Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

AN OVERVIEW OF AN INTEGRATED BUILDING SIMULATION TOOL - DESIGNER'S SIMULATION TOOLKIT (DEST)

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ABSTRACT

In early 1980s, Tsinghua University has started to develop a new building simulation tool with the aims to benefit for teaching, research and practical use of HVAC related applications in China. With the concept of "base temperature" of a space, it provides a handy link between thermal behaviour of buildings and dynamic performance of HVAC systems. It emphases on finding the predicted ideal performance of a system and compare with the user selected design conditions of a space, ie the degree of satisfaction, rather than go straight to find the size and capacity of the system. This paper reviews the theory and main features of DeST.

INTRODUCTION

Building energy simulation tools play an important role in modern building design processes. They provide a wide range of functions for building designers. Enhanced virtual and graphical presentations from these tools help to explain the results to decision makers. To name a few of these tools include, DOE-2, BLAST, EnergyPlus and ESP-r. However, computers are as good as the person running it. Thus, the accuracy of simulation results is a matter of debate for a long time. It is a major issue on how to use the tools right rather than the tools developed are accurate enough. It is believed that the cost for setting up a system to run building energy simulation tools is comparatively lower than exactly hiring experienced professionals to use the tools.

The objectives of simulation for buildings and HVAC systems are very different. Conflicts between system description and flexibility; time step selection and control mode are almost unavoidable. Modern building simulation tools must take into account practical aspects of design and analysis processes; to effectively and efficiently couple building models and system models. To handle these factors in a simulation tool; its concept, computational method and structure are all related. Adapting and integrating practical design process into simulation tools enables it to integretae the buildings and systems.

About 10 years ago, DeST (Designer's Simulation Toolkits) [Chen 1999] has recognized special characteristics and shortfalls of various software tools for building simulation, and continuously developed to become a dynamic building simulation tool. It is based on the concept of "simulation by stage", to couple the simulation of buildings and systems.

DeST research commenced in 1989. It was developed, in its early stage, a simulation engine for handling building thermal calculations. Before 1992, the simulation engine is called BTP (Building Thermal Performance). Progressively, HVAC simulation modules were added to BTP to become a prototype integrated building simulation tools called IISABRE [Hong 1997]. To enhance a higher degree of integration to various stages of practical design process with simulations, an extensive version, based on IISABRE, was developed from 1997. From then, a structured map of DeST development has been established. DeST1.0 version was completed and released in 2000. In 2002, the DeST-Housing version (DeST-h) released. Right now, DeST has been used in China, Europe, Japan and Hong Kong.

MAIN FEATURES

To practice the objective of "simulation by stage", DeST has the following special features evolved from the design and development:

Use base temperatures to couple buildings and systems

Base temperature is the temperature of a space when there is no HVAC system in place and the space is subject to the combined effect of all indoor and outdoor heat sources. This temperature reflects the nature of the building itself in response to various passive heat disturbances. To study the building thermal process using simulation, it starts from buildings with very accurate models to obtain base temperatures of all rooms. On the study of HVAC systems, simulations are made based on the results of base temperatures to integrate with other building parameters to become modules for buildings. System modules are linked with these base temperatures building modules to become a system model, taking the advances of modular system models, eg TRNSYS.

This is the basic coupling method between buildings and systems in DeST.

Design by stage, simulation by stage

Practical building design process includes various stages with different design objectives and focuses for each stage. As the design progress from initial to detail, information will be increased to assist the design but at the same time its design flexibility will be reduced. For different stages in the design process, there are defined and uncertain design parameters which will be changed with the progression of design process. The uncertain parameters from the former stage will be changed to defined parameters for the next stage through the design decision made at that stage. For example, in the preliminary design stage, internal heat gains and weather data are defined parameters, however the thermal properties of the building under these two parameters are uncertain; in the scheme design stage, these thermal properties of the building will become defined parameters, designers can use these defined parameters to compare and select various HVAC systems for the next stage of design.

