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Advances in building simulation and computational techniques: A review between 1987 and 2014

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ABSTRACT

Computer simulation for buildings has become affordable and possible in both research and industry during the last decades with rapid progress of computer industry as well as fundamental advancement of computational techniques. This paper provides an overview of such advancements achieved between 1987 and 2014, during which Professor Branko Todorovich served as Editor in Chief of Energy and Buildings Journal. The review, however, was not restricted to this journal only, in order to provide a fair snapshot on overall technique advances. Simulation and computational techniques cover a variety of aspects of building. This paper focuses specifically on six different topics including ventilation performance prediction, whole building energy and thermal load simulation, lighting and daylighting modeling, building information modeling, indoor acoustic simulation, and life cycle analysis of buildings. Major advances in each area are highlighted, as well as the trends for development and application.

1. Introduction

Computer simulation tools and computational techniques have been widely and successfully applied to building design, optimization, construction, operation, and research for decades. These tools and techniques are credited to accelerate the design process and optimize building performance with relatively low cost [1]. Before the wide availability of computer-aided simulation, building designers and engineers relied mainly on manual calculations and resorted to "rule of thumb" methods and extrapolations in extending a design beyond conventional concepts [2]. During 1990s, right within the period of this review, personal computer (PC) hardware and software have both come to the point that graphical user interface (GUI) and computer modeling are affordable and possible in both research and industry [3], leading to a comprehensive progress in building simulation, on both techniques and tools. Building simulation is now involved in the design, engineering, operation, and management of buildings, and becoming an indispensable part of building industry.

Simulation based design and optimization of buildings can help achieve a number of specific targets, such as, reducing energy consumption and environmental impacts, and improving indoor environment quality, thus opening a new era of design to architects and engineers [4]. The ultimate goal of developing and promoting building simulation techniques and tools is to facilitate the creation of a built environment that fulfills the living needs with the least possible construction and operation costs and resource consumptions. One of the significant and distinct aspects of the simulation tools and techniques booming in the last decades is that it provides quantitative data supporting decision making, and consequently assists the achievement of the ultimate objective. The increasing number of building performance codes and standards, with more stringent requirements, is one of the main driving forces for promoting and enforcing the adoption of computer simulation tools to evaluate building performance compliance. ASHRAE 90.1 requires to use whole year building energy simulation results to rate building energy performance. Green building rating systems, such as Leadership in Energy and Environment Design (LEED), adopt the same approach as ASHRAE 90.1 for energy performance rating and approve several different simulation tools such as for daylighting and natural ventilation to score building performance. To achieve low (or net zero) energy buildings as well as various government's aggressive energy and greenhouse gas (GHG) reduction targets (e.g., European Energy Performance of Buildings Directive – EPBD) also demands and accelerates the usage of simulation tools for building design, construction and operation. At the same time, the validation of building simulation models and predictions draws a relatively new level of attentions [5], indicating the critical trust

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issues on the simulation techniques (including both mathematical models and input parameters).

The nature of available building performance simulation tools and modeling approaches is fairly diverse, ranging from basic heat transfer physics to complicated material science, from simple living schedules to sophisticated human behaviors, from typical meteorological data to global warming impacts. Fundamentals on most of these disciplines were created decades ago, but have been undergoing continuous evolvement. The current building simulations tend to integrate different building performance aspects such as thermal, visual and acoustical impacts [6], so as to predict the inherent correlations and interactions among building elements. The diversity and multidisciplinary characteristics of these interactions impose a major challenge to building modeling development and application. It is the ability of dealing with resulting complexity of scale and diversity of component interactions that gains building simulation a well-respected role in the prediction, assessment, and verification of building behavior [7].

Specifically, these building related simulation and computational techniques focus on a variety of important aspects of building performance including building energy efficiency and consumption, indoor environment such as thermal comfort, ventilation and indoor air quality, as well as lighting and acoustic environment. In addition, techniques to improve the efficiency and effectiveness of design and construction proficiency of buildings, such as building information modeling (BIM), as well as life cycle analysis (LCA) or carbon emission prediction of a building, are of growing interests. This review is structured accordingly to provide an overview of the advancement for each of these aspects during 1987–2014.

2. Indoor ventilation simulation

Ventilation and indoor thermal environment can be predicted by various methods. The well-mixing assumption that indicates uniformly distributed air parameters such as temperature, velocity and species concentration results in a single zone model. For certain conditions, the non-uniform distribution of indoor air parameters becomes a concern, thus requiring different modeling techniques. The typical methods for indoor environment modeling are: analytical method, computational fluid dynamics (CFD) approach, zonal approach, multi-zone approach, and the coupling method to take advantage of two or more approaches.

2.1. Analytical method

The analytical models in building research are usually derived from mathematical analysis or using theoretical formula, which can be accurate and reliable for cases with the same assumptions. The analytical and semi-empirical models are often developed with solid physics, but with significant approximations [8], while some are regressed from parametric studies without knowing the inherent physics. Small-scale or full-scale experimental models are conducted to verify the accuracy of theoretical solutions. The derived formula from analytical analysis can be readily used for predicting building performance of similar configurations and conditions.

Analytical method has been extensively used in natural ventilation study. Li et al. obtained an analytical solution for natural ventilation induced by combined wind and buoyancy forces in a single-zone building with two openings [9], and conducted analytical and experimental analysis for three two-opening-buildings of different structures in a following research [10]. Chen et al. investigated buoyancy-driven displacement natural ventilation in a single-zone building with three-level openings and provided a guideline for optimizing natural ventilation of similar buildings [11]. An analytical solution for natural ventilation driven by thermal buoyancy due to uniform temperature in a two-opening room is derived [12], and guideline for unambiguous solutions in the situation of natural ventilation with opposing wind in a two-opening-room is developed [13]. Leung explained and developed analytical models for natural and hybrid ventilation in simple buildings [14]. Analytical method can also be applied to solar chimney [15] and natural ventilation with explicit thermal stratification [16]. Most of these models need temperature as an input parameter.

Analytical model is also commonly used for evaluating contaminant distribution in indoor environment. Mazumdar developed a 1-D analytical model for airborne contaminant transport in airliner cabins [17] by taking into consideration of both diffusive and convective transport of air contaminants. Parker gave an analytical solution for contaminant ingress into multi-zone buildings [18]. The result showed that the peak exposure of all zones can be estimated by the maximum zone exterior air change rate. Nazaroff showed Inhalation intake fraction of pollutants from episodic indoor emissions [19] to assess pollutants' exposure risk of building occupants.

Analytical models based on data regression constrain the applicability of the models due to unclear underlying physics. Modifications or amendments are thus applied to existing models in an attempt to correct them by introducing new parameters to explain new observed physics or adapt to varying application conditions. For example, Bastide [20] compared the results of heat and mass transfer predicted by the Walton model and CFD on cross-ventilated buildings that have two large external openings. A building coefficient taking into account of kinetic energy that passes through openings was used to improve this model. Results of the modification showed better agreement with the CFD results in calculating mass flow and indoor pressure.

2.2. CFD approach

Computational fluid dynamics (CFD) was first introduced to building industry in the 1970s [21]. CFD software has been extensively used since the 1990s with the increasing computing speed and the reduction on the cost of computing hardware. CFD is popular in the building ventilation and architectural design to provide visual and quantitative results for decision making. It is mainly used in this community to predict indoor and outdoor airflow, pressure, temperature, humidity, and chemical species distribution. Several review papers are discovered on CFD and ventilation research, indicating a growing interest of ventilation community of CFD. CFD has become an integral part of scientific research and engineering development of complex air distribution and ventilation systems in buildings [22]. Norton reviewed various CFD applications in 2006 and 2007 [23,24]. Blocken reviewed CFD for architectural design in 2011 [25]. Nielsen reviewed the application of CFD for room air distribution in the last 50 years [26] in 2014.

CFD simulation is essentially numerical solution of the governing equation of fluid flow. The prediction accuracy and computational speed can be influenced by many factors, including numerical method, turbulent model, mesh quality, differencing scheme of discretization, and pressure-velocity decoupling algorithm.

2.2.1. Turbulence modeling

Turbulence modeling is one of the most significant factors that affect ventilation performance prediction. Turbulence modeling techniques for ventilation performance prediction have been greatly improved on the aspect of obtaining accurate simulation results but with less computational cost. New turbulence models for building indoor simulation have been proposed and proper tur-

Table 1
Summary of the performance of turbulence models in indoor environment modeling [34].

