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Review Article

Advances in Modeling and Simulation Tools

DeST 3.0: A new-generation building performance simulation platform

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Abstract

Buildings contribute to almost 30% of total energy consumption worldwide. Developing building energy modeling programs is of great significance for lifecycle building performance assessment and optimization. Advances in novel building technologies, the requirements of high-performance computation, and the demands for multi-objective models have brought new challenges for building energy modeling software and platforms. To meet the increasing simulation demands, DeST 3.0, a new-generation building performance simulation platform, was developed and released. The structure of DeST 3.0 incorporates four simulation engines, including building analysis and simulation (BAS) engine, HVAC system engine, combined plant simulation (CPS) engine, and energy system (ES) engine, connected by air loop and water loop balancing iterations. DeST 3.0 offers numerous new simulation features, such as advanced simulation modules for building envelopes, occupant behavior and energy systems, cross-platform and compatible simulation kernel, FMI/FMU-based co-simulation functionalities, and high-performance parallel simulation architecture. DeST 3.0 has been thoroughly evaluated and validated using code verification, inter-program comparison, and case-study calibration. DeST 3.0 has been applied in various aspects throughout the building lifecycle, supporting building design, operation, retrofit analysis, code appliance, technology adaptability evaluation as well as research and education. The new generation building simulation platform DeST 3.0 provides an efficient tool and comprehensive simulation platform for lifecycle building performance analysis and optimization.

Keywords

DeST,
building performance,
simulation,
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1 Introduction

1.1 The importance of building energy modeling programs

Currently, building energy consumption accounts for 30% of the total worldwide energy consumed and continues to grow rapidly with the increase in economic development and living standards (Jiang et al. 2018; IEA 2019; Cabeza et al. 2022). Buildings play an important role in addressing climate change; therefore, the reduction of building energy consumption and carbon emissions has been attracting increasing research attention in recent years (Zhang et al. 2021), which requires the proper utilization of energy-saving technologies in newly built buildings and the implementation of energy-saving reconstruction in existing buildings (Hu et al. 2020a,b). Therefore, because of the complexity of building energy modeling, building energy modeling programs (BEMPs) (Zhu et al. 2013) are essential for designers and engineers to optimize their design and operation in real applications and thus achieve low energy goals in the building industry.

Building energy modeling technology is an essential component of the computer-aided design phase (Yan et al. 2008). The suitable chiller selection could promote significantly the efficiency of HVAC system while it was difficult to improve the performance of energy system if the equipment selection was too large or small. When constructing new types of buildings, such as stadiums, transportation hubs, and large office buildings, energy system design is indispensable for the future operation phase. The building thermal process can be simulated during the building energy modelling procedure, and the most adverse conditions may be located for adjusting the design.

Building energy modelling technology is important for building energy system operators. Although the construction equipment has been fixed, the building energy consumption depends on weather conditions (Gui et al. 2021), occupant behavior (Jin et al. 2021a) and other uncertain parameters (Tian et al. 2018). Different system operation patterns can be determined based on the building energy modeling analysis for different usage modes and heat disturbances.

Building energy modeling technology can reduce the cost of building an energy-saving retrofit. Different retrofit schemes can be compared before construction, which reduces the errors in empiricism and the cost invested in construction. When evaluating the adaptability of a new energy-saving technology (Bu et al. 2022), building energy modeling can also supply reliable simulation analysis to reduce the number of experimental schemes.

Building energy modeling has played a growing role in the development of low-energy, high-performance buildings and in achieving the goal of reducing energy use and greenhouse gas emissions in the building sector (Clarke 2007). BEMPs have been widely and successfully used to: (1) evaluate design alternatives during the design of energy-efficient envelopes and heating, ventilation, and air-conditioning (HVAC) systems for new buildings (Østergård et al. 2016); (2) optimally manage, operate, and control building equipment systems for existing buildings (Wei et al. 2014); and (3) evaluate energy-saving retrofit measures of existing buildings (Azevedo et al. 2021). Overall, BEMPs are increasingly being used throughout a building's lifecycle for the analysis and prediction of building energy consumption, measurement and verification, carbon evaluation, and cost analysis of energy-saving measures. In addition, with the rapid advancement of global energy saving and carbon reduction work, BEMPs will play a bigger and more basic role in the building sector and provide support for policy making and development planning in the future (Huang et al. 2017).

1.2 The development of BEMPs

To solve the basic problem in building performance analysis, building energy modeling has developed rapidly worldwide since the 1960s (Clarke 2007). Over 100 BEMPs have been developed to support policymaking, project design, and scientific research (Zhu et al. 2013). In general, these can be classified into three categories.:

- **Independent simulation programs**

BEMPs that have been continuously developed and widely accepted and used in the building industry include ESP-r (Strachan 2000; Strachan et al. 2008), DOE-2 (LBNL and Hirsch 2004), EnergyPlus (Crawley et al. 2001), TRNSYS (TRNSYS Group 2022), IES<VE> (Qu et al. 2014), and DeST (Yan et al. 2008). These programs have an independent simulation kernel that enables them to operate independently without calling for other programs. Some tools consist of graphical user interfaces (GUIs), such as IES<VE> and DeST, while others use general-purpose scripting languages accompanied by a suite of programming features and libraries (for example, EnergyPlus). Through the dynamic simulation of heat and mass balance and building systems, building performance and energy use can be estimated. One group of programs, TRNSYS, SPARK (Obst and Rollmann 2005), and HVACSIM+ (Clark and May 1985), is mainly used to simulate the control process of HVAC systems; thus, they adopt a simplified heat and mass balance model for rooms/zones, and a precise and complex system model to present the rapid dynamic response of each component under various control strategies. Another group, ESP-r, EnergyPlus, and DeST, mainly focuses on the long-period dynamic thermal performance of buildings and systems; therefore, they use a complete room/zone model and simplified system model, which are more suitable for simulating the operational energy consumption of buildings during the entire year.

- **Software based on a simulation kernel**

This type of software (for example, DesignBuilder, OpenStudio (Roth et al. 2016), eQUEST (Hirsch 2022)) needs to call other individual simulation kernels to conduct building performance simulations, but has the advantages of being simple and easy to use, user-friendly, and able to offer a quick combination of design options, which is appropriate for designers and engineers to use in the building industry. Among these programs, DesignBuilder and OpenStudio (using EnergyPlus as kernel for its free, open-source, and cross-platform characteristics) is the most popular simulation software, followed by eQUEST (using DOE-2 as kernel), PKPM (using DeST as kernel), etc. These programs support users to establish building models in an easier way, then translate them into specialized models for the corresponding simulation kernel, and eventually carry out building performance simulation and results analysis.

- **Individual modules integrated with other software for certain function**

In recent years, an increasing number of new materials and technologies have been adopted in buildings to reduce energy consumption, such as double-skin facades (Wang et al. 2019, 2020), phase change walls (Liu et al. 2018), and passive radiative cooling (Zhao et al. 2019), which require more precise and specialized modules to achieve co-simulation between BEMPs and individual modules. In addition, with the increase in the understanding of building performance simulations, numerous researchers have developed a variety of modules related to climate, occupant behavior, building envelopes, and HVAC equipment.

1.3 The concept of DeST

“Designer’s simulation toolkit”, or DeST, has been developed continuously since 1989 by Tsinghua University (Yan et al. 2008). Initially, it was developed for the building thermal environment simulation and was referred to as the building thermal process (BTP) before 1989. The HVAC system simulation modules were added to the BTP to become an integrated building performance simulation tool, referred to as IISABRE (Hong et al. 1997; Hong and Jiang 1997). To serve various stages in the practical design process and to apply the simulation technique to a real project, DeST was developed in 1997 based on IISABRE. Subsequently, a structured map of DeST development was established. DeST 1.0 version was completed and released in 2000. From 2001 to the present, DeST 2.0, which contains various versions for different applications (for example, DeST-h for residential building simulation and DeST-c for commercial building simulation), has been continuously developed. Compared with the DeST 1.0 version, the DeST 2.0 version has greatly improved in the areas of user interface, program robustness, and general data interface. In 2019, DeST 2.0 successfully passed the ASHRAE-140 standard test and was regarded as a qualified software for calculating commercial building tax reductions. Since 2008, the frame of DeST 3.0 has been in the process of being developed. This separated it from the limits of the AutoCAD and Windows systems, increased its speed to support more complicated simulations of buildings, and simplified its use for users to build in their own plug-ins and support more new building components and building systems. The first version of DeST 3.0 was released in 2021. The history and milestones of DeST research and development are shown in Figure 1.

With over 10,000 users in China, Japan, Europe, and the USA, DeST has been adopted by more than ten national/regional energy-saving standards for research and evaluation of building energy simulation. It has been used to analyze building energy conservation in vast building projects over 200 million m^2, including the National Grand Theater, Beijing Capital Airport Terminal 3, Beijing Daxing International Airport, Beijing Olympic Main Stadium, and Beijing Winter Olympic Main Stadium, leading to remarkable economic and environmental benefits in building energy in China.

2 Issues and challenges

Building energy modeling programs plays an important role in scientific research and engineering applications in the field of urbanization, in the context of informatization and intelligence. It predicts and analyzes the actual performance of building design and energy-saving measures, which is the key foundation for realizing energy-saving construction in the entire process, starting from the source. Over the past 50 years, BEMPs have been applied for design consultation in many projects, including building design, HVAC design. BEMPs have been widely used in the energy-saving design of many major projects, solving the difficulties of energy-saving calculations and design optimization in the complex design of large projects. The applications of BEMPs involve several main fields: building design consultation, building environment commissioning, building energy conservation assessment, building energy labeling systems, and scientific research. According to the search results of research papers in the field of building energy consumption by the Web of Science, more than 4000 research papers in the past 5 years have applied BEMPs for research.