The main purpose of building simulation software is to assist data analysis and design of building environment and its control systems. The applications of simulation process must be paralleled with the characteristics and logical relationships of each stages of the design process. DeST has incorporated to different stage of practice building design processes and has five main simulation stages, ie building thermal process, system scheme analysis, AHU system analysis, duct/pipe networks and plant. These simulation stages will provide accurate results to fulfill the needs for different stages of design. For example, in the building thermal process, the simulation will provide results on thermal properties of the buildings; in the system scheme analysis, the simulation will provide results for HVAC systems. This is the basic for DeST to carry out "simulation by stage" for building environment and its control systems.

Ideal control

There are certain conditions required for the computational models of simulation by stage approach. For every stage, the simulation must be based on design parameters obtained from previous stage. As the next simulation stage has not been started yet, all relevant modules and control modes are uncertain. It is necessary to define the computational method for the next stage. Because of the current stage of simulation is to evaluate whether the design would satisfy certain criteria and to identify problems in case these criteria cannot be met; and to provide design parameters for the next stage. DeST did not adopt the approach of "default system" which has been used by DOE-2 and TRNSYS, but to use an "ideal" method to handle the simulation input for the next stage. It is to assume that the all parameters of the next stage are ideal and can fulfill any criteria of the next stage (cooling/heating capacity, water flow rates, etc). This approach has the following advantages:

- Remove limitations for simulating the current stage that may be caused by "standard"or inflexible systems types provided as the "default" and a more "flexible" evaluation of results can be obtained;
- Using the same input and assumptions the simulation results are parametric and have great practical meanings;
- To carry out simulation of the current stage without information necessary from the next stage so that workload can be reduced;
- Useful information for the next stage can be obtained from this stage.

Graphical interface

The buildings and its environmental control systems are very complex. To describe the buildings and all its related systems is also a very complicated task. If the description is to be done by texts and tables input, the workload is enormous. Errors and omissions for this form of input can be very easy. To simplify the description of buildings and its associated systems, DeST developed a graphical input interface that based on AutoCAD for all simulation stages. This interface is run on Windows operating systems. The interface is based on the most commonly used design and drafting software in which most of the related database (materials, geometric dimensions, internal gains, etc) can be linked with DeST very easily. Users can describe the building through a very familiar drafting environment and therefore it should be easier to use. DeST results are in Excel table formats for easy reference.

Compatible platform

Although the concept of DeST is to couple buildings and systems in various stages of simulations, it also has the modular concept in place. This modular concept has adopted the flexible style of TRNSYS that is open and extensible. DeST can be a general simulation platform for buildings and its related systems.

STRUCTURE

To practice "simulation by stage" concept, DeST comprises a number of different module for handling different functions and areas. These modules are interrelated and as shown Figure 1.

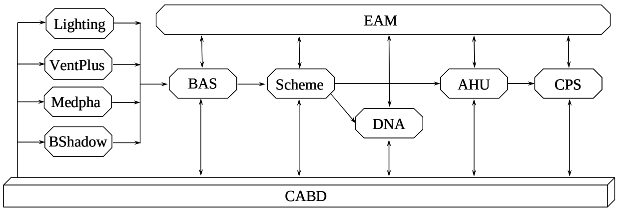

Figure 1 DeST Schematic Diagram

Medpha (Meteorological Data Producer for HVAC Analysis)

For simulating system dynamic responses of HVAC systems, weather data in forms of hourly and daily for a month, a quarter or a year is required. General speaking, the major weather data that affect building thermal process includes air temperature, humidity, solar radiation, wind speed and direction and sky background radiation temperature, etc. To reflect the effects on building thermal process by these climatic data, DeST has investigated the subjective behaviour of these data and has established a weather data model that based on collected daily observations can be generated to hourly data for the whole year - Medpha. The raw data for Medpha came from 194 meteorological stations at different parts of China. These data are daily measurements for the past 50 (including, air temperature, humidity, solar radiation, wind speed and direction). Adopted the typical reference year approach for HVAC load calculations, Medpha first select the year which is the most typical (for example, typical weather year, extremely high temperature year, extremely low temperature year, extremely high solar radiation year, extremely low solar radiation year, etc.), daily data will be extracted to generate as hourly data according to their daily pattern of change (including, air temperature, humidity, direct solar radiation, diffuse solar radiation, wind speed and direction, and sky background radiation temperature), this generated typical weather year will be used for whole year simulation in DeST.