Cases	Compared Items	Turbulence Models							
		0-eq.	RNG k-ε	SST k-ω	LRN-LS	V2f-dav	RSM-IP	DES	LES
Natural convection	Mean temperature	B	A	A	C	A	A	C	A
	Mean velocity	D	B	A	B	A	B	D	B
	Turbulence	n/a	C	C	C	A	C	C	A
Forced convection	Mean velocity	C	A	C	A	A	B	C	A
	Turbulence	n/a	B	C	B	B	B	C	B
Mixed convection	Mean temperature	A	A	A	A	A	B	B	A
	Mean velocity	A	B	B	B	A	A	B	B
	Turbulence	n/a	A	D	B	A	A	B	B
Strong buoyancy flow	Mean temperature	A	A	A	A	A	n/c	n/a	B
	Mean velocity	B	A	A	A	A	n/c	n/a	A
	Turbulence	n/a	C	A	B	B	n/c	n/a	B
Computing time (unit)		1	2–4		4–8		10–20	10^2–10^3	

A = good, B = acceptable, C = marginal, D = poor, n/a = not applicable, and n/c = not converged.

bulence models that work best for specific room conditions have been identified.

The most prevalent turbulence model used in building related research is RANS (Reynolds-Averaged Navier-Stokes) along with different versions of the k-ε models as have been widely studied and validated by different scholars. For example, Brau [27] tested the accuracy of four different two-equation-turbulence models and Murakami [28] compared the prediction results of k- ε models with the measurement data.

Revision to turbulence models for improving simulation accuracy and adapting it to indoor air simulation is a common and important practice. In 1998, Chen [29] brought out an empirical zero-equation model applicable to indoor environment modeling based on mixed length hypothesis. The method based on eddy viscosity concept assumes turbulent viscosity to be a function of length-scale (L) and local mean velocity (u); such a treatment shows great possibility of reducing computational cost and meanwhile predicting airflow accurately. The algebraic formula of turbulent viscosity (ν_t) is expressed as

$$\nu_t = 0.03874uL \quad (1)$$

With the advancement of computing hardware, large eddy simulation (LES) gradually becomes feasible for engineering applications these years and gains some popularity. Unlike RANS models, LES approach does not use Reynolds averaged equations but uses a spatial filtering operation to separate the large and small eddies in turbulent flow, such that the computing speed is much slower than RANS models. Recently, detached eddy simulation (DES) method taking advantage of both RANS and LES models has been developed and applied successfully in building simulation especially for natural ventilation [30]. It provides similar or slightly better prediction than unsteady RANS model under displacement configurations [31].

Since all turbulence models are derived for certain flow regimes or conditions with empirical parameters engaged, there is no single turbulence model that performs the best for all conditions in building environment modeling. Therefore, understanding the applicability of different turbulence models is critical for turbulence model selection in practice. There are many articles on comparing the predictions or evaluating the scope of different conditions with different turbulence models. Chen compared different k-ε models for indoor airflows, and the results showed that the RNG k-ε model provides the best overall solution comparing against experimental data [32]. A similar study reviewed 18 different popular turbulence models of RANS, LES and DES category in predicting indoor airflows by CFD [33] and compared the performance of 8 of them by comparing the predicted results against experiment data [34]. The conclusion as shown in Table 1 provides good guidance for subsequent CFD users in selecting the proper turbulence model for indoor environment modeling.

2.2.2. Pressure-velocity decoupling algorithm

Various versions of CFD SIMPLE algorithms are prevalently used to decouple the simulation of pressure and velocity in practice. Issa proposed a non-iterative PISO [35] (Pressure-Implicit with Splitting of Operators) algorithm that works better than SIMPLE for time-dependent flows. PISO has been adapted to steady flow simulations and works better than SIMPLE for conditions where scalars are not closely linked to velocities [36].

Another non-iterative method is the projection algorithm. Since pressure-velocity decoupling is a critical factor that determines the computing speed of CFD simulation, improvement on these decoupling algorithms draws attentions for real-time CFD simulation. The projection method has gone through some improvements. Almgren presented a conservative adaptive projection method for calculating variable density incompressible N-S equations [37] in 1997. Kim et al. developed a two-step optimal design method for CFD [38] in 2007.

Stam [39] replaced the implicit projection method with the semi-Lagrangian advection to animate the fluid-like flow physically, and Wang [40] applied such a semi-Lagrangian method to PISO algorithm to improve the speed and accuracy of CFD simulation in indoor environment. Zuo [41] first applied Stam's method to indoor environment modeling, improved the sequence of operators, tested higher order of differencing schemes, and evaluated the accuracy. This method is also denoted as fast fluid dynamics (FFD) as the simulation speed is significantly improved comparing to regular CFD algorithms. The computational speed of FFD can be further improved by using graphics processing unit (GPU) [42], and the speed can be hundreds to thousands of times faster than running FFD and CFD on regular CPU. This provides a potential direction for future fast CFD simulation.

Using the calculus notation to express the general format of the momentum equation as Eq. (2), the right side of the equation are advection, diffusion, pressure and source term, respectively.

$$\frac{\partial u}{\partial t} = -(u \cdot \nabla)u + \nu\nabla^2 u - \frac{1}{\rho}\nabla p + S \quad (2)$$

The FFD method assigns some intermediate velocity field u^1, u^2 and u^3 between the time step $t + \Delta t$ and t. The evolution of velocity field from u^n to u^{n+1} employs the following sequences to add the force, advection, and diffusion term sequentially as expressed by the following five equations. Such a decomposition treatment makes the equation in each step much easier to solve. Semi-Lagrangian advection algorithm is applied to replace the advection term as in Eq. (4) to avoid non-linearity and help accelerate computation.

$$Force: \frac{u^1 - u^n}{\Delta t} = S \quad (3)$$

$$Advection: \frac{u^2 - u^1}{\Delta t} = -(u \cdot \nabla)u \quad (4)$$

$$Diffusion: \frac{u^3 - u^2}{\Delta t} = \nu \nabla^2 u \quad (5)$$

$$Pisson\ Eqn: \nabla^2 P = \frac{\rho}{\Delta t} \nabla \cdot u^3 \quad (6)$$

$$Projection: \frac{u^{n+1} - u^3}{\Delta t} = -\frac{1}{\rho} \nabla p \quad (7)$$

2.2.3. Computation grid

The computing grid can significantly affect the simulated results, and a grid independency study is recommended for CFD simulation practice to exclude the effect of grid resolution on simulation results [43]. Local refinement is common in practice especially in vicinity to human body [44] and near boundaries. For regions with large variable gradients observed from a preliminary simulation, adaptive grid for local refinement can be employed [45] by dividing cells apart. As grid resolution is a key factor determining the computing cost of CFD, efforts to apply coarse grids sacrificing accuracy have also been made in order to obtain quick and reasonable CFD results [46].

2.2.4. Air contaminant modeling

CFD is not only useful for predicting airflow in buildings, but also important for simulating contaminant transportation. Airborne contaminants including both gas and particles can have very adverse effect on human health such that it is intensively studied in the past decades by different means including CFD. As gaseous contaminant such as VOC [47] is continuously distributed in indoor environment, it can be simulated under Eulerian regime. Simulating indoor airborne particle transport can employ either Eulerian or Lagrangian approach [48,49], working with RANS turbulence models as particulate matter exhibits discontinuous status in air. The Lagrangian approach is also tested to integrate with LES model so as to improve the accuracy in predicting particle transportations [50]. The dragging force of airflow on particles varies with the size of particles, and the distribution and ventilation removal efficiency of fine and coarse particles are quite different [51]. The particle modeling method has been applied to study virus and bacteria in mission critical spaces such as hospital operating room [52], where infectious diseases spread in the form of particle transportation.

2.3. Multi-zone approach

Multi-zone approach is based on fluid network model similar to electrical circuit analogies [53]. It assumes a uniform air temperature and contaminant concentration in a confined space/zone, and air momentum effects are neglected, which makes it much faster than CFD. Quantitative studies show that these assumptions in multi-zone model are acceptable for spaces with dimensionless temperature gradient less than 0.03, Archimedes number of the source zone greater than 400, and the jet momentum effect dissipated before reaching an opening in downstream [54]. Infiltration simulation of complex buildings by multi-zone approach is not practical. It is further simplified on the basis of their ratio of permeability and lumped together the physical parameters describing the air permeability distribution needed to calculate the building's overall and each zone's infiltration/exfiltration rate [55].