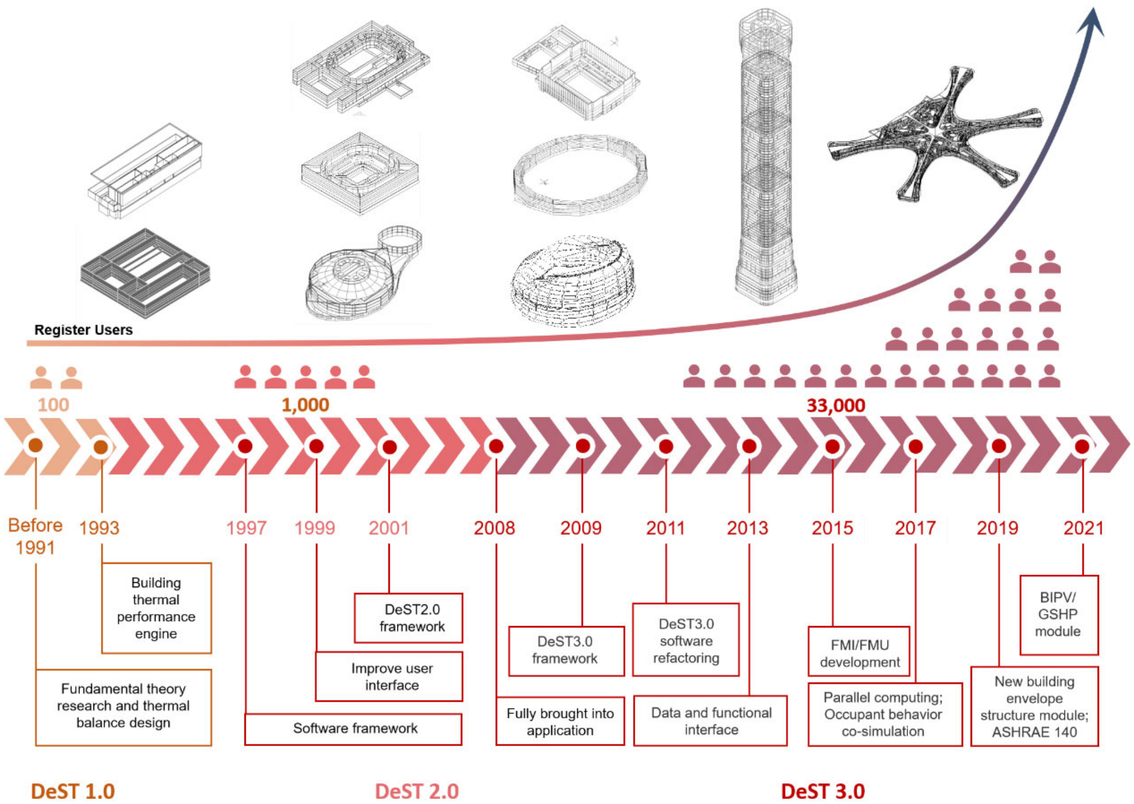


Fig. 1 The history of DeST research and development

However, considering social concerns, such as carbon reduction and climate change, it is difficult for existing software cores to meet the needs of comprehensive performance analysis of buildings and their environmental control systems in the presence of many influencing factors and complex operating conditions. Therefore, as shown in Figure 2, the following challenges currently exist in the field of building energy-consumption simulations.

- **Capability**

New enclosure structures, planted roofs, and complex spatial forms continue to emerge. At present, the basic assumptions of constant physical properties and lumped parameters commonly used in simulation software are often not applicable, which results in higher requirements for building simulation technology. Occupant behavior is one of the main factors that affects building energy consumption and causes large deviations in operating results and design values (Wang et al. 2011; Zhou et al. 2021b). However, owing to the significant randomness and complexity of occupant behavior in buildings and the huge differences in occupant behavior between individuals, it is impossible to use a fixed schedule to simplify the description of it (Zhou et al. 2022b). Therefore, it is necessary to develop a simulation method adapted to the characteristics of occupant behavior in different regions, so that the calculation results of the simulation software are more in line with the actual situation (Yan et al. 2017).

- **Calculability**

In the energy-saving design and optimization simulation of the electromechanical system, the control and adjustment time inertia of the electromechanical system is small, while the time inertia of the building envelope is large; therefore, it is necessary to coordinate the inconsistency of the two in the calculation of the annual energy consumption (Clarke and Hensen 2015). However, there are more diverse forms of cooling/heating sources, and an increasing number of renewable energy sources are being used in buildings, such as heat pumps, combined heat and power, and solar photovoltaics. The simulation of the electromechanical system should accurately reflect the control and adjustment process and energy consumption level of the actual system, as well as the analysis and application of renewable energy (Fan et al. 2021). Simultaneously, with the increasing complexity of building energy consumption simulation and building volume in actual projects, the traditional single-core single-platform simulation computing core can no longer meet the current growing demand for simulation computing. Therefore, it is necessary to significantly improve the calculation speed of the simulation core through high-performance computing algorithms for building full-performance simulations.

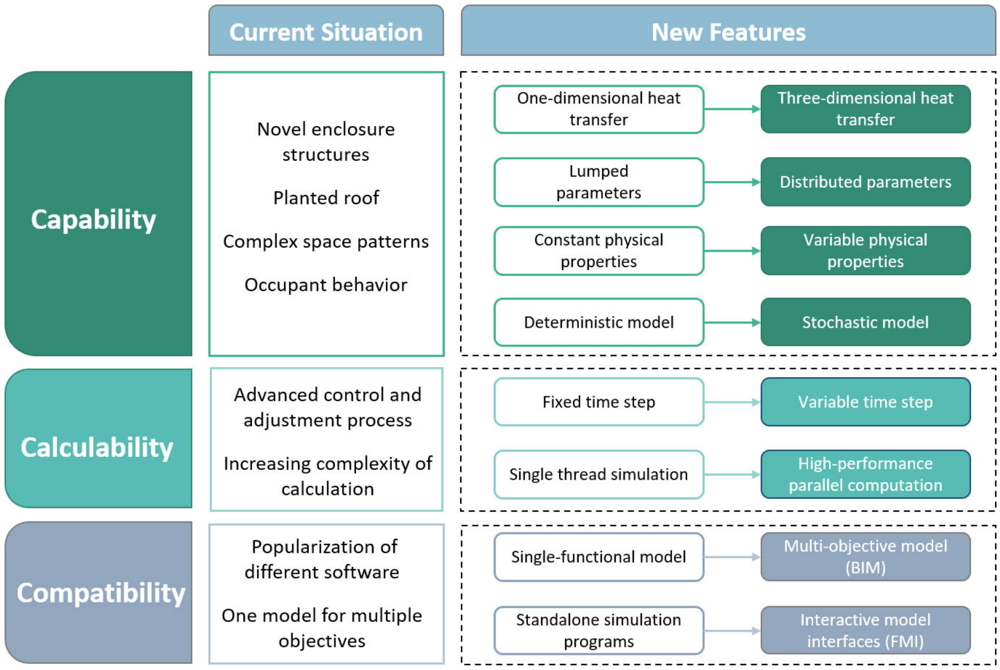


Fig. 2 Main challenges in the field of building energy simulations

- **Compatibility**

The continuous popularization of different commercial software, the wide range of requirements in the process of building design and operation, and the geometric complexity of the actual building increase the workload of the modeler. At the same time, to meet the needs of different simulations, such as building energy consumption, indoor light environment, and acoustic environment, there is an urgent need for simulation software that can realize multipurpose computation based on a single model (Bürgy et al. 2020), to greatly improve the efficiency and accuracy of modeling work. Therefore, it is necessary to achieve breakthroughs in general integrated applications through methods such as BIM and data dictionaries (Delavar et al. 2020), to realize the seamless integration of the platform kernel and different commercial software, and then promote the application of building simulation technology to practical engineering. In addition, with the development of data technology, the quality and versatility of data in the building simulation process play an important role in its efficient application. The standardization of building data and the generalization of collection, transmission, and storage paths have become important bases for the application and promotion of current building simulation software in different scenarios.

3 DeST 3.0 structure

The overall structure of the DeST is shown in Figure 3. Building thermal performance calculation is realized by building analysis and simulation (BAS) engines, which can perform calculations for indoor air temperatures and cooling/heating loads for buildings based on the state-space method. Considering the HVAC system, the HVAC system engine is applied to simulate the indoor temperature under different types, sizes, and control modes of terminal equipment (for example, air-handling units [AHUs] and fan coil units [FCUs]). The HVAC system engine is also connected to HVAC plants such as chillers, heat pumps, boilers, and water pumps. A combined plant simulation (CPS) engine can perform detailed calculations of plant performance considering the impact of terminal equipment. The energy system (ES) engine can conduct other energy components in buildings, such as BIPV, DHW, mechanical ventilation, and elevator systems. An economic analysis was also conducted for the ES engine. An important feature of DeST is that each system can be executed repeatedly to converge before interacting with the other systems. For example, the room heat balance in the BAS system can be calculated repeatedly before transmitting the air temperature to the system module, which remains the same when executing water system calculations. The entire process is similar to a loop calculation that includes both the air and water loop sides.