VentPlus

When the outdoor temperature and humidity are not inside the indoor comfort zone, wind pressure, stack effect and infiltration from windows, doors, etc. (hereafter called natural ventilation) will become HVAC load for the space. According to a recent research that natural ventilation contributes about 30% of building total energy consumption [Axley, 2001], it is a rather large percentage. In building simulation exercise, the accuracy of natural ventilation calculations is therefore an important factor of the final energy results. The natural ventilation module in DeST calculates constant volume natural ventilation and to determine the effect for HVAC loads. This provides a guidance for sensible use of natural ventilation for achieving better energy conservation design.

Natural ventilation is driven by means of wind pressures and stack effects. Simple addition of ventilation rates is not appropriate since the mechanisms of these two driving forces of natural ventilation are very different; and also ventilation rates and pressure differences have a non-linear property. DeST considers both wind pressures and stack effects at the same time when calculating natural ventilation. This is to integrate the computation approach for both thermal properties and fluid dynamic properties.

A multi-zone network model has been developed for natural ventilation simulation [Orme, 1999]. This model describes the whole building as a system and a zone for each room in the building (or a network node). In the same zone (node), it is assumed that air is well mixed and all parameters of air in the zone are homogeneous. Every node is linked by all sorts of air paths (door, window opening, crack) to form a fluid flow network. Air flow calculation is based on steady flow Bernoulli equations that resistance are defined at all branches (ie air flow path). Equations sets can be created by taking energy balance at all branches and mass balance at all nodes. These equations can then solved by Newton's method to obtain air flow rates for each branch.

DeST use the air flow rates obtained by VentPlus for BAS for further thermal environment calculations.

CABD (Computer Aided Building Description)

CABD is the graphical interface module for DeST. It is developed based on AutoCAD as the interfacing media in describing the buildings. Building elements, building materials, geometry and dimensions, internal gains, etc, can be obtained from the database to describe and edit building data input directly.

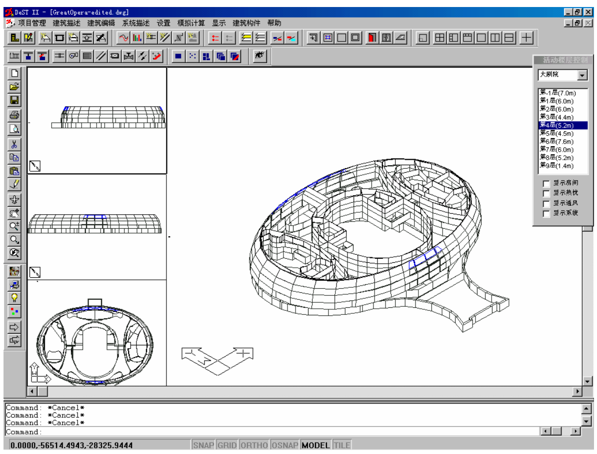

Figure 2 DeST Graphical Interface

BShadow

Shadows cast on building by other buildings, building itself, overhang and side fin affects solar radiation received by the buildings greatly. Therefore, solar radiation on buildings must take this into account. The shadow calculation module, Bshadow in DeST, considers all the above shadow cast factors and used geometric projection methods to calculate the shadow cast on the surface of the buildings. The following will be obtained:

- Shadow distribution on different part of buildings at any time of a year;
- Detail geometrical information about shadow cast;
- Light-spot distributions for atrium, lightwell (re-entrance), etc.; special areas of buildings.

Figure 3 is a screen shot of the Bshadow interface window.