Multi-zone modeling of airflow and contaminant transportation within a building has been validated on various subjects, and fairly good accuracy has been verified for similar engineering applications. Musser compared the simulation of a two-story classroom-office building with published data and additional tracer gas decay tests [56]. Field tests of a proposed efficient air flow model calibration method were performed on two classroom/office buildings, and the interactive tuning procedure produced satisfactory improvement on existing multi-zone models [57]. The influence of infiltrating air is significant on building heat loss and indoor air quality. Such influences were modeled and validated by a 3-week monitoring campaign of a multi-family building [58] and across the entrance doors of a retail store [59].

Several multi-zone software are available, such as, COMIS, CONTAM [60], AIRNET, ASCOS, BREEZE, et al. ASCOS was most widely used and representative for network airflow models between 1980 and 1990s. Currently CONTAM has been one of the most popular software using multi-zone method. It has a relatively user-friendly interface and the results of calculation are easy to understand in post-processing. CONTAM was developed by National Institute of Standards and Technology (NIST) in 1993. The early version was CONTAM 93 for DOS system evolved from AIRNET (1989) [61]. CONTAM has been greatly used for environment simulation such as building air infiltration [62] and particle dispersion [63].

COMIS (Conjunction of Multi-zone Infiltration Specialists) [64] is another popular multi-zone software developed by Lawrence-Berkeley National Laboratory (LBNL) around 1989. The performance of different software in predicting airflow rates or contaminant distributions in buildings has been intensively compared. For example, COMIS, CONTAM and ESP-r were compared fundamentally and validated with experimental data collected in a controlled environment test laboratory and field measurement data of two single-family houses in Ottawa. Good agreements between the predictions and test results were observed [65] and predicted airflow rates in single-family houses were similar [66]. A comparison of BREEZE, COMIS and CONTAM with experiment data showed that all the model predictions agree well with the measurements, although the interfaces provided for input/output and the simulation time differ considerably [67].

2.4. Zonal approach

Zonal approach subdivides a single room into a number of subzones (cells) in which air parameter is assumed to be homogeneous. Zonal model is based on the energy and mass balance equation, and the momentum/turbulence is not considered or in implicit format. The detailed principles and early history from 1970s can be referred in the review conducted by Mergri and Haghighat [68].

Many validated cases proved that zonal model can be a useful tool for predicting room temperature distribution and air velocity [69]. Zonal model has been improved by different efforts. For example, Boukhris extended the zonal model ZAER (Zonal AERial model) to enable predictions of air flow pattern and thermal distributions between and within rooms, which can also couple with a thermal comfort model [70]. Zhou developed a new integrated modeling tool for zonal model, which integrated the zonal model with room air age and other key sources that are of concern (e.g., temperature, air pollutant). Results demonstrated that the new zonal model is more accurate than the conventional zonal model [71,72], and the tool could be used for design of HVAC systems with IAQ control devices as well as for the simultaneous analysis of thermal performance and IAQ in buildings. Huang [73] integrated zonal model with air jet model and building material VOC emission/sink model. Simulation results showed agreement with the experiment. Wurtz [74] developed a zonal model called Sim_Zonal, which yields rather accurate results even with a rough partitioning.

SPARK environment [75] and TRNSYS library are commonly used platforms to implement zonal method. Backer coupled a zonal model with a building energy simulation model [76]. One coupled TRNSYS-zonal models, POMA (Pressurized zOnal Model with Air-diffuser) [77] was validated to exhibit good agreement with CFD results and experimental data [78,79]. Yu and Megri developed and calibrated a new zonal model POMA+ for airflow and temperature prediction [80,81].

2.5. Coupling of different models

A variety of simulation models and techniques are employed in building environment study, each presenting its own pros and cons. For instance, CFD can provide more informative data than analytical method but the computational cost can be a main drawback. Network airflow simulation of multi-zone model is based on well-mixing assumption of each zone. It simulates airflow and contaminant transportation quickly but parameter spatial distributions in a zone are neglected. Different types of methods therefore can be integrated with each other in order to take advantage of each method. Coupling different models is also promising for improving the prediction results and reducing the simulation time. Some essential progresses have been found in the past decades.

Pioneering work of linking CFD results with multi-zone models was conducted in 1993 by manual input [82]. Clarke [83] and Negrao [84] implemented CFD model internally in ESPr for automatic airflow simulation. Treatment of complex geometries, blockages, buoyancy, ventilation openings, surface heat transfer and the assessment of the spatial and temporal variation of thermal comfort and indoor air quality in CFD module is refined to improve the simulation capabilities of the CFD module of ESP-r [85]. A CFD0 program has been successfully integrated into multi-zone program CONTAM by direct and indirect couplings, and showed reasonable accuracy while preserving acceptable computing costs [86]. The assembled airflow equation solved in such a coupling is

$$C \cdot P + F = B \quad (8)$$

where C is the airflow coefficient matrix, P is the pressure vector of zones and cells, F is the flow rate vector of paths and cells at multi-zone and CFD zone interfaces, B is the vector of air mass sources. This equation is solved iteratively in which CONTAM provides pressure boundary conditions to CFD0 and CFD0 returns pressure boundary conditions to CONTAM until converged results are obtained.

For large openings, bi-directional flows with both infiltration and exfiltration need to be addressed. A pressure difference model [87] is proposed by considering the pressure difference profile at the boundary of the integration. The implementation of this method into the CFD SIMPLE algorithm can be performed as follows:

1. Solve discretized momentum equations;
2. Compute boundary velocities;
3. Correct boundary velocities;
4. Solve pressure correction equation;
5. Solve all other discretized transport equations.

Zonal model in certain circumstances can be used as a substitute of CFD model as it also reveals parameter distributions in a single zone. As a result, another possible coupling is between zonal model and multi-zone model. As a modified version of COMIS, COwZ included sub-zonal divisions and nested a zonal model within COMIS in 2003 [88,89].

2.6. Summary and trends

As stated above, each modeling approach has its own merits and drawbacks. A higher resolution approach does not necessarily address all the design questions that may be answered by a lower resolution approach, as concluded by analyzing the capabilities and applicability of the various approaches in the context of a displacement ventilation system [90], as summarized in Table 2.

Table 2
Summary of prediction potential (– – = none, ++ = very good) for airflow modeling levels in the context of displacement ventilation system [90].

Aspect	Fully mixed zones	Zonal method	CFD
Cooling electricity	– –	++	– –
Fan capacity	++	++	– –
Whole body thermal comfort	+	++	+
Local discomfort, gradient	– –	+	++
Local discomfort, turbulence intensity	– –	– –	++
Ventilation efficiency	– –	0	++
Contaminant distribution	–	–	++
Whole building integration	++	++	– –
Integration over time	++	++	– –

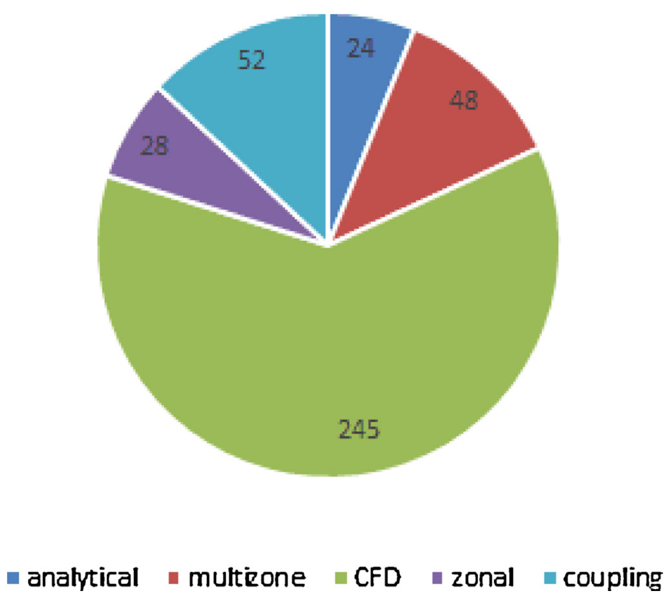


Fig. 1. Share of literature number on each indoor environment modeling method.

Fig. 1 shows the number of literature in each simulation method category collected in this review. Research on CFD approach has the largest proportion, indicating the popularity of CFD in building ventilation community over the other methods. Coupling method has the second largest share. Fig. 2 presents the number of literature collected each year. Generally the publication of using computer simulation for building ventilation research exhibits a growing trend, with a burst between the years of 2007 and 2008 (likely due to some international conferences on this topic).