With the development of building technology and building simulation approaches, many new features have been developed in DeST 3.0 to address different simulation purposes (Table 1), such as heat and mass balance simulation of new envelope materials (that is, PCW, double-skin envelope, aerogel glass, and planted roof), occupant behavior modeling,

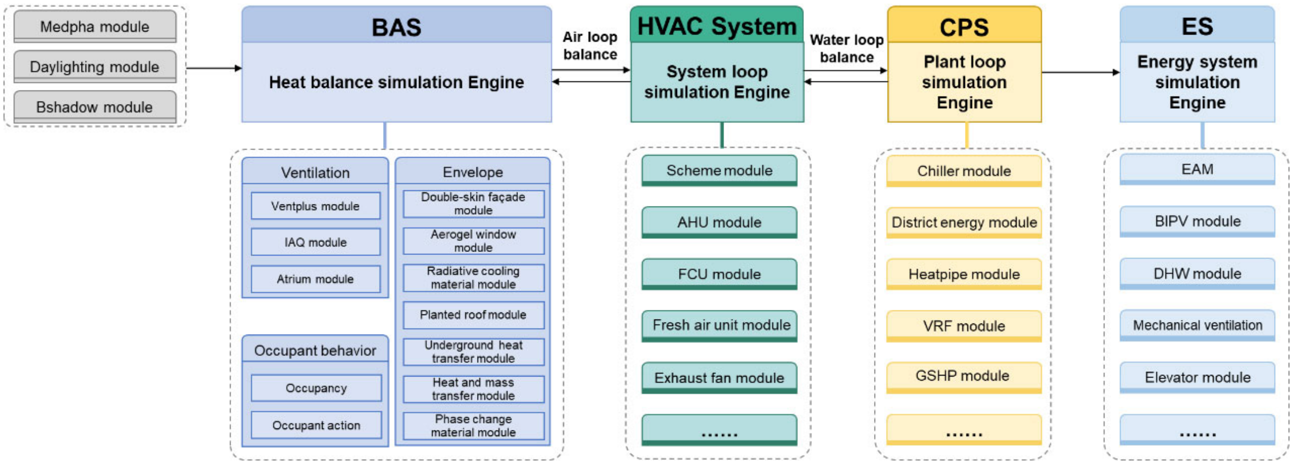


Fig. 3 The structure of DeST 3.0

Table 1 Major modules in DeST 3.0

Engine	Module	Description	Reference
Input engine	Medpha	Providing local meteorological parameters	Cui et al. 2017; Guo et al. 2020; Zhou et al. 2022a
	Daylighting	Providing daylighting calculation	Luo et al. 2015; Dong et al. 2021
	Bshadow	Providing shadow calculation	Yan et al. 2008
BAS engine: ventilation	Ventplus	Providing ventilation balance calculation	Zhou et al. 2021a
	IAQ	Providing indoor air quality evaluation	Yan et al. 2008
	Atrium	Providing thermal process calculation in atrium	Qin et al. 2012; Lu et al. 2019, 2021; Li et al. 2020; Lu et al. 2020a,b; Man et al. 2020
BAS engine: occupant behavior	Occupancy	Providing calculation of occupant movement	Jin et al. 2021b
	Occupant action	Providing calculation of occupant action	Wang et al. 2016
BAS engine: envelope	Double-skin facade	Providing calculation of double-skin facade	Wang et al. 2019, 2020; Wang et al. 2021
	Radiative cooling materials	Providing calculation of radiative cooling materials	Bu et al. 2022
	Planted roof	Providing calculation of planted roof	Zhang et al. 2019a
	Underground heat transfer	Providing calculation of underground heat transfer	Kang et al. 2022
	Phase change material	Providing calculation of phase change material	Liu et al. 2018
	Hygrothermal transfer	Providing calculation of combined heat and mass transfer	Dong et al. 2020; Fang et al. 2020, 2021
HVAC System engine	Scheme	Providing calculation of air-condition system	Yan et al. 2008
	AHU	Providing calculation of air-handling unit	Yan et al. 2008
	FCU	Providing calculation of fan coil unit	Yan et al. 2008
	Fresh air unit module	Providing calculation of fresh air unit	Yan et al. 2008
	Exhaust fan unit module	Providing calculation of exhaust fan unit	Yan et al. 2008
CPS engine	Chiller module	Providing calculation of chiller operation	Yan et al. 2008
	District energy module	Providing calculation of district energy	Clustering and statistical analyses of air-conditioning intensity and use patterns in residential buildings
	GSHP	Providing calculation of ground source heat pump system	Qian et al. 2020
	Heatpipe	Providing calculation of heat pipe	Yan et al. 2008
	VRF	Providing calculation of variable refrigerant flow system	Qian et al. 2021
ES engine	EAM	Providing economic analysis	Yan et al. 2008
	BIPV	Providing calculation of building integrated photovoltaic	Lan et al. 2020; Lovati et al. 2021
	DHW	Providing calculation of domestic hot water system	Feng et al. 2017

and performance simulation of renewable energy systems, which are specified in detail in the following sections. Additionally, the impact of surrounding buildings can be solved based on geometric projection principle in Bshadow module. If users want to consider the impact of surrounding buildings, shading module must be operated in advance in order to determine the reduced solar radiation on building surfaces.

4 New features in DeST 3.0

Table 2 summarized the limitation in past version. Also, research efforts and new features of DeST 3.0 were included in the Table 2. In general, DeST 3.0 broadened the usage scenarios and functions in order to adapt to the developing new materials and simulation tasks.

4.1 Advanced simulation modules for building envelopes, occupant behavior, and energy systems

Building envelopes and energy systems are critical components that affect building energy performance (Kheiri 2018). With the development of innovative building materials and technologies (Fan et al. 2021), advanced building envelopes, complex spatial structures, and novel renewable energy systems (Foucquier et al. 2013) are emerging in buildings to reduce energy consumption and carbon emissions. Detailed simulations of the transient heat transfer process of elements with variable physical properties and nonlinear features are major challenges in current BEMPs. Moreover, occupant behavior has proven to be one of the most essential factors determining building energy consumption (Yan et al. 2015), due to its remarkable randomness and diversity (Hong et al. 2017). Thus, the definition of occupants' energy-related behaviors and simulation of occupant-building-system interactions are also significant challenges for the accurate modeling of building energy performance (Yan et al. 2017). Therefore, the development of advanced simulation modules for building envelopes, occupant behavior, and energy systems is essential to enhance the functionalities of BEMPs.

In DeST 3.0, various simulation modules for advanced building envelopes were extended and integrated. These modules are based on an in-depth thermodynamic analysis, solution algorithms, and numerical calculations for the heat and mass transfer processes of such elements. Advanced modules, including daylighting and shading (Luo et al. 2015), airflow in atriums (Lu et al. 2019, 2021; Lu et al. 2020a,b; Man et al. 2020), phase change materials (PCM) (Liu et al. 2018), aerogel glazing systems (Zheng et al. 2020), double skin facades (DSF) (Wang et al. 2019, 2020), plant-embedded walls (PEW) (Zhang et al. 2019a), hygrothermal transfer modeling (Dong et al. 2020; Fang et al. 2020, 2021), spectrum-selective radiative cooling membranes (Bu et al. 2022), and three-dimensional underground heat transfer (Kang et al. 2022), have been successfully developed and integrated into the DeST 3.0 framework through the Functional Mock-up Interface/Units (FMI/FMU) interface (introduced in Section 4.3). The accuracy of each module was verified by comparing the simulation results with the analytical solutions, simulation solutions from other technical software, and experimental results.

The occupant behavior (OB) modules have also been developed in DeST 3.0. The OB modules include the occupancy and occupant action modules (Jin et al. 2021a). The occupancy module was proposed by Wang et al. (2011) based on the Markov chain, which simulates the occupant movements among the spaces inside and outside the buildings. It may also generate an array of occupant number in buildings or zones (Jin et al. 2021b; Wei et al. 2019a; Kang et al. 2021). Occupant action modules have been proposed with an environment and event-driven stochastic infrastructure based on a three-parameter Weibull distribution (Wang et al. 2016). The instances of occupant action modules include occupant shading behavior modules (Li et al. 2021), window opening behavior modules (Pan et al. 2019; Wei et al. 2019b), lighting behavior modules, and AC/heating control behavior modules (Zhu et al. 2021; Zhou et al. 2021c).

Table 2 Limitations in past version and new features in DeST 3.0

Limitations	Research efforts and enhancement	New features	New use cases
Linear and constant physical property	Restructure of state space method	Three-dimensional heat transfer; Distributed parameters; Variable physical properties; Stochastic model	Spectral-selective radiative cooling materials; Plant-embedded roof; Phase change materials; Underground heat transfer; Double skin facades; Hygrothermal transfer modeling
Fixed platform	FMI/FMU; Open sources	Multi-objective model; Interactive model	
Calculation efficiency	Multi-thread simulation	Variable time step; High-performance parallel computation	

All stochastic OB modules have been developed from real observed OB data (Feng et al. 2015) and have been verified from a hypothesis testing perspective to ensure their validity in practical applications.

