IEQ criteria. Figure 4 shows the diagram for the evaluation sheet of the simulated results in relation to hygric, thermal, IAQ and in a future stage also acoustic criteria like reverberation time. Since lighting was out of scope of the ECO-SEE project it was integrated into the IEQ assessment toolset.

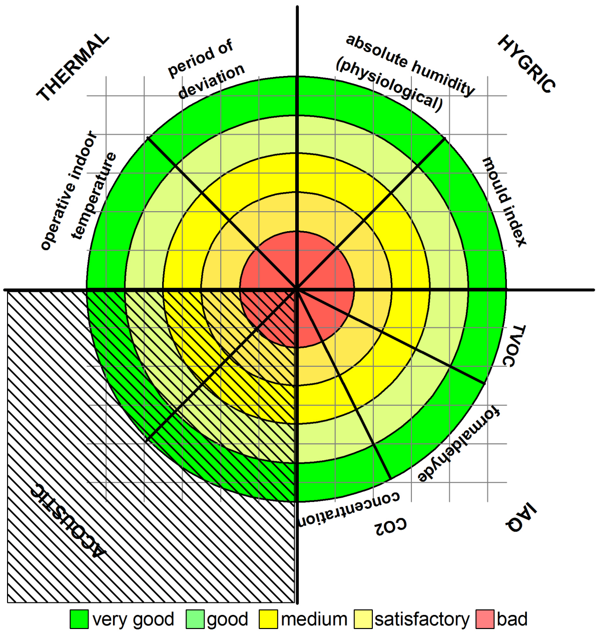

Figure 4. Diagram for the evaluation of the results subdivided into relevant KPIs.

Each criteria (see Table 1) has five classification levels between very good (green) and bad (red) based on the requirements stated in (Viitanen and Ritschkopf, 1991; Bundesamt für Arbeitsschutz und Arbeitsmedizin, 2012; Deutsches Institut für Normung, 2012;

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2015). The results of the simulations are processed to be represented in the diagram for a fast and easy evaluation in terms of thermal, hygric, IAQ performance of the previously defined materials in the room.

Table 1. List of standards and guidelines for different classifications.

Topic	Category	Standard/Guideline
THERMAL	Operative indoor temperature	DIN EN 15251
	Period of deviation	DIN EN 15251
HYGRIC	Absolute humidity	ASR 3.6
	Mould index	Vittanen – Model
IAQ	TVOC	BNB_BN2015_3.1.3
	Formaldehyde	BNB_BN2015_3.1.3
	CO_2-concentration	BNB_BN2015_3.1.3

4 DISCUSSION

The purpose of the tool is to provide fast evaluation of eco-friendly materials in early design stages in an easy to use environment. Implementation of the prototype showed promising results. Implementation of the proposed infrastructure was feasible and allows for execution of a holistic performance assessment solution with a one-click user interface. The functionality includes testing of different design options in a room varying materials, geometry, window size and position as well as boundary conditions like adjacent air temperatures and infiltration rates. However, to decrease complexity of the tool and to ensure fast familiarization, not all possibilities provided by the underlying physical model can be exploited. Due to the zoning of the room, information about spatial differences is available such that 3-D sampling of IEQ parameters is possible. In the existing prototype, the resulting values in the centre of the room are taken as reference values. Furthermore, several options could additionally be user-defined, like positioning of air inlets and outlets, heating or cooling systems etc. Besides that, model extensions are necessary to increase the number of supported room geometries.The presented workflow is linked to a material database represented by Excel tables, which should be migrated to a more user-friendly database management system.

5 CONCLUSIONS

The creation process of an integrated design tool to assess thermal, hygric and IAQ performance criteria in buildings based on the newly developed ECO-SEE materials is discussed. Viable technologies for realization are identified and their interaction within a prototype implementation is illustrated. Emphasis is put on the automated integration of building information data and the simulation (BIM enabled). This is achieved through the scripting language Python and its connection to 3-D geometry information provided in SketchUp. Independence of licensed software is ensured with the usage of an FMU incorporating the physical model created in Modelica. The resulting tool provides basic capabilities to easily assess the mentioned IEQ performance criteria at an early design stage limiting end-user interaction to the wide-spread tools SketchUp and Excel.

6 ACKNOWLEDGEMENT

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