As an intermediate approach between multi-zone and CFD method, zonal model used to be considered a promising method, as its computing time is less than CFD and its ability to provide detailed air parameter distributions [91]. An improved zonal model for the forced convection by adding standard cell model and jet cell model shows great improvement on the prediction and requires less computational efforts and returns more accurate results than coarse-grid CFD and FFD [92]. But most studies on zonal models concern the principal development of zonal models rather than practical applications, making it not an easy tool to use [93]. One of the challenges for practically using zonal model is that prior knowledge is needed to preset the subzones, with which the prediction results are fairly sensitive. Studies also revealed that coarse-grid CFD is a better-suited method to predict airflows in large indoor spaces coupled with complex multi-zone buildings, than are the zonal methods for isothermal airflow [94]. As for mixed convection

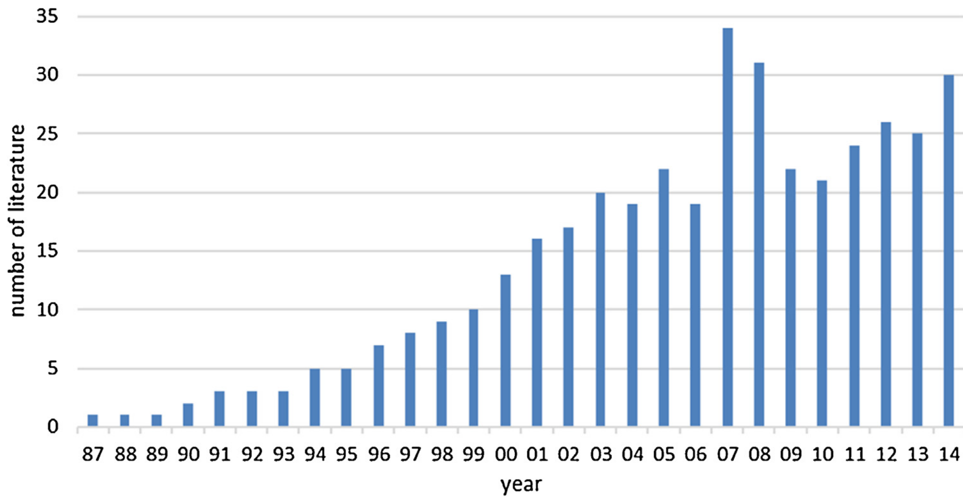


Fig. 2. Number of literature on indoor environment modeling per year collected by this review.

Table 3
detailed summary of capability of different BES program [101].

Modeling characteristics	Building energy simulation programs								
	BLAST	BSim	DeST	DOE-2.1e&2.2	ECOTECT	EnergyPlus	eQuest	ESP-r	TRNSYS
Simulation solution	PI	CI	PI	NI	NI	CI	CI	CI	CI
Time step approach	PI	PI	OI	NI	NI	CI	PI	CI	PI
Geometric description	CI	CI	CI	CI	CI	PI	CI	CI	CI
Simulteneous radiation and convection	CI	CI	CI	CI	NI	CI	CI	CI	CI
Combined envelope heat and mass transfer	CI	CI	NI	NI	NI	CI	NI	CI	CI
Solution method for conduction transfer of heat	TFM	NI	TFM	TFM	FDM	TFM	TFM	FiDM	TFM
Internal mass considerations	CI	CI	CI	CI	CI	CI	CI	CI	CI
Occupant comfort	CI	NI	NI	NI	PI	CI	NI	PI	PI
Solar gains, shading and sky considerations	NI	NI	PI	NI	CI	CI	PI	PI	CI
Variable construction element properties	NI	NI	NI	NI	CI	NI	NI	NI	NI
PCMs	NI	NI	OI	NI	NI	NI	NI	OI	OI
EIA	PI	NI	NI	PI	NI	CI	PI	PI	OI

Nomenclature: CI: Completely/wholly implemented (Issue is well addressed and backed by program's supportive documentation); PI: Partially implemented (Issue is partially implemented and is not fully addressed by the program); OI: Optionally implemented (Issue is addressed for research and is not included in the standard feature); NI: Not/Negligibly implemented (Issue is not included or only a very small part of it is implemented in the programs); TFM: Transfer Function Method; FDM: Frequency Domain Method; FiDM: Finite Difference Method.

where both mechanical force and temperature difference exist in a ventilated room, both zonal model and coarse-grid CFD can be suitable tools for the simulation [95,96]. Using GPU instead of CPU in CFD and FFD simulation shows great potential in reducing computing time [42], indicating another possible direction for future ventilation simulation.

3. Building energy and load calculation

3.1. Detailed building energy simulation

Building consumes more than 30% of energy generated worldwide, and it is of vital importance to reduce this percentage, leading to an increasing demand for building energy simulation (BES) to improve building energy efficiency. Detailed building energy simulation program dated back to the 1970s when oil embargo raised energy awareness. Software with capability of treatment of multiple thermal zones and HVAC systems under different operating conditions such as DOE-2, Blast [97] and ESP-r [98] all emerged after this period of time.

With ever-increasing capability of computers and improved programming languages, next generation of BES programs such as EnergyPlus and DeST [99] were developed during mid-1990s and have become commonly used tools in engineering design and scientific research nowadays. The heat balance approach adopted by EnergyPlus and BLAST has the potential to be the most accurate method of solving for the heating and cooling loads in a building because it accounts for all energy flows in their most basic, fundamental form and does not impose any simplifications on the solution technique [100]. Third-party modules and interfaces for these programs were developed to make them easier tools for engineering applications. eQuest, OpenStudio and DesignBuilder are good examples of such efforts. The capability of different available BES programs is listed in Table 3 [101].

Detailed building energy simulation relates to all components such as building envelope and HVAC system of a building, such that the research activities on this topic are quite diverse. Detailed building energy simulation generally employs mathematical model of each building component. The transient analysis of heat flow in building envelope adds considerable complexity and computational expense to the dynamic building thermal processes. The effort to develop better methods for performing this transient heat flow calculation leads to a comprehensive progress of building energy simulation.

3.1.1. Conduction transfer function method

Conduction transfer function (CTF) method is one of the most conventional approaches used for transient heat transfer calculation. It is used in the simulation software such as BLAST, TRNSYS and EnergyPlus to evaluate the thermal loads through building

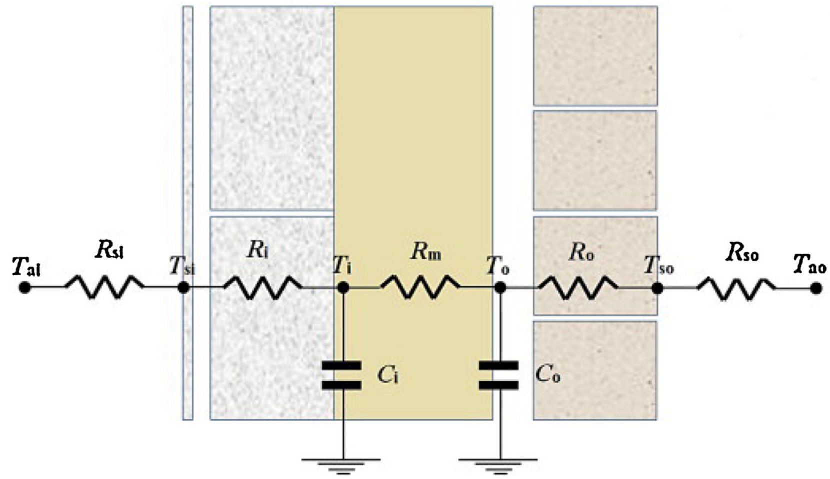


Fig. 3. Simplified 2nd-order construction element model [113].

constructions. It has been successfully programmed to predict the hourly cooling load of different types of wall, roof and fenestration [102]. As instability issue raises when large time step is used in CTF method at an initial startup of a simulation or during a period when sudden change occurs, a novel and simple model for building thermal load calculation based on polynomial s-transfer functions of transient heat conduction through a building construction is proposed [103].

Calculating CTF coefficients is a root finding process. Mainly there are direct root finding, state space (SS) method [104], time domain method [105], and frequency-domain regression (FDR) method [106]. The state space method has the prominent advantages that the time step does not affect the stability of the system. A test with ASHRAE wall 19 and 24 showed that FDR method is more robust and reliable than SS and direct root finding methods, and it is more practical to calculate CTF coefficients and may be a better choice to calculate the cooling/heating loads for building structures for architects/designers [107]. SS method is used in energy simulation software such as DeST [99]. A State Space Plus model based on SS method was developed to model large scale buildings with hundreds of zone simultaneously more efficiently [108].