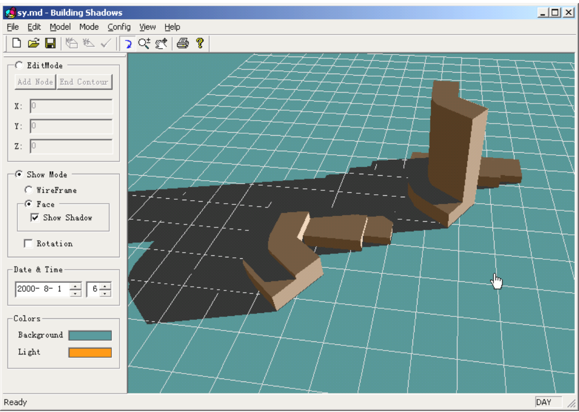

Figure 3 Bshadow Interface

Lighting

Daylight is a non-polluted and sustainable natural light source with high quality, eg evenly distributed, non-glare, and long duration, etc. Because of energy crisis, environmental pollution, etc; daylight for modern buildings has received increased attention. For example, substantial energy saving by artificial lights and air conditioning systems can be achieved if daylighting can be applied to the large space, spaces in the underground and tunnels. Lighting, therefore, can also be a factor that affects energy consumption of buildings.

The module Lighting in DeST is responsible for indoor lighting calculations. Based on the shadow calculation results for windows from Bshadow, the daylight factors for each room under different sun positions can be obtained. From Medpha and comparing the calculated illuminance and design illuminance, the required supplementary lighting on/off pattern can be determined.

BAS (Building Analysis & Simulation)

BAS is the core module for building thermal performance calculation. It can do hourly calculations for indoor air temperatures and cooling/heating loads for buildings. BAS adopted the state space solution method for building thermal heat balance equations [Jiang 1981]. State space solution method is continuous in time, but discrete in space. Through solving the discrete nodes of the energy balance equation sets, all response factors for all heat disturbances can be found. These are the thermal properties for the room itself. This method can not handle directly non-linear problems. However, it can obtain the solution of the equation sets directly that without calculating the temperature field. Its stability and errors are independent of its time step selection. Thus, the calculation speed is very fast. Therefore, it is very suitable for systems analysis of building simulations. There are tools that also use state space solution method as the core method, eg EnergyPlus.

DeST is a few building simulation tool in the world that considers multiple rooms heat balance [Hong 1997]. DeST takes into account of the thermal process that affected by adjacent rooms to each individual rooms. DeST can handle complicated multiple rooms buildings of up to about 1000 rooms.

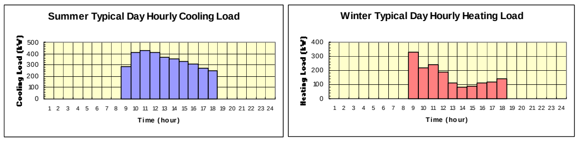

Figure 4 DeST Hourly Loads Diagrams

Scheme

HVAC scheme design is an important stage of the entire HVAC system design process. As the design progress, the thermal properties of the building will be fully understood by simulation, then system design can be commenced. "Scheme" normally refers to secondary HVAC equipment. In practice, scheme design has two levels: scheme design and equipment selection. Designers should have to define the following prior to select appropriate equipment:

- Zoning of buildings, how to divide HVAC systems according to orientations?
- What kind of HVAC scheme should be used? VAV, CAV, CAV + reheat, VAV + reheat or FCU? There are obvious differences of occupant satisfactions and energy consumption under various conditions of all the above HVAC schemes.
- How to analyse novel systems? Such as: FCU + seasonal variable PAU, etc.

If the above problems cannot be taken care of, it is very easy to have uneven cooling and heating in many rooms. Simulation for HVAC systems is to identify this sort of problems before construction and to allow designers to make sensible decisions.

HVAC scheme simulation has the following content:

- Zoning: which rooms belong to the same system;
- HVAC system type (CAV, VAV, FCU, terminal reheat, other possible combinations);
- Terminal maximum/minimum heating/cooling capacity (for FCU and terminal reheater);
- Room maximum/minimum air flow rates (for VAV);
- System operation mode (variable supply air temperatures for VAV).

Through simulation and evaluation of the above content, a scheme design analysis tool can be built. Designers calculates the results very quickly for various system types and to compare them to obtain an optimized solution.