The energy system modules were also developed and integrated into DeST 3.0. Traditional water-loop and air-loop simulations of HVAC systems have been refined with equivalent room and building architectures that characterize the time-average thermal state of individual rooms and the whole building, aiming for coupled simulation of rooms with AHUs/FCUs, as well as buildings with cooling/heating plants. For renewable energy systems, the BIPV module was developed to simulate building-integrated photovoltaic systems, which characterize the coupled thermal-electric process with PV panel installations along with panel shadings and air gaps (Lan et al. 2020). The GSHP module was developed to simulate the thermal process of buried tubes under soil and heat exchangers in the plant for ground source heat pumps (Zhang et al. 2019b; Qian et al. 2020). The current renewable energy system modules have been incorporated into DeST 3.0 framework for energy consumption simulation and evaluation.

Figure 4 illustrates a sketch of the current simulation modules incorporated in DeST 3.0 for advanced building envelopes, occupant behavior, and energy systems.

4.2 Cross-platform, compatible, and open structure of DeST 3.0 kernel

Traditional DeST 2.0 program is bound by the AutoCAD platform, which makes it easy to build models through a graphical interface and adapt to the requirements of designers and engineers. However, the hard connection of DeST to AutoCAD makes it incompatible with other software and restricts the possibility of cross-platform and high-performance computation. Moreover, the use of the Access database limits compatibility and reduces computational efficiency. The increasing computational demand requires a cross-platform, compatible, and open structure of the DeST kernel.

The new kernel of DeST 3.0 has been refactored with a new internal structure and ecology. Figure 5 presents the new structure of the DeST 3.0 kernel. The input and output of the new kernel are both designed and built upon a new data structure based on SQLite, which makes the kernel compatible with diverse platforms and programming languages. The input database could be generated from various graphical modeling software, including BIM modeling tools, the original CABD for DeST 2.0 based on AutoCAD, and other software, under the same model definition protocol called the input data dictionary (IDD). The introduction of

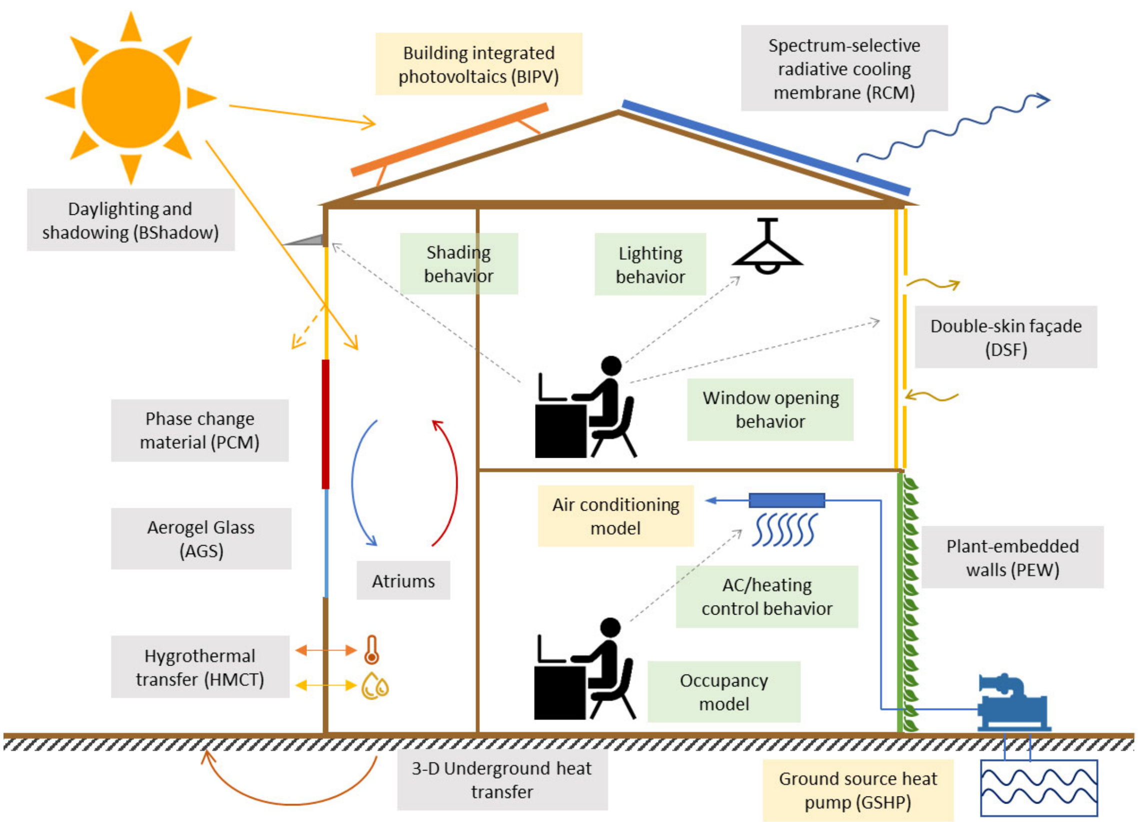


Fig. 4 Sketch of advanced simulation modules in DeST 3.0

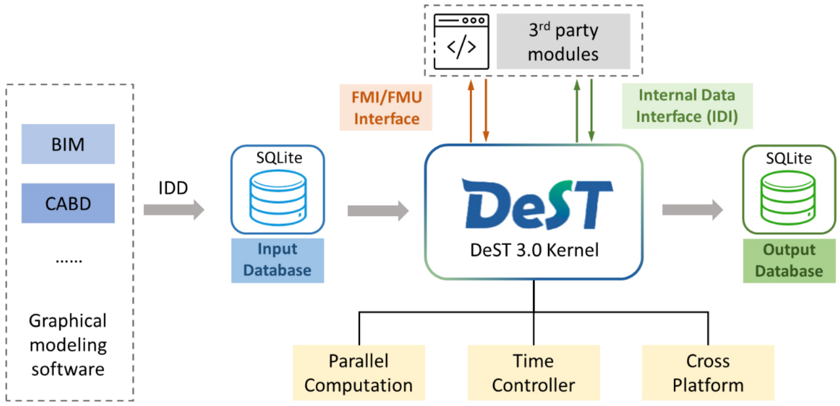


Fig. 5 The structure of DeST 3.0 kernel

IDD in the structure of DeST kernel allows the modelers from BIM and other platforms to import existing models into DeST 3.0. A conversion tool is developed for users to convert BIM model files (IFC, gbXML, etc.) into input model files that follow DeST's specific IDD definitions and dictionaries, thus improving the overall interoperability of the kernel. The outputs of DeST are also stored in an SQLite database with a pre-defined data structure. The original data file can then be transferred into various types of result reports with a set of templates. The DeST 3.0 kernel enables integration and co-simulation with other 3rd party modules via either the FMI/FMU interface (introduced in Section 4.3) or the internal data interface (IDI). The FMI/FMU interface follows a universal data exchange protocol and provides high-level interfaces, whereas the IDI is generally a base-level functional interface for programmers with more flexible and complicated functions, making DeST 3.0 an open platform for customized simulation requirements.

The new DeST 3.0 kernel has offered new features, including parallel computation (introduced in Section 4.4), the time controller, and cross platform. The introduction of the time controller constructs a dynamic data structure and stepwise simulation mechanisms that enable user-defined time intervals for building energy simulation. The highest temporal resolution for the current simulation kernel is a 1-second interval. The cross-platform functionality benefits from the refactoring of the kernel based on C++11 and the introduction of the portable MySQL database. The DeST 3.0 kernel now runs independently without relying on the MS Access database and the AutoCAD platform. The DeST 3.0 kernel can also be compiled and run on current mainstream operating systems, including Windows, Linux, and MacOS, which further improves its compatibility.

4.3 Co-simulation functionality based on FMI/FMU

Building thermal process simulation is a fundamental module for many advanced simulation requirements, such as PCM and DSF. The co-simulation of external functional modules with thermal process simulation kernel is of extensive significance. This requires iterative runtime data exchange, as well as a coordinated modeling of external modules and thermal process simulation kernel.

DeST 3.0 kernel enables co-simulation based on its internal data interfaces. The current co-simulation framework builds upon the internal data interface and follows the FMI/FMU protocol, which is a widely adopted co-simulation interface. The FMI/FMU-based co-simulation framework follows the master-slave mode, with the DeST kernel operating at the master stream and loading FMU modules at the slave stream for initiation, data exchange, and solution. DeST allows any legal compiled functional libraries (.dll in Windows or .so in Linux) to integrate with kernel. Users of other coding languages could use corresponding packages to building functional libraries and integrate with DeST kernel efficiently.

Three FMI interfaces were developed for co-simulation with third-party simulation modules: Envelope FMI, AC FMI, and OB FMI, as shown in Figure 6.

The Envelope FMI was designed for the co-simulation of the heat transfer process of opaque and transparent building envelopes such as walls, roofs, floors, and windows. This interface passes the inner-surface temperature and solar radiation intensity to the DeST kernel and receives the simulated room air temperature and equivalent radiation temperature from the DeST kernel.

The OB FMI was designed for OB modeling (Hong et al. 2016). This interface passes OB parameters such as occupancy schedules and occupant energy-related actions to the kernel, while receiving environmental variables such as temperature, CO_2 concentration, and PM2.5 concentration for OB modeling.