3.1.2. Thermal response factor method

Thermal response factor method is another most adopted approach for transient heat transfer calculation, which was brought up in the 1960s. The method assumes that coefficients are constant values, whereas the coefficients change with the temperature variation. For systems with radiant heat transfer, this method does not work properly. DOE-2 adopts response factor to solve opaque retaining structure heat transfer and use cooling load coefficient method to calculate the room load and temperature [109]. The program does not directly calculate inner surface long wave radiation heat transfer but takes this into account in convective heat transfer coefficient between inner surface and air. Air temperature is set to a fixed value when calculating convective heat transfer between inner surface and air.

3.1.3. Radiant time series method

The radiant time series (RTS) method was developed by Spitler [110] for cooling load calculation, especially on radiant cooling load. This method converts the radiant portion of hourly heat gains to hourly cooling loads using radiant time factors, the coefficients of the radiant time series. The method is based on heat balance method, a simplified method for calculating the cooling load. As the RTS method uses periodic response factors to model transient conductive heat transfer, it consumes less computational power than CTF method [111].

3.1.4. Lumped parameter models

Since building structure elements have the characteristics of both thermal resistance and capacitance, a reduced order lumped parameter model can be used to model the thermal performance of a building. This method has the capability of hourly simulation of whole building energy consumption but the computational intensity is much less. This modelling approach is often referred to as "analogue circuit" models due to their connotation with electric circuits. Lumped-parameter building simulation techniques have been used since the early 1980s [112]. Building structural elements consist of several layers of different materials and each layer has different characters (thickness, thermal conductivity, specific heat capacity, and density). With this method, elements consisting of n layers of materials can be combined to form two "lumped" thermal resistances, and one thermal capacity, as illustrated in Fig. 3.

Since the first lumped parameter model is first-order that may cause accuracy concern in application, higher order models were proposed and demonstrated. A third-order model [114] was proposed based on the initial models to overcome the reported inadequacies of poor modelling performance of buildings with very high thermal capacity. The accuracy is significantly improved without compromising their simplicity or speed. A second order model [115] for the optimization of reduced-order lumped capacity modelling of the dynamic thermal behaviors of building spaces was demonstrated with better accuracy. The method is based on a nonlinear multi-variable constrained optimization problem driven by Kuhn-Tucker equations and involves minimizing the error between the step responses of a high-order reference model whilst tuning the parameters of a lower order mode. Fraisse et al. [116] compared first- and second-order element models and proposed a fourth-order model with aggregated resistances. Lumped parameter model can be coupled with hourly building energy consumption software [117]. Usually it can be used with modular-graphical modelling tools such as Simulink [118], or equation-based methods such as Modelica [119] or EES [120].

3.2. Simplified energy and load evaluation models

Simplified building energy and load evaluation approach is useful and appropriate for applications where the purpose of building energy analysis is to quickly study trends and/or compare systems alternatives. Different from detailed simulation techniques, which consider the dynamic process of heat transfer, the simplified energy evaluation method assumes a steady-state characteristic of building thermal system to estimate building energy consumption.

3.2.1. Degree-day method

The degree-day method is suitable for heating energy consumption estimates of small buildings by hand calculation or simple computer program. The procedure is based on the assumption that on a long-term average, solar and internal gains will offset heat loss when the mean daily outdoor temperature is 18.3 °C (65°F), and that energy consumption will be proportional to the difference between the mean daily temperature and 18.3 °C (65°F) [121]. Variable based degree-day method is proposed for base-temperature correction of mean annual degree-day totals [122]. Another method used correction factors to calculate degree-days. Since the correction factors are not of general validity, they should be consequently produced for each location separately [123]. The methods proposed above need statistical analysis for the identification of the parameters. Gelegenis developed a simplified second-degree expression for the approximate estimation of annual heating degree-days to various base temperatures. The only data needed for the application of this relation is the degree-day value to some reference base temperature and the mean annual temperature of the location [124].

3.2.2. Bin method

The Bin method is one of the most popular ways to estimate the energy performance of a building. This method is based on the degree-day method and counts a certain interval of temperature. Obtaining bin temperature data is critical and is the main prerequisite for this approach. As bin data is usually obtained from statistical analysis of historical hourly outdoor air temperature record [125], a methodology for estimating the ambient temperature bin data, based on monthly average outdoor temperatures and solar clearness index is presented [126] and validated. The bin data can also be generated with the long-term daily weather record or TMY weather data [127].

3.3. Statistical and regression methods

3.3.1. Multiple linear regression

Building thermal load is a function of various building variables from indoor set-point temperatures to envelope properties. Multiple linear regressions (MLR) method predicts the cooling and heating load based on the regression of recorded building operation data. Predicting energy consumption at the early design stage is of vital importance, and a model to quantitatively predict building energy performance at early design stages [128] is proposed. The model utilizes EnergyPlus, within a Monte Carlo framework, to develop a multivariate linear regression model. Input variants can be different for such a regression, depending on how the energy consumption is to be correlated with targeted influencing factors. The regression model with three inputs and one output presents a good match with the simulations. Energy certification calculations and human behavior correction [129] are proposed to predict the heating energy demand, based on the main factors that influence a building's heat consumption.

3.3.2. Artificial neural network

Artificial neural network (ANN) is a generic denomination for several simple mathematical models that tries to simulate how a biological neural network (for instance the human brain) works. The main characteristic of ANN is the capability of learning the "rules" that control a physical phenomenon under consideration from previously known situations and extrapolating results for new situations. ANN is an effective method to predict building energy consumption. The most known, simple and used network arrangement is the feed-forward model [130].

ANN can precisely calculate hourly load of a building, and can be applied to forecast the short-term load for a large power system. A nonlinear load model with several structures of an ANN for short-term load forecasting was tested [131] and showed good load prediction. A method based on a special type of ANN is proposed, which feeds back part of its outputs and train ANN by means of a hybrid algorithm [132]. The system used current and forecasted values of temperature, the current load, and the hour and day as inputs, and demonstrated a high precision in load prediction. ANN method can be also used to obtain long-term energy demand prediction based on short-term data [133].

3.3.3. Support vector machine

Support vector machine (SVM), developed by Vapnik and his co-workers in 1995 [134], has been broadly applied in classification, forecasting and regression. SVM is a highly effective approach to solving non-linear problems even with small quantities of training data. Many studies of these models were conducted on building energy analysis and energy use prediction in the recent years. Dong et al. first applied SVMs to predict the monthly electricity consumption of four buildings in the tropical region [135]. SVM can also be used as a data mining tool to predict the electrical consumption of a building. One study derived a model from one year's performance and then tested it on three months' behaviors [136]. An application of SVM to an office building in Guangzhou, China demonstrates that the SVM method can achieve better accuracy and generalization than the traditional back-propagation neural network model, and it is effective for building cooling load prediction [137].

3.3.4. Behavior model

Behavior models derived from field studies can provide the basis for predicting personal actions taken to adjust lighting levels, remedy direct glare, and save energy in response to physical conditions. Human behaviors play a very critical role in the overall building energy management and it is an important and fundamental factor in building energy simulation yet hard to represent due to its temporal and spatial stochastic nature [138]. Markov chain approach can be employed to simulate the stochastic movement processes of a building and handle the straightforward result of occupant movement processes that occur between the spaces inside and outside a building. Markov chain models can help learn occupant behavioral patterns from a building and reproduce them to predict the building energy consumption and identify potential areas [139]. A large group of researchers from 24 countries are working on data, analytics, modeling and simulation tools to integrate occupant behavior models into building simulation, under the IEA EBC Annex 66 [140] in order to avoid inconsistency and lack of common language problem of working individually.

3.3.5. Faults model

Operational faults of HVAC and control systems are common in buildings and lead to significant energy waste. Fault detection and diagnosis (FDD) strategy is intensively studied for various common faults in literature. However, they are usually not captured in building simulation tools. New development in EnergyPlus trying to fill such gaps [141] shows the feasibility of assessing the effect of HVAC faults on whole building performance.

