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A review on coupled building physics analyses

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Abstract. This paper reviews methods and tools for coupled building physics analyses in the context of Building Performance Simulations (BPS) with a focus on Building Energy Simulations (BES) and Computational Fluid Dynamics (CFD) as a common application. Furthermore, requirements regarding the necessary information for simulations, data models and coupling are identified. Possibilities of automated simulation model generation, data exchange and the performance of existing multi physics simulation models are analysed and limiting factors are discussed.

1. Introduction

Building Performance Simulations (BPS) can be used to optimize buildings in different areas such as comfort, energy consumption or hygric behavior [1, 2]. BPS involve various analyses like Building Energy Simulations (BES) or Computational Fluid Dynamics (CFD) and cover a variety of disciplines. These reach from heat and mass transfer to thermodynamics, fluid mechanics, control and regulation, environmental science or occupant behavior to analyze whole buildings or neighborhoods.

Although a variety of calculation methods and tools exist, most tools address a specific problem, simplifying the calculation or boundary conditions to reduce complexity or calculation expense [2, 3]. For example, most Building Energy Simulations (BES) like EnergyPlus [4], TRNSYS [5], ESP-r [6] or IDA-ICE [7] assume simplifications like a homogeneous distribution of temperature and pressure in each zone or one-dimensional heat flow through surfaces, which considerably lowers the complexity of the calculation. However, this simplification leads to reduced accuracy and lacks local flow variables needed for comfort or hygric component behavior evaluation. To avoid these problems, CFD can be used to generate very accurate results here [8, 9, 1, 10, 11]. Other applications of CFD include the calculation of convective heat transfer coefficients (CHTC), thermal comfort, wind loads or the investigation of natural or cross ventilation [12, 11, 13, 14, 15].

However, an isolated consideration of a problem is often not adequate to generate sufficiently precise results or to investigate multiple interdependent problems. Therefore calculation methods or tools must be coupled in an interdisciplinary manner. Hence, coupling BES with CFD offers significant added value to the areas of application as mentioned above. [16, 8, 1].

Nevertheless, by combining multiple analyses, new challenges like incompatible or proprietary data models, the high effort required to create the complex computational models, high computing expenses or data exchange between different tools have to be faced. Furthermore, quick and easy access to detailed analyses is a basic requirement for a broad and economic use of

BPS [17]. In order to apply optimisation algorithms or to develop predictive operating strategies by means of machine learning, automated model generation and high-performance calculation is necessary [18, 19, 20, 21, 22].

2. Coupling Methods

Due to the of performance and capabilities of BES, the system boundaries of CFD are usually defined as the surfaces of the air volume and inlets or outlets of vents, fan coils or windows [23]. The BES handles the conjugate heat transfer with a suitable radiation model, HVAC system models and plant models [24].

2.1. Data exchange

Tian et al. [1] divide the data exchanged between BES and CFD into interface data and state data. Interface data is defined as data at the boundary of the physical domains while state data is defined as data of the respective domain and is mainly used for control purposes of the HVAC. Zhai et al. [23] investigated different combinations of Dirichlet-, Neumann- or Robert-BCs as interface data for the thermal coupling of fluid and solid domains. Surface temperatures (Dirichlet-BC) as BC for the CFD and CHTC, as well as temperature gradients of the air (Robin-BC) as BC for the BES showed to provide the best performance and the most numerically stable coupling and are used in most studies [25].

The coupling of state data is more difficult because HVAC and plant models often differ a lot in the complexity of their structure. Therefore valid descriptions are hard to make [25, 26]. A common approach nowadays is the use of the Functional Mock-up Interface (FMI) [27], a standardised interface for model exchange and co-simulation of dynamic systems [28, 29, 30]. Complex systems can thus be built from modular Functional Mock-up Units (FMU), pre-compiled models with a standardised description of the exchanged data, parameters and values for the initialisation of variables. While there is a large library of FMUs [31, 32] and many BES are compatible with the FMI standard, there is little compatibility on the CFD side [33, 16, 1, 34], especially when it comes to commercial software.

2.2. Synchronization schemes

Due to the fact that interface and state data vary with time, it is theoretically necessary to run each BES and CFD simulation for each time step. Even during each time step, iteration between BES and CFD may be needed to reach a convergence [35]. Tian et al. [24] summarized coupling methods with a focus on synchronising data, which is mainly synchronised in three ways: Static coupling, dynamic coupling and bin coupling. The amount of time for these different strategies, as well as their simulations speed and accuracy vary broadly. To determine which coupling strategy is used, building characteristics, the required results and accuracy have to be taken into account. [25, 35].