The AC FMI was designed for the thermal process co-simulation of the AC with rooms. The AC module passes the cooling/heating energy loads to the room in the DeST and receives the room air temperature in return for the

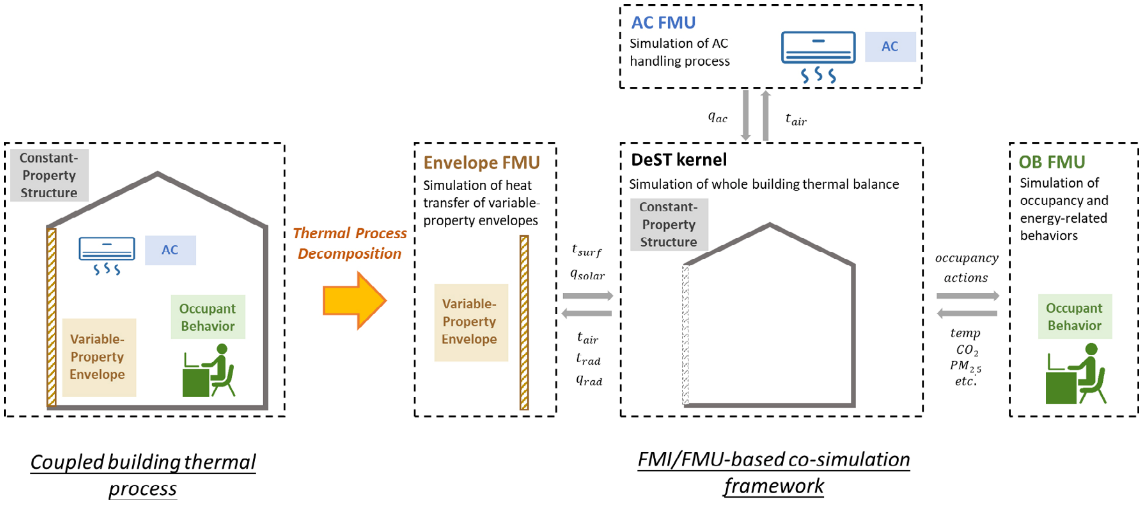


Fig. 6 The co-simulation framework of DeST based on FMI/FMU

simulation of the FCU, AHU, etc.

Various functional third-party modules are integrated with the DeST kernel under the FMI/FMU co-simulation framework. The current FMU instances are listed in Table 3.

4.4 High-performance simulation based on parallel computation

The increasing complexity of building structures has brought tremendous challenges to building performance simulation in terms of computational speed. Improving the computational efficiency is of vital importance for the simulation of both single complex building and building sets with massive number of cases.

The DeST 3.0 kernel enables high-performance computation based on the refactoring of the kernel and integration of parallel computation (Figure 7). The kernel was rewritten and compiled under the C++11 standard, and redundant functions were removed from the original software infrastructure. Moreover, parallel computation is realized based on the decomposition of the thermal process functionalities. During the preparation phase, the calculation of the building shadow was parallelized by assigning shadow modeling of different sunlight directions to different CPU cores. For the stepwise thermal process modeling, instead of between-room parallelization of thermal balance calculation, the calculation is parallelized by assigning the modeling task of different rooms to different CPU cores because the DeST kernel conducts room-based simulation. Parallelization based on the decomposition of the thermal process functionalities enables substantial improvements in the computational speed of the DeST kernel.

Parallelization is achieved in two ways: multi-thread parallelization and multi-process parallelization. Multi-thread

Table 3 List of FMU instances in DeST 3.0

No.	FMU module	FMU description	FMI applied	FMI description
1	shadowFMU	Co-simulation of building shadows and indoor working plane illumination	Envelope FMI	Co-simulation interface for heat transfer process of building opaque and transparent envelops
2	atriumFMU	Co-simulation of atriums with surrounding rooms		
3	pcmFMU	Co-simulation of phase change materials		
4	dsfFMU	Co-simulation of double skin facade		
5	agsFMU	Co-simulation of aero gel glasses		
6	chmtFMU	Co-simulation of hygrothermal transfer		
7	pewFMU	Co-simulation of plant-embedded walls		
8	ob_acFMU	Co-simulation of AC setpoint and control behavior	OB FMI	Co-simulation interface for occupancy and occupant energy related behaviors
9	ob_winFMU	Co-simulation of window opening and air purifier behavior		
10	ob_shadeFMU	Co-simulation of shading behavior		
11	fcuFMU	Co-simulation of fan coil units (FCU)	AC FMI	Co-simulation interface for air-conditioning
12	ahuFMU	Co-simulation of air handling units (AHU)	AC FMI	Co-simulation interface for air-conditioning

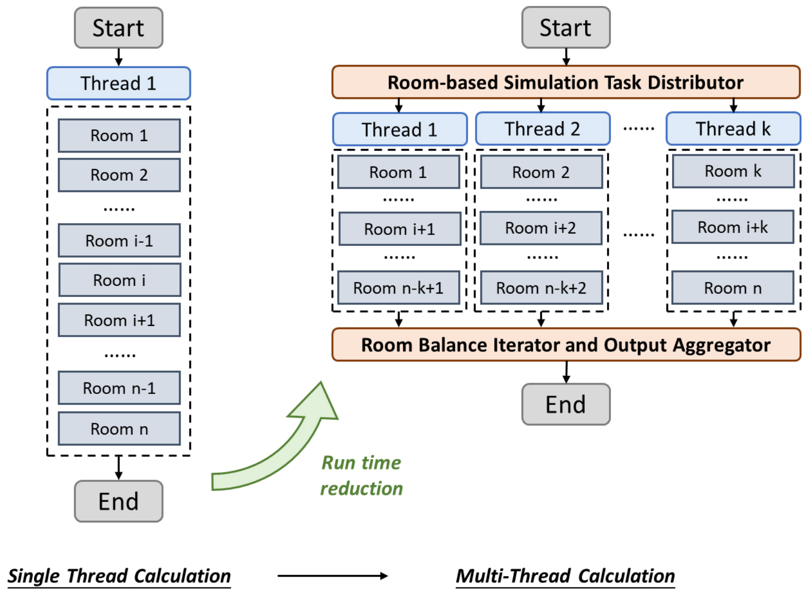


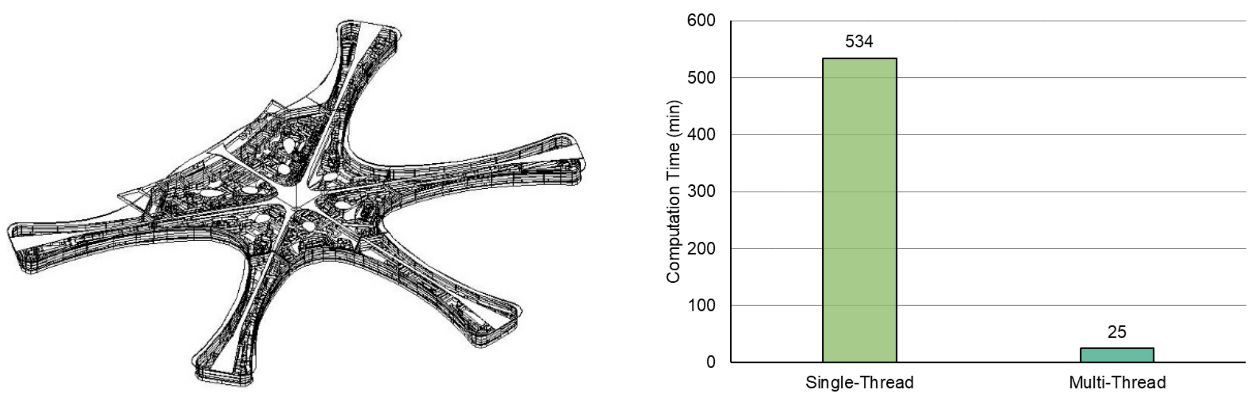
Fig. 7 Illustration of high-performance parallel computation of DeST

parallelization targets the utilization of different cores on a single machine. Using the ThreadPool technique, different simulation functionalities were assigned to different cores of the same CPU when simulating a single case, thus significantly improving the computational speed. In the case of simulating the energy performance of Beijing Daxing International Airport, with a gross area of 1.4 million m^2 and more than 24,000 surfaces and elements, the multi-thread parallelized high-performance DeST 3.0 kernel could finish the whole-year performance simulation in 25 minutes, 21 times faster than the original DeST 2.0, which takes almost 9 hours (shown in Figure 8).

Multi-process parallelization focuses on the simulation of a massive number of building cases and is especially applicable for urban-scale building energy modeling. Multi-process parallelization is based on the MPI technique and coordinates computational resources from different machines to simulate cases simultaneously in a local server group. Considering the example of simulating all 190,000 buildings in Beijing City, the multi-process DeST 3.0 simulation platform achieves a speed improvement of 169 times on a 220-core server group compared to the single-core DeST 3.0 kernel (shown in Figure 9).