3.4. Coupling between building energy and environment simulation

Building energy simulation (BES) assumes a well-mixed indoor environment for energy and load calculation, which is not always the case, especially when a room or a zone has large height or volume. Using CFD to consider the impact of distribution of room air temperature is a good option. This coupling method has been implemented and becomes available and mature in several commercial software such as DesignBuilder. Integrating simulation programs can provide complementary information of the building performance and thus provide accurate prediction of building thermal and flow behaviors. BES provide more realistic boundary conditions for CFD and CFD returns higher resolution modeling results of flow and temperature patterns within air volumes as well as accurate convective heat transfer coefficients for BES. In 1988, the idea of combined building energy and environment simulation is proposed [142]. Consequent study [143] to couple CFD solver with whole building energy simulation program ESP-r further confirms that this approach can improve result significantly.

Before 2000, three staged coupling strategies are usually suggested [144]. Zhai proposed a two staged coupling strategy [145] in 2002 to bridge the gap of two programs and to reduce the computing costs while achieving accurate results.

Load estimation of large spaces in a building is a major challenge and concern when using well-mixing assumption based BES. A standard method is proposed to simulate cooling load of atria in EnergyPlus based on different room air temperature patterns as a result from CFD simulation [146]. Qin found a new simulation method based on an artificial neural network predicting dynamic energy consumption and thermal environment parameters for atrium where ANN model is iterated with the energy simulation model [147].

Computational cost of CFD is a major barrier to couple with BES. As an alternative, zonal model can be a substitute for CFD to reduce the computational intensity [148,149]. BES is essentially multi-zone energy simulation model, which employs similar approach as multi-zone airflow simulation. As multi-zone software such as COMIS calculates the impact of temperature on airflows, it does not simulate the thermal conditions of the spaces but requires zone temperatures as inputs. BES software such as Energyplus can supply temperature values as inputs for COMIS to calculate the flow field and correct Energyplus [150].

4. Lighting and daylighting

Daylighting is recognized as an important element to supplement electrical lighting, save energy, and improve visual comfort. Simulating daylighting in a building mainly has two different but related aspects of purposes: determining illuminance and energy reduction.

4.1. Simulation tools

Daylighting simulation tools and software include those commonly used such as SuperLite, Micro Lumen, Radiance [151], Lightscape, Daylight Visualizer Velux, Ecotect [152], and PKPM-daylight. New lighting simulation tools were developed during the review period. DElight as a simulation engine of the lighting was brought out to achieve the requirements of indoor lighting level through the calculation of the daylight and electrical lighting [153]. ADELINE (Advanced Daylight and Electric Lighting Integrated New Environment) program package was proposed in 1996, which can solve the obstacles received by the lighting simulation [154].

The performance of different tools is quite diverse, and thus selecting a proper tool is critical and related to the simulation goal. Physical accuracy of Lightscape, Specter and Radiance for lighting simulation was compared [155] and Specter has the best overall performance. Comparisons of different commonly used lighting simulation software versus measurement data: Lumen Micro, SuperLite, Radiance and Lightscape [156]; Radiance, Lightscape, Micro Lumen, RadioZity, FormZ, SuperLite [157] showed that Radiance is able to predict illumination levels in an overall better accuracy. Lightscape 3.2, Radiance Desktop 2, Micro Lumen 7.5, Ecotect 5.5, Dialux and 4.4 were also evaluated for the analysis of the distribution of light under different conditions (location, time, and geographical conditions) [158]. The number of literature discussing various simulation tools accounts for 43% of the total number of lighting simulation related papers during the reviewed period, indicating that instead of addressing the fundamental mathematical models, lighting simulation tool capacity, accuracy and applications draws great interests among the society.

Many studies tested and recommended Radiance for various lighting projects and researches. A survey in 2006 showed that Radiance with backward raytracing simulation engine is the design tool of choice for the majority (over 50%) of design professionals that use computer simulations. Comparison on prediction method and application of commercial ray tracing software [159] showed that raytracing based simulation is more accurate than other existing methods. The accuracy and usability of raytracing and radiosity for architectural design highlighted the role of Radiance [160]. Radiance over-performs Sustarc when modeling an office building lighting performance [161]. Radiance has been used for the architectural design in tropical areas [162], as recommended by the Asian Civilization Museum (ACM) due to its high accuracy in cloudy conditions. In addition, for rendering effectiveness, it is found that no widely used rendering software is better than Radiance [163].

The backward raytracing method used by software such as Radiance traces light ray in the opposite direction to where they naturally follow. The process starts from the eye (the viewpoint) and then traces the rays back to the light sources taking into account all physical interactions (reflection, refraction) with the surfaces of the objects composing the scene. Polarization of light rays is not taken into account. Each single ray "carries" a certain amount of radiance expressed in the unit of W/m^2sr. The radiance is divided into three "channels" corresponding to the red, green and blue primary colors (abbreviated as r, g, and b). The total radiance R is calculated as a weighted sum of the radiances R_r, R_g and R_b carried by the three channels:

$$R = 0.265 \cdot R_r + 0.670 \cdot R_g + 0.065 \cdot R_b \quad \left(W/m^2sr\right) \tag{9}$$

The transformation from radiance R (radiometric unit) to luminance L (photometric unit) is given by:

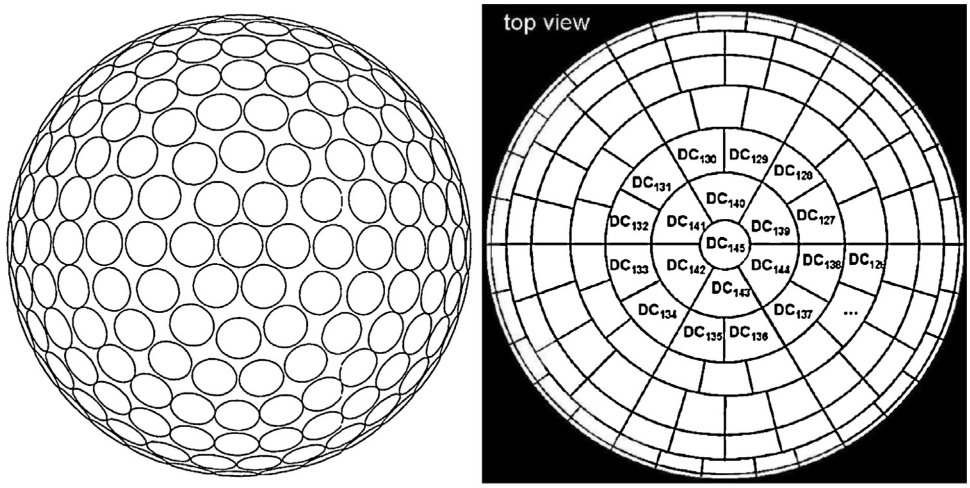
$$L = 179 \cdot R \quad \left(cd/m^2\right) \tag{10}$$

In order to produce a sky giving a specified horizontal illuminance E_h (in lux), the zenith radiance R_z has been explicitly given using the following formulae for International Commission on Illumination (CIE) overcast sky and uniform overcast sky:

$$CIEovercstsky : R_z = \frac{9}{7} \cdot \frac{E_h}{\pi \cdot 179} \tag{11}$$

$$Uniformovercstsky : R_z = \frac{E_h}{\pi \cdot 179} \tag{12}$$

As daylighting is highly associated with building energy saving by reducing electrical lighting and cooling load, integrated building thermal simulation and daylighting simulation is requisite [164]. A collection of building life cycle, energy consumption, lighting, indoor comfort, indoor sound environment and other architectural features is evaluated with a single software ESP-r [165]. And a daylighting simulation tool integrating thermal analysis function is also found, which can handle window information system (WIS) program in a variety of situations [166].



(a) Tregenz model (b) DDS scheme

Fig. 4. Division of the sky by different DC models.

4.2. Simulation models

4.2.1. Illuminance prediction

The illuminance of daylight in a building space is conventionally estimated in terms of the daylight factor (DF). Daylight coefficient (DC) that considers the changes in the luminance of sky elements offers a more effective way for calculating indoor daylight illuminance under various sky conditions and solar locations [167]. DC relates the luminance distribution of the sky to the illuminance at a point in a room. The accuracy and efficiency of the daylight coefficient method lies on the number of sky division patches; the higher the number of patches, the better the accuracy and the lower the computational efficiency. Tregenza [168] proposed 145 sky patches with a cone opening angle of 10.15°. A dynamic daylight simulation (DDS) scheme adopts the Daysim approach, rectangular sky segments that completely cover the celestial hemisphere without any overlap, no rays hitting the hemisphere are ever discarded or double counted [169]. The division of the sky by the two different DC models is shown in Fig. 4.