3. Tools

Rodríguez et al. [25] and Harish et al. [10] give an overview of current studies on BES-CFD co-simulations and the used tools. Most commonly used BES tools are TRANSYS and EnergyPlus, while ANSYS Fluent [36] is predominantly used for CFD. For the coupling of the tools in the mentioned studies, a customer-specific solution is used in most case, in which the CFD simulation is executed by the BES by means of scripts and the results are read in by the BES via files. For the more advanced coupling via FMI, Zuo et al. [34] developed the FMU "Rooms.CFD", available in the Modelica Buildings library, which was used in a study to successfully couple the Modelica Buildings library and the fast fluid dynamics (FFD) program by Jin et al. [37]. Qiao et al. [16] also used this FMU to couple openFOAM and Modelica with a CFD-side adaptation.

4. Performance
As CFD simulations have a high computational effort, fully dynamically coupled simulations for longer periods are not possible, yet [38, 39]. Consequently, the development of methods to reduce the computational effort of CFD while maintaining accuracy has become a major area of research [39]. Hosain et al. [40], Feng et al. [41] and Morozova et al. [39] reviewed such methods, with Fast Fluid Dynamics (FFD) and Reduced Order Models (ROM) in particular appearing promising and being increasingly used in current work [19, 42, 43, 44, 45, 46]. Machine learning is also a heavily researched field and has already been successfully used to accelerate CFD [47, 48, 49]. With these methods, calculation in real time or even faster is possible [49, 39]. In addition to the use of new computational methods, the appropriate choice of the level of detail (LOD) of geometry is also a decisive factor. On the one hand relevant details should be taken into account [50, 51, 52, 53], but on the other hand complex geometries need a finer discretization and make high-quality meshing more difficult [54]. Furthermore, the computational time can also be significantly reduced by use of GPUs [55, 39], high performance computing [56] or distributed computing [57, 1].

5. Automated model generation
The automated generation of simulation models for CFD-BES co-simulations is a complex process that can be divided into the creation of a model for the BES with the building, HVAC system and equipment and the CFD model. The current standard and research focus is the use of Building Information Models (BIM) with the open exchange formats IFC and gbXML. Wetter et al. [27] describe workflows and tools for generating BIM models for BES from BIM (BIM to BES) in Annex 60, which have been implemented and further developed in numerous studies [58, 59, 60, 61, 62].

The CFD model requires a different kind of geometry than the one of the BES. The geometry for the CFD model has to be watertight and in most cases simplified to be able to generate a mesh with a high quality [50, 51, 53]. The meshing can then be performed considering the mesh quality [54, 63, 64] and boundary conditions can be assigned. Lee et al. [50] and Delavar et al. [65] describe a BIM-to-CFD workflow and its application but manual work will still be a part oft that method.

6. Limitations
While the performance of BES coupled with CFD puts a limit to accuracy and the cases in which it can be applied, the high amount of work required to create the simulation models is also a major hurdle to widespread use. With BIM as the current standard, it is currently not possible to create stable and reliable simulation models. While Annex 60 lists some limitations, numerous studies also deal with problems in practical application. Common problems are missing data [66, 59, 67, 68, 10], data loss [69], geometry errors [69, 60, 70] or inconsistencies [66, 71]. Furthermore, there is still a high level of manual effort required to create the simulation models, which is error-prone and tedious due to the high level of complexity [10].

7. Conclusion
This paper has provided an overview of methods and tools for coupling BPS with a focus on BES and CFD. CFD is a discipline with a high computational cost as a limiting factor. Therefore, coupling has to be balanced between performance and accuracy through the choice of the synchronization scheme, solver method and LOD depending on the building characteristics and the required results. Current research focus is therefore the development of faster CFD methods such as FFD, ROM or machine learning. Further research is needed here, especially to assess which method is suitable for a certain accuracy standard and the respective application.

Automated model generation has only been possible in some areas so far, as the current implementation of BIM in software requires a high level of manual effort to generate physically correct models with a suitable LOD. Here, compatibility between different software and the implementation of standards is an important direction for future research.

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