5 Verification of DeST 3.0

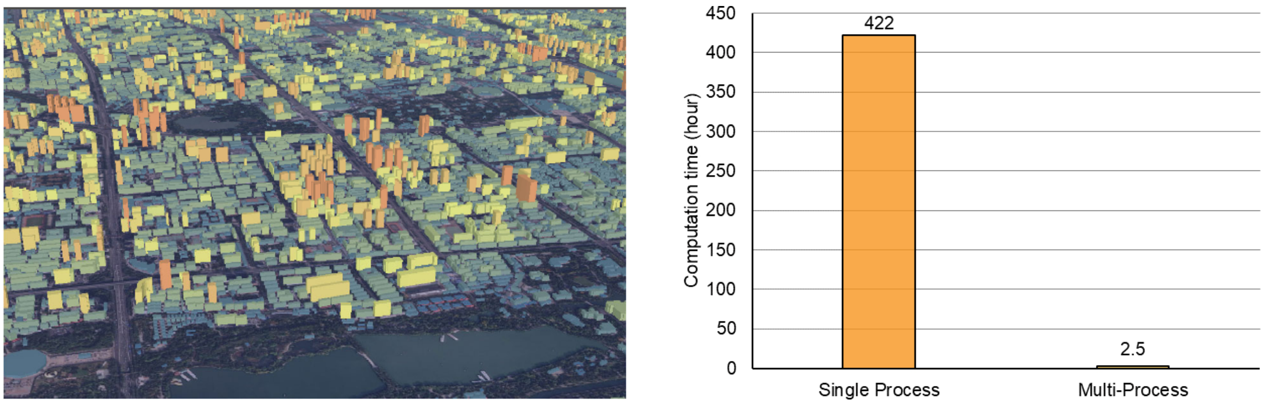
The question of how to ensure that the results given by BEMPs accurately reflect the actual simulation objects remains. This question has been discussed previously in the field of building thermal simulation. This question was raised when the BEMPs appeared in the early 1970s. For this reason, experimental buildings have been specially



(a) The energy model of Beijing Daxing International Airport

(b) The comparison of computation time of single thread and multi-thread modeling

Fig. 8 Simulation results of multi-thread parallel computation (the computation environment of the result is: CPU i7-3770, 3.7 GHz, 4 core, RAM 16 GB, Windows 10 system)



(a) The 3D energy model of 191,615 buildings in Beijing city

(b) The comparison of computation time of single process and multi-process modeling

Fig. 9 Simulation results of multi-process parallel computation (the computation environment of the result is: CPU E5-2403v2, 1.8 GHz, 220 cores, Linux system)

constructed in the United States, Canada, Japan, and other places for testing, and it is expected that BEMPs can be verified. However, it was found through experiments that the measured and simulation results were always difficult to match. Later studies found that because the thermal conditions of buildings are affected by many factors, and it is difficult to accurately measure all of them, it is impossible to carry out rigorous test comparisons with actual buildings.

To verify the correctness of BEMPs, first, the rationality of basic assumption and the sources of problems must be carefully deliberated. According to the analysis and simulation software, there are three main reasons for errors: problems in the program and calculation methods, including algorithm errors, calculation failures, code errors, etc.; physical details parameter setting problems, such as convection heat transfer coefficient determination; and the reasonableness of certain assumptions, such as simplifying the three-dimensional heat transfer to one-dimensional heat transfer for simulation and constant approximation of the surface convective heat transfer coefficient.

To address these problems, DeST has adopted a series of verification methods, which mainly include the following three methods: code verification, inter-program comparison, and experimental verification.

5.1 Code verification

Software testing and reliability are important aspects of software development. For a software platform jointly developed by multiple units, each development team is responsible for the development and testing of one module. This is complex system engineering. As shown in Figure 10, DeST3.0 has code quality inspection tools and a functional correctness online test system, which supports each team to independently complete the correctness of the developed functional modules, as well as the development quality and reliability of the platform kernel integration. This method

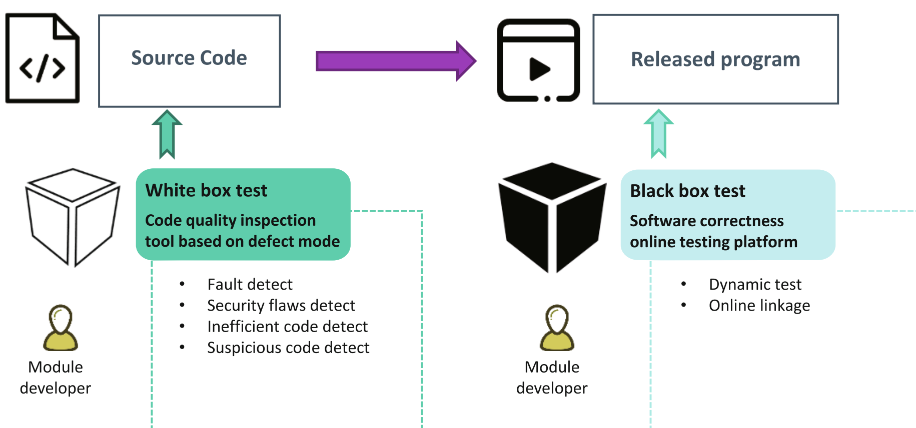


Fig. 10 Approach of code verification

can effectively identify problems caused by programming errors and improper algorithms (Wang et al. 2018).

- **White box test—code quality inspection tool based on defect mode**

DeST3.0 developed a C++ code quality inspection tool based on the defect mode to expand the detection of more types of defects and integrate multiple defect detection tools with complementary capabilities, so that it can detect more types of defects and reduce underreporting and false alarms to improve the accuracy of defect detection.

First, based on the study of the basic working principle of the open-source tool Cppcheck, the C++ defect detection method based on the defect mode is studied, 12 C++ defect modes are abstracted into regular expressions, and corresponding defect detection methods are designed and implemented. Then, to further reduce the false negatives and false positives of defects, the method of integrating the improved Cppcheck, Clang Static Analyzer, and Flawfinder tools was studied. A C++ code quality inspection tool was developed, and its functional structure is illustrated in Figure 11.

The initial version of the platform kernel was tested using a code quality inspection tool. There are three major types of defects: (1) fault-type defects, such as memory leaks and uninitialized variables, (2) buffer area overflow and other defects that cause system security problems, and (3) suspicious code that may have problems, such as dead code. Consequently, the modification of the platform kernel code was guided in a targeted manner, and the quality of code development was effectively ensured.

- **Black box test—software correctness online testing platform**

The entire platform kernel consists of many independent modules, and these modules are developed by multiple units, which brings inconvenience to the joint testing of the kernel. The amount of test data for each module is large, and the resulting data cannot be manually errored. Therefore, an online software correctness test system was developed in DeST, which is a distributed test platform, and its system structure is shown in Figure 12.

The process of the joint testing was as follows. First, each module implementer created a test project. One or more test cases (including the specified test results) were created in the project as needed, and the test accuracy was specified. Second, the code under test was synchronized from the code management platform to the test platform for compilation and grammar checking. Finally, the test was performed automatically, and the evaluation result was given. During this process, the tester can adjust the algorithm according to the given test results to meet the requirements.

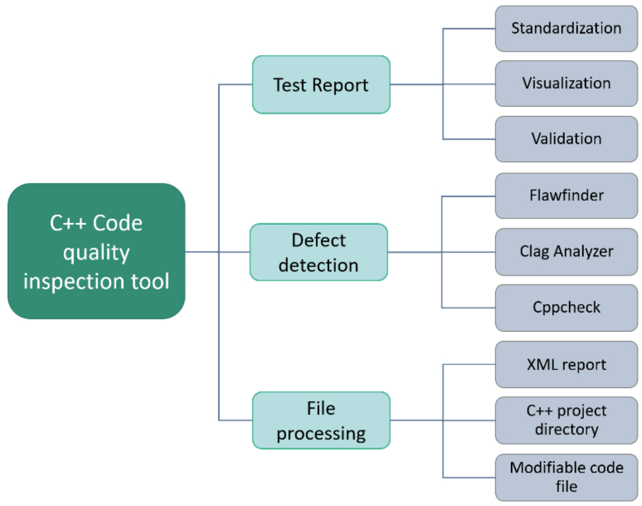


Fig. 11 Functional structure of defect-detection tools

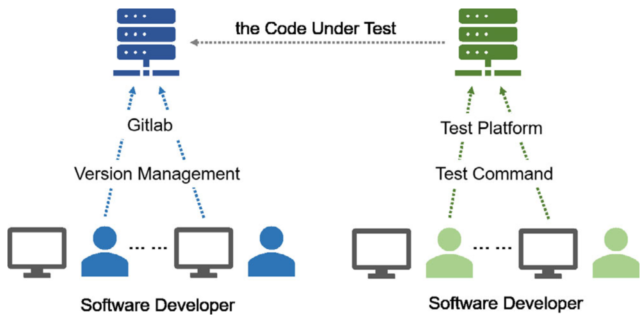


Fig. 12 Structure of distributed test system

The actual application of the software collaborative development research project shows that the test platform solves the problem of joint testing of complex platform kernel modules, can perform joint testing of modules efficiently and quickly, greatly improves the test efficiency, and ensures the correctness of the function calculation of the platform kernel and each independent module.

5.2 Inter-program comparison

Inter-program comparison is a more in-depth and detailed verification method based on code verification. After a simulation program has passed the basic requirement of code correctness, it should be compared with other simulation programs of the same type worldwide to verify its own settings in physical detail and improve its physical model. This is also a basic requirement of the simulation program.