DC approach is time consuming but it is more accurate than DF method, as shown in a study that compared the simulation results with measured data of a day-lit classroom and corridor [170]. Six different simulation methods, based on Radiance, were used to simulate two offices' annual indoor lighting distribution. Results showed that annual lighting simulation methods in terms of accuracy is not necessarily required to simulate the time-dependence of lighting, and its quality relies more on the sky lighting efficiency model and whether or not the model considers the direct and scattering light. The two methods with daylight coefficients exhibit the lowest relative root mean square errors (RMSEs) for the straightforward office geometry [171]. The use of time series data to predict the annual use of the sky and sun conditions of each hour of indoor lighting brightness reveals that DC approach is accurate under the condition of using BRE-IDMP database [172].

In the meantime, DC approach should be applied carefully to specific cases. A dynamic lighting simulation method DAYSIM (Radiance-based) utilizes DC approach and the Perez sky model to predict the short time step development of indoor lighting [173]. The study shows that the direct processing will greatly affect the accuracy of the DC method. The performance of the existing lighting simulation method for predicting the complex fenestration system (CFS) was evaluated by comparing the experimental data with the simulated data using Radiance [174]. Similarly, Radiance based DAYSIM method was used to study the effect of short term dynamic lighting simulation on the availability of building lighting in the whole year [175]. The author pointed out that all available daylight simulation methods are based on hourly radiation data while ignoring the short-term changes in the sunlight, the errors can be found through the introduction of the radiation data per minute of the stochastic Skartveit – Olseth model.

Applying daylight evaluation models to develop and evaluate lighting devices is another important topic for practice. Performance of a micro-light guiding shade daylight redirecting device was tested by computer simulation versus experiment [176], recommending a new daylighting technology for sub-tropical area. Literature [177] developed an advanced simulation model of the light tube in comparison with other visual ergonomics lighting simulation models. Other lighting simulation practices on shading control systems [178] and shape of light-shelf [179] reveal that optimization of control and shape of the shading device can improve daylight level effectively.

4.2.2. Daylight energy saving evaluation

Energy efficiency of daylight is another aspect of significance of daylighting, such that many energy simulation tools has daylight saving module integrated, and modeling energy saving effect of daylighting has been a common practice. A direct link between building energy simulation and global illumination was implemented using Radiance and ESP-r to complement lighting simulation [180]. Lighting sensor was simulated to assess office building energy-saving potential, and test the energy-saving prediction by the simulation model with the measurement of two different conditions [181]. The difference between static and dynamic conditions of shutter systems in an office building was also analyzed using EnergyPlus and MATLAB [182].

Several methods are developed for better prediction of building energy saving by utilizing daylight. A model using ideal window area was proposed [183] and applied to two cities in Britain and Brazil with VisualDOE to find the energy saving potential of daylight worldwide. A Lightsolve method was developed to emphasize the need of early synthesis design [184]. Advanced windows in the office space was proposed and simulated, in which the use of a lower luminance of the light was accepted to reduce the electricity consumption [185].

Table 4
Worldwide BIM standards.

Country/Region	BIM standards	Organization	Year
USA	BIM Guide Series	GSA	2006
	National Building Information Model Standard	National Institute for Building Science	2007
UK	AEC(UK)BIM Standard		2009
	AEC(UK) BIM Standard for Autodesk Revit		2010
	AEC(UK)BIM Standard for Bentley Building		2011
Norway	Information Delivery Manual	STATSBYGG	2009
Singapore	Singapore BIM Guide		2012
Denmark	Digital Construction	NAEC	2006
Germany	User Handbook Data Exchange BIM/IFC	Building Smart GS	2006
Finland	BIM Requirements 2007	Senate Properties	2007
The Republic of Korea	BIM Application guide in the construction field	Public Procurement Service	2010
	BIM application design guide—A Guide to 3D building design	Public Procurement Service	2010
	South Korea infrastructure industry BI basic guide book—building BIM Guide	Public Procurement Service	2010
China	Unified standard for building information model application	China Bureau of Housing and Urban-Rural Development	draft

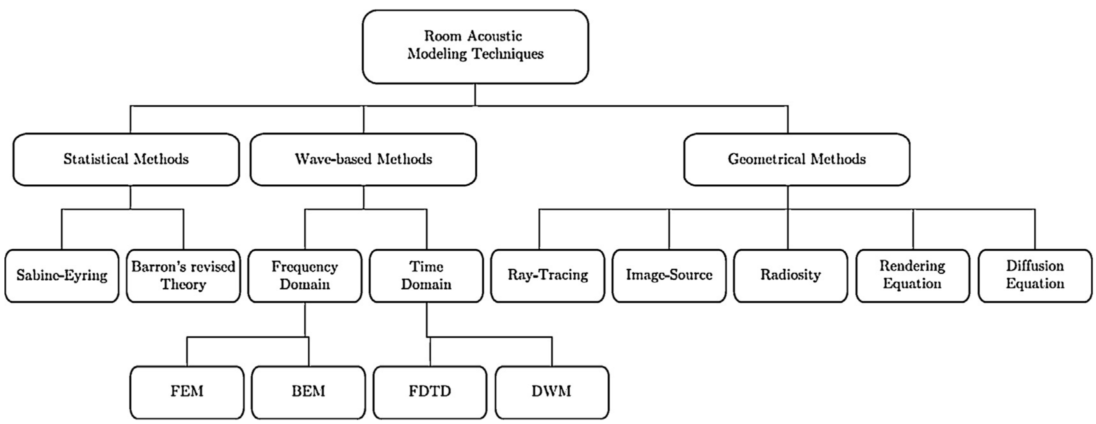


Fig. 5. Categories of different acoustic modeling approaches [204].

5. Building information modeling

5.1. Introduction and standard

The concept of building information modeling (BIM) was initially proposed in 1975 in order to realize visualization and quantitative analysis of construction projects and improve the efficiency of construction. BIM has characteristics of visualization, coordination, stimulation availability and optimization. By the mid-1990s, building model standard has been taken over by International Alliance for interoperability (IAI). The first version of industry foundation classes (IFC) was published in 1997. But these standards and building models have not been widely used in practice by that time [186]. ISO developed a series of standards from IFC to IDM and IFD. These built a foundation for BIM technology and standard. Another popular format gbXML is the de-facto industrial BIM standard in the U.S. It is being integrated into a range of CAD software and engineering tools. In contrast to IFC data schema, gbXML employs "bottom-up" schema that is simpler and easier to understand and facilitates quicker implementation of schema extension for different design purposes [187].

The success of BIM in the standard management drives people to study the importance of building information technology in the use of the standards, starting from the Nordic countries such as Finland though not broadly used. A case study of Hilton Garden Inn Springfield Hotel in Atlanta showed that in the pre-design stage due to the collision detection function of BIM, 55 collisions were detected and $124,500 was saved. The cost of BIM was $90,000. BIM also helped find 590 collisions and saved about $560,000 and 1143 h of work during the construction stage [188]. Commonly used BIM software are categorized to drawing-based, such as Autodesk Revit; specialty-based, such as Archicad (this is the first BIM construction software, introduced in the 1980s) and Tianzheng construction; management-based, such as Archibus.

STEP (Standard for the Exchange of Product Data) was initially proposed by ISO, based on IGES [189], to solve a large amount of data exchange required for manufacturing industry. Early attempts at building standardization using STEP include the global AEC (architecture, engineering, and construction) reference models and the architecture models. However, network questionnaire of BIM showed that it was not widely used, highlighting the significance of establishing a unified BIM standard [186]. A summary of BIM standards used in different countries/regions is shown in Table 4. This summary reveals that all these standards took effect after year 2006.

5.2. Models and methods

General AEC reference model (GARM) [190] and RATAS model [191] were developed with the similar concept and attributes as BIM before 1990. In 1991, DEM, which is capable of expressing design process and building information, was proposed [192]. This method attempts to accomplish a conversion between CAD systems, engineering applications and filing by using a typical pattern that includes a comprehensive engineering database. IISABRE (Intelligent Integrated System for the Analysis of Building thermal Environment) [193] is an integrated building design analysis system that enables users to draw building and define information. It is built upon CAD tool and transfers information via the STEP, IFC standard. A simulation environment suitable for the global model and the large-scale model project was introduced to use ISO standard model language and can provide users with both text and graphics simulation information [194]. An activity process model that can be used in the construction phase [195] and a parametric model that is considered as an effective model for construction of the knowledge embedded in the professional domain [196] were both introduced in 2006. In 2010, a new approach was presented for automated recognition of project 3D CAD model objects in large laser scans [197].