The ASHRAE-140 standard (standard method of testing for the evaluation of building energy analysis computer programs) (ANSI/ASHRAE 2014) was used to test the performance of DeST3.0, as shown in Figure 13. The ASHRAE-140 standard specifies test procedures for

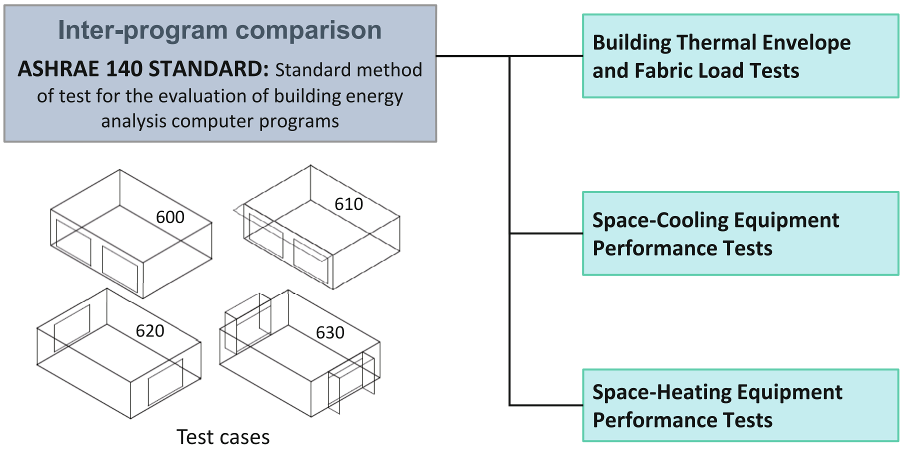


Fig. 13 Inter-program comparison based on ASHRAE 140 standard

evaluating the technical capabilities and ranges of applicability of computer programs that calculate the thermal performance of buildings and their HVAC systems, which can be used to indicate major flaws or limitations in the capabilities. Most popular BEMPs such as EnergyPlus, DOE-2, ESP, BLAST, and TRNSYS have participated in the tests of the ASHRAE-140 standard.

The building thermal envelope and fabric load tests contained 17 basic cases and 22 in-depth cases. The space-cooling equipment performance tests contained 34 air conditioning system test cases, and the space-heating equipment performance tests contained 11 heating system test cases. As shown in Figures 14 and 15, the DeST results were very close to those produced by other simulation programs.

The inter-program comparison verified 453 calculation indicators, including 148 calculations for load test cases, 266 calculations for AC equipment system performance test cases, and 39 calculation items for the heating equipment system performance test cases. The statistical results of the percentage frequency of the deviation rate of the load comparisons and the air conditioning and heating equipment system performance tests are presented in Table 4 and Figure 16. To ensure that there is no overlap between different statistical intervals and the range of all deviations can be included, for the distribution frequency of deviation rate, the left side of the intervals is not included and it is presented by curved brackets. Meanwhile, the right side of these intervals are in square brackets, which means that the right boundary is included in the statistical range. The statistic of cumulative frequency needs to start at 0%, therefore, for the cumulative frequency of deviation rate, these intervals have square brackets in left and right sides.

It can be seen from Table 4 and Figure 16 that the calculation results of DeST completely fall within the calculation interval of the other software, a total of 322 items,

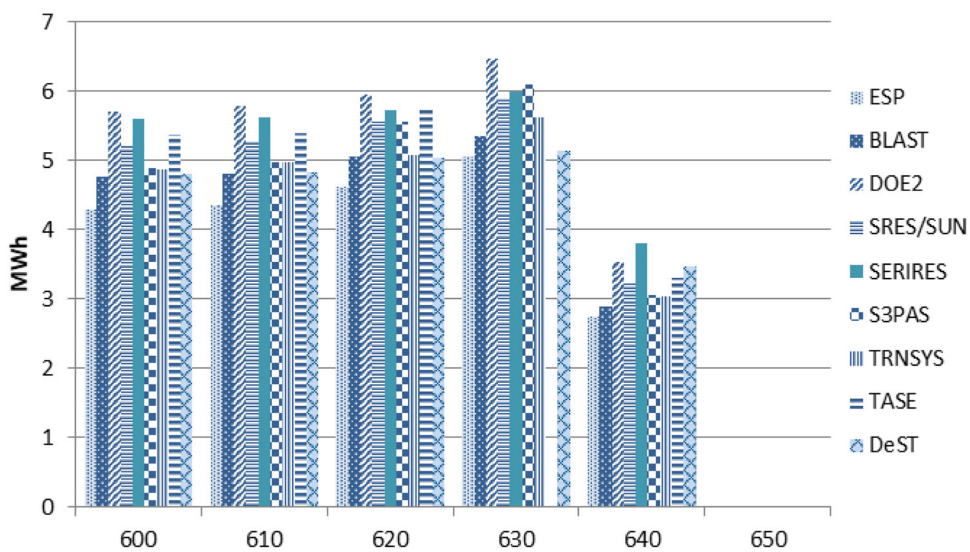


Fig. 14 Annual heating loads in different cases

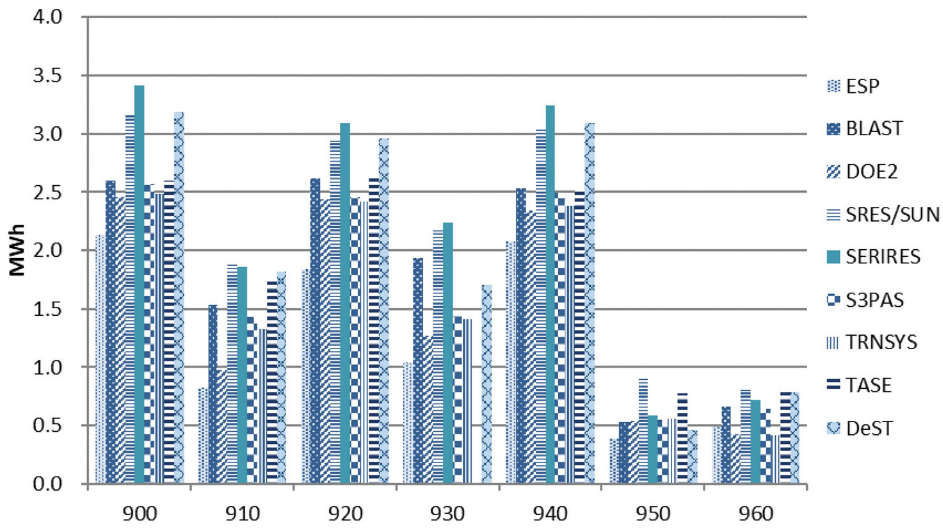


Fig. 15 Annual sensible cooling loads in different cases

Table 4 Statistics of percentage frequency of example deviation rate

	Deviation	Number of cases	Percentage (%)
Distribution frequency	0%	322	71.1
	(0%, 5%]	72	15.9
	(5%, 10%]	33	7.3
	(10%, 20%]	11	2.4
	(20%, +∞)	15	3.3
Cumulative frequency	0%	322	71.1
	[0%, 5%]	394	87.0
	[0%, 10%]	427	94.3
	[0%, 20%]	438	96.7
	[0%, +∞)	453	100.0

accounting for 71.1%; the percentage of deviation rate falls within the (0, 5%) interval, a total of 72 items, accounting for 15. 9%; the percentage of deviation rate falls in the interval of (5%, 10%], a total of 33 items (7.3%), and the percentage of deviation rate falls within the interval of (10% and 20%), a total of 11 items, accounting for 2.4%; and the percentage of deviation rate falls in the (20%, +∞) interval, a total of 15 items, accounting for 3.3%.

From the above analysis, it can be concluded that for most load comparison examples and air conditioning and heating equipment system performance tests, the comparison calculation results of the DeST and other building energy consumption simulation software participating in the test are relatively consistent. The DeST results are very close to those produced by other simulation programs, and the deviation of most calculation results was within 5%.

Besides, from the perspective of software features and scope of application, the comparison of DeST and EnergyPlus are mainly conducted during the development of DeST 3.0, which was mainly focused on load and HVAC system calculation. Zhu et al. (2013) compared the differences in the calculation cores of DeST, EnergyPlus and DOE-2. Based on the simulation results of the standard tests in the ASHRAE-140 standard, a series of examples were designed to analyze the key reasons for the differences between DeST

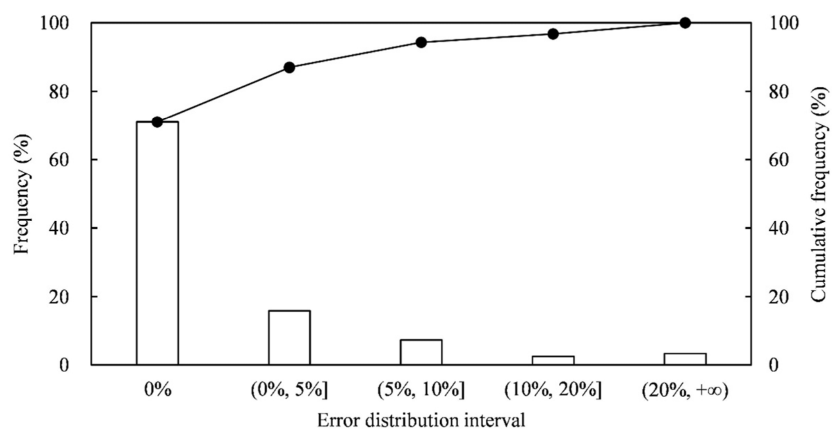


Fig. 16 Distribution of test cases deviation rate

and EnergyPlus load calculations. This research revealed that even though there are many discrepancies in the heat balance algorithm, when the input parameters are the same or equivalent, the calculation results of the DeST and EnergyPlus are very close. DeST and EnergyPlus both have a strict zonal heat balance routine, so they can handle heat transfer for cases when adjacent zones have very different conditions, or a zone is part-time conditioned while adjacent zones are unconditioned.

Methodologies, processes, and the main modeling assumptions of DeST, EnergyPlus and DOE-2 in HVAC calculations were summarized in the study by Zhou et al. (2014). With similar component model and equivalent inputs, small differences between the total energy consumption of HVAC systems can be detected from DeST and EnergyPlus. The two BEMPs are capable of simulating complex HVAC systems and control strategies due to their integrated solution of load, system, and plants.

5.3 Calibration case study

The calibration case study compared the simulation results of each program with the actual measurement records to evaluate the accuracy and reliability of each program.

Two public buildings in different climate zones were selected to monitor actual energy consumption data throughout the year. At the same time, the necessary parameters for the simulation calculations, such as meteorological parameters, enclosure structure, and building functions, were collected, and the simulation results of DeST were verified with the measured data in detail. The error meets ASHRAE Guideline 14 (ASHRAE 2014), of which the required statistical value error cannot be greater than 5%, and the instantaneous value error cannot be more than 15%.

Two public buildings in Zhengzhou, Henan (cold area) and Ningde, Fujian (hot summer and cold winter area) were selected as study cases. Related computer-aided design (CAD) drawings, including architectural drawings and HVAC drawings, as well as meteorological parameter files of the city where the building is located, were collected. Therefore, key information was obtained including the geometric dimensions of the envelope structure, thermal properties, interior design parameters, AC equipment parameters, and annual meteorological parameters. To ensure that the simulation was consistent with the actual situation, the collected parameters were validated based on an on-site investigation.

The two building models are shown in Figure 17. Various simulation processes of the platform kernel DeST were run for 8760 h to obtain the annual energy consumption simulation data.

The calculation results of the DeST simulation platform were checked in detail using measured energy consumption data throughout the year. The test standard adopted the ASHRAE Guideline 14 statistical value error NMBE (normalized mean bias error) and instantaneous value error CV (RMSE; coefficient of variation of the root-mean-square error), as shown in Eqs. (1) and (2). The error values of the simulated and measured data during the cooling period of the two public buildings are listed in Table 5, and all met the ASHRAE Guideline 14.

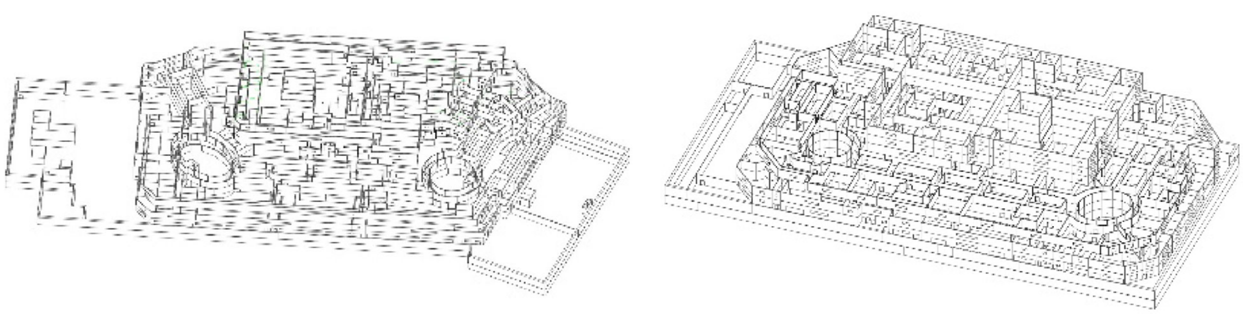
$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(E_i - \hat{E}_i)}{(n-1)\times \overline{E}} \times 100\% \tag{1}$$

$$\mathrm{CV[RMSE]} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(E_i - \hat{E}_i)^2}{(n-1)}}}{\overline{E}} \times 100\% \tag{2}$$

where E_i is the measured energy consumption data; $\hat{E}_i$ denotes the simulated energy consumption data; n represents the number of data; $\overline{E}$ is the arithmetic mean of the measured energy consumption of n observations.

6 Applications of DeST 3.0

The applications of DeST 3.0 has been involved in the whole life cycle of buildings, as shown in Figure 18. DeST



Building A

Building B

Fig. 17 Architectural models of the two calibration cases

Table 5 Error in comparison of simulation and measurement results

	Error (%)	
	Building A	Building B
NMBE	−0.15	2.29
CV(RMSE)	3.81	5.35

3.0 has been applied in new important constructions for its reliable and professional ability in building thermal process analysis. For unique new constructions, such as CITIC Tower and Daxing airport, there is little design experience to refer to. As a supplement, DeST 3.0 could provide reliable thermal process simulation analysis for designers (Lin et al. 2021). In addition, building system operation can be simulated using DeST. For example, by analyzing the number of occupants and movement, the cooling system can be optimized with the cooling load simulated ahead. A considerable building energy consumption fee can be saved through accurate building simulation work (Jiang et al. 2018). When considering building energy-saving retrofit, different retrofit schemes can be compared before construction, thereby saving considerable material costs and avoiding unnecessary construction (Ye et al. 2021).

Not only can DeST 3.0 be applied in a single building lifecycle, but it can also be adopted in code compliance. Energy saving and green buildings can be evaluated using DeST before construction. Currently, DeST is required for mandatory use in Beijing and Tianjin's Design Standard for Energy Efficiency of Residential Buildings. Over 350,000 prototype buildings were simulated in DeST based on batch calculations, supporting the rationality of code compliance.

For new technology applications, DeST 3.0, which can supply various data interfaces, namely FMI/FMU, is used for adaptability analysis. For example, it is difficult to extend spectrum-selective cooling materials and their energy performance on building facades to different climate zones and building types. With a surface heat flux data interface, this type of new cooling technology can be used in building simulations.

Despite engineering utilization, DeST 3.0, is helpful for researchers as well. Considering the state-space model as the core, various functions can be developed by individuals. Different building envelopes, air-handling units, water systems, and chillers can be integrated with building thermal process functions, significantly broadening studies and scopes of researchers.

Modeling process could cost much time of engineers and designers. In order to reduce this kind of modeling cost, a series of prototype buildings were supplied for software user, including 11 commercial buildings and 4 residential buildings. These prototype buildings could cover over 70%

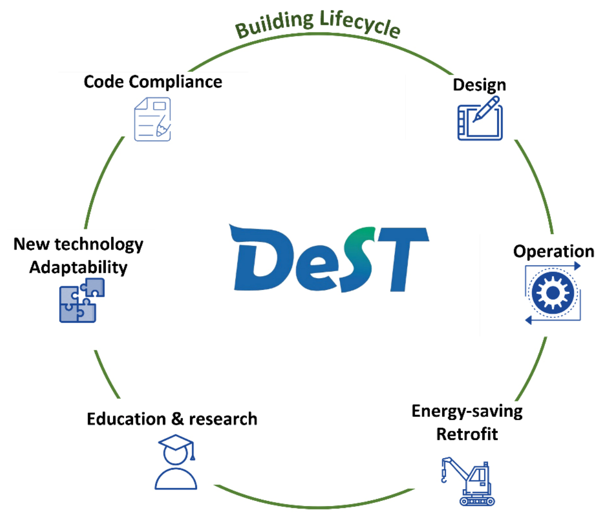


Fig. 18 Applications of DeST 3.0 throughout building lifecycle

of Chinese building sectors. All the prototype building models were well tested and verified based on stationary data. The prototype building models could support code compliance and carbon emission estimation (Gui et al. 2019; Zhang et al. 2019c; Zhang et al. 2022).

7 Conclusions

Building energy modeling has been widely applied in the assessment and optimization of building lifecycle performance and has significantly contributed to energy-efficient low-carbon targets in the building sector. With emerging building technologies and increasing simulation requirements, building energy modeling programs are facing new challenges in terms of capability, calculability, and compatibility. To address these needs, the latest DeST 3.0 has been developing since 2008. The overall DeST 3.0 structure connects the BAS, System, CPS module, and ES modules with the air loop balance and water loop balance calculations. DeST 3.0 introduces new functional simulation features including: (1) advanced simulation modules for building envelopes; occupant behavior and energy systems; (2) cross-platform, compatible, and open simulation kernels; (3) FMI/FMU-based co-simulation functionalities; and (4) high-performance parallel simulation. The correctness and reliability of DeST 3.0 has been verified through a series of methods, including code verification, inter-program comparison and experimental verification.

Although DeST kernel has been verified with code verification, inter-program verification and case study calibrations, the precision of energy performance simulation could still be further improved. Results from inter-program comparisons suggest that, although most of the cases have minor deviations on the simulated results compared with other software, there are still 3.3% of the cases with a deviation rate of more than 20%. Results from calibration case studies suggest that the NMBE and CV(RMSE) of the test cases are still 2.29% and 5.35%, respectively. Future efforts will be devoted into precise thermal balance simulation and system modeling by in-depth comparative validation with similar simulation software and real cases. Moreover, with the increasing stress from climate change and carbon emission control, quantified evaluation of building energy-related carbon emission and the effect of climate change/micro climate on building environment should be enhanced and integrated in future versions of DeST. Currently, DeST works as a simulation kernel for building performance simulation. Additional efforts will be focused on user-friendly graphical interfaces, between-program interactions with BIM and cross-platform integrations with various scripting languages and operating systems.

DeST 3.0 has been widely applied in all perspectives throughout the building lifecycle, benefiting designers, operators, and engineers in the building energy industry. DeST 3.0 represents a significant and efficient step forward for building energy performance simulation, providing a general platform that enables reliable, practical, efficient, diverse, and collaborative modeling functionalities for improved building environments and advanced building technologies.

Data availability

Information, examples, tutorials and supporting resources of DeST 3.0 can be found on the official website in both English and Chinese at https://www.dest.net.cn/. A video tutorial of DeST can be accessed from the online MOOC course in Chinese on xuetangX https://www.xuetangx.com/course/THU08101000328.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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