The biggest bottleneck in the use of online information collaborative decision-making is that it is not simple and effective enough to share and use the information [198]. The ability to deal with different BIM information of a building must solve the problem of contacts between different models [199]. A Product Information Specification (PIS) framework for information specification was introduced that can potentially enhance the quality of the results and reduce the modeling time [200]. Despite the visible advantages of using BIM as it provides new possibilities for building design and construction, risks cannot be ignored [201], including legal and technical risks [188].

BIM technology also makes it easier for life cycle cost analysis of building. Life cycle cost analysis is possible only when the whole life cycle process information needed is included into consideration, and the digital model of the non-model information is considered into the construction [202]. Vanlande [203] established a semantic indexation method based on IFC to store the life cycle information. In order to be adaptive to building management and information update, a framework CDMF is proposed for facility management.

6. Indoor acoustic simulation

Acoustic comfort in buildings is another important feature as it protects humans against adverse health effects and promotes well-being and performance such as working productivity and quality of spaces like concert halls. There is a strong interest in predicting acoustic performance of building at design stage.

Three categories of acoustic prediction methods can be distinguished, which can be used to evaluate the acoustic performance of spaces: wave-based method, geometrical acoustics method, and diffuse field method/statistical method. A comprehensive summary of categories of different acoustic modeling approaches is presented in Fig. 5 [204]. Wave-based method is capable of predicting the acoustics for the full frequency range of interest and solving sound propagation in inhomogeneous media in complex environments as in outdoor acoustics, thus attracting increased attentions in recent years [205]. Comparison shows that for rectangular shaped sports halls acoustic simulation, wave-based method is the most appropriate [206].

Time-domain method are favored for auralization purposes over frequency-domain methods. They are based on discretizing the wave equation in the time domain instead of the frequency providing a considerable accuracy, especially at low frequencies. It was proposed by Botteldooren [207]. Savioja [208] who adapted the suitability of the method to the room acoustics simulation through a finite difference time domain (FDTD) discretization of the wave equation as shown in Equation (13).

$$P_{J,k}(n) = \frac{\sum_l P_{J,l}(n-1)}{N} - P_{J,k}(n-2) \tag{13}$$

where $P_J(n)$ represents the signal (pressure or velocity) at a junction at time step n; N is the dimension, k is the position of the junction to be calculated and l represents all the neighbors of k. Indoor acoustic simulation focuses on a more accurate modeling of propagation effects and powerful numerical method is applied to indoor acoustic, such as finite element method, boundary element method in wave-based model category. Those methods require a large amount of calculation and are applied to the small size, simple structure of the internal sound field analysis and calculation.

When building geometry is complex and computation demand is high, wave-based approaches are often difficult to be applied. Statistical method provides simple formulae but the assumption of diffuse field limits the usages to some specific types of room. Geometrical acoustics method as a practical and general purpose technic draws much attentions for practical engineering use. Among various geometry method category models, commonly used in engineering applications are Ray-tracing method [209], image source method [210] and hybrid method.

Hybrid method can combine the advantages of different methods and improve accuracy of results. Vorländer [211] proposed a method for the calculation of room acoustical impulse responses. The method is based on the ray-tracing and the image-source models. With the method, the procedure of sieving the "visible" image sources out of the enormous quantity of possible sources is carried out by examination of the histories of sound particles. This method is the basis of many practical methods. A recent hybrid method for room acoustic predictions denoted as PARISM [212]. The method combines acoustical radiosity and the image source method. The predictions are validated by comparison with published measure data for a real music studio hall. The proposed model is found to be promising for acoustic predictions providing a high level of detail and accuracy.

Ray-tracing may result in the loss of reflection paths and beam tracing is an extension of ray tracing. There are intractable problems with computer models of enclosed spaces using geometric acoustic assumptions. A beam tracing method for finding image-receiver paths using triangular section beams is proposed [213]. Most current beam-tracing methods use conical or triangular beams that may produce overlaps and holes in the predicted sound field, and many methods have been proposed to revise it. Drumm [214] proposed an adaptive beam-tracing method whereby the shape of reflected beams is governed by the shape of reflecting surfaces so as to produce a geometrically perfect description of the sound propagation for halls with occluding surfaces. Results show this adaptive beam-tracing method compares well with other methods in terms of speed and accuracy. For validation purpose, a benchmark to measure the accuracy and performance of different software packages for sound field calculations was developed. Both finite element method and boundary element method provide good estimation of the measurement [215].

Indoor acoustics simulation software has typically been used for the prediction and assessment of indoor acoustics performance in the early design stage of various spaces in engineering. Various acoustic simulation software are available, such as Odeon [216], Epidaure [217], Soundplan, Raynoise, Ramsete, EASE, Cadna. As a result of continuous effort on research and development, indoor-acoustical simulation software has been quite mature for both engineering and academic application.

7. Life cycle analysis (LCA)

Sustainable development has been a global wave in the last 20 years not only in building industry, for which LCA is an effective method to evaluate environment impact of a certain industry. LCA methods have been used for product development processes in other industries for a long period of time [218], but application of this to the building sector was not started until late 1980s. Building consumes large proportion of primary energy and natural resource, resulting a great contribution of the CO_2 emission of human activity, not only in operation stage but also during construction, renovation and demolition, even design activity. As a sophisticated and holistic approach, LCA provides building industry an opportunity to act in a more proactive and preventive way for development sustainability [219].

General LCA tools/methodologies are not necessarily suitable for building evaluation, five tools/methodologies were identified in 2003 as applicable for building industry [220] as follows:

- ATHENA Sustainable Material Institute [221], by ATHENA™
- Envest [222], by BRE
- Eco-Quantum 3 [223], by IVAM
- BEAT 2000 [224], by SBI
- BEES [225], by US EPA

ATHENA developed ecoCalculator [226] and impact then Estimator around 2014 [227] to enhance the ability for existing building LCA assessment. As two well-known classification systems exist, ATHENA classification system has three levels for generic environment assessment tools [228]. BEES is categorized to level 1 as product comparison tools, while the other 4 are categorized to level 2 as whole building design or decision support tools; IEA ANNEX 31 classification system [229] classified these tools to the second class "Environmental LCA tools for buildings and building stocks" and the same level as previous categorization. Most LCA tools such as BEES, Athena, Eco-Quantum, and BEAT take a bottom-up approach, in which the software begins with the building materials themselves, assuming that the design stage has already taken place; while Envest system takes a top-down approach by starting with the building shape, then moving through material specifications, and finally construction details [230].

As a growing body of literature focus on LCA methodology applied to building industry, there are several review paper published after 2005 [231–238]. One of most up-to-date reviews [237] can be referred to obtain a detailed comprehensive overview of different models, tools and methodologies developed all over the world for LCA applied in building sector and a summary of different type of case studies. Recently, LCEA (life cycle energy analysis) and LCCA (life cycle cost analysis) were also used as the similar concept as LCA, highlighting the energy and economic aspects of building during lifetime respectively.

8. Summary

This paper presents a review on the advances of building related simulation and computation techniques between 1987 and 2014. This is a period of time that essential changes occured in the way building is designed, constructed, operated, and researched. Although fundamental work on most computational cores of building simulation has been established before this period, rapid progress of computer hardware and computing techniques starting from the 1970s greatly accelerted the progress of building simulation, especially in software tools with respect to robustness and fidelity. This observation can be corroborated by the fact that building energy simulation related tools alone counts for 123 totally as listed by IBPSA-USA, BEST directory [239]. With the growing importance of simulation playing in building industry, the attention and effort on improving and expanding building simulation capacity and accuracy and speed by academia keeps growing.

The review covers several of main aspects of building physics simulation techniques, including indoor air, building load and energy consumption, lighting and daylighting, BIM, acoustics and LCA. Though not covered in this review, there are many other significant developments and advances in building simulation community, such as building control system, model calibration, uncertainty quantification, and urban scale simulation. A visible trend found in various topics is that coupling simulation draws great effort and attention, such as coupling of building indoor environment and energy simulation, airflow and energy, daylighting and energy; coupling between well-mixed assumption model and detailed distribution model. Such a coupling effort is mainly to evaluate the comprehensive performance of building as a whole. As components and aspects of a building are closely connected and integrated with each other, simulation and computation should be able to handle such complexity and provide holistic data for decision making.

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