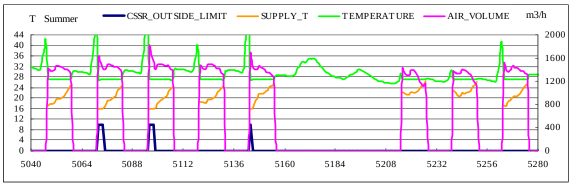

Figure 5 Scheme Module Results Diagram

DNA (Duct Network Analysis)

DNA is a module to carry out duct network calculations for both system design and validation. The system design is to size the duct netword and to select a fan based on defined duct layout, length and air flow rates for each duct sections. The validation is to check whether the air pressure can satisfy the needs for each section based on defined duct size, length and fan capacity. As the air flow rates for calculations are all design flow rates, the duct design is also the "design" duct network.

For CAV systems, as the air flow rates is constant for all conditions, the "design" duct network can be accepted. Howver, for VAV systems, it is not appropriate to use design flow rates to size the duct as part load operation happens most of the time. The following criteria must be ascertained:

- Under all working conditions, the network must meet all design criteria;
- To find the fan performance under all possible working conditions and to select equipment to suit;
- The difference of system performance under different control modes.

Fluid flow network called "forward" model is to find flow rates and pressures at each branch of defined duct layout, fan capacity, damper conditions, fan speed and other control mode. This is acceptable for the "design" conditions only. In practice, all dampers at branches and fan speed change continuously to meet the demanded flow rates. It is therefore a "reverse" model is proposed to define duct layout and flow rates at each terminal (branch). Assuming "ideal" controls for all dampers and fan speed that to check whether the duct network can meet all design criteria. This "reverse" simulation approach can also called "comparative" simulation. DNA module is to carry out duct network design and comparative simulation.

AHU (Air Handling Unit)

Designers have to select appropriate AHU equipment and capacity after the scheme design is fixed. Possible problems that the stage would ask are:

- How to select AHU equipment and capacity?
- Select variable fresh air system, and its control scheme?
- Use 4 pipe AHU?
- Is it economical to use sensible heat recovery or total heat recovery?

If the above problems are not handled properly, then the AHU may not be able to meet its design criteria and energy wastage will occur. The objective of AHU module is to provide designers sufficient hourly data through simulation.

AHU module includes the following content:

- Primary return/secondary return system;
- AHU equipment (cooling coil, humidifier, washer, reheater, etc);
- Cooling coil capacity and sensible and latent heat characteristics;
- Fresh air control scheme (constant/variable);
- Fresh air sensible heat recovery/fresh air total heat recovery.

Through simulation on hourly performance for the above content, the hours that can meet the design criteria and the energy consumption of the AHU scheme can be worked out. Designers can carry out similar calculations for different AHU setup in order to find the optimal configurations for AHU.

CPS (Combined Plant Simulation)

Cooling/heating sources and water system is an important step in the detail design stage. Upon the completion of AHU system design, the next step is to determine the central plant and its distribution systems. The following must be decided:

- Energy sources Natural gas/oil/electric/city heat network;

- Cooling/heating plants Centrifugal/screw/direct fire, etc.;
- Chilled water systems Primary pump/secondary pump;
- Pump controls Variable frequency control/multiple on/off control;
- Cooling tower controls;
- Use of ice storage; etc.

If the above cannot be dealt with properly, energy wastage from the central plant and its water system will happen.

EAM (<u>E</u>conomic <u>A</u>nalysis <u>M</u>odel)

For a HVAC system, it is necessary to have two aspects of analysis so that a complete and subjective description for the system is obtained. On one hand, it is the simulation for all possible working conditions that all these points can be assessed whether the design criteria are met. On the other hand, it is the calculations of initial and operating costs such that life cycle cost of the system can be obtained [Wang 2001]. Designers have to balance these two aspects to come up with a optimised system design. Economic analysis is an vital part of the overall evaluation of the systems. DeST is closely coupled with various HVAC system design stages in terms of economic analysis. In different design stages, DeST uses all available data to provide economic calculations about the cost involved for that stage.

The economic analysis model of DeST divides into four sequential stages: concept design stage, preliminary design stage, detail design stage and pro-design stage.

Concept Design Stage: it is concentrated on the building envelope. For this stage, the hourly cumulative loads and hourly loads are used through a neural network model to calculate the initial and operating costs. The results will train the neural network so that the trained model can be used to predict other systems.

Preliminary Design Stage: through the simulation of various HVAC systems, it is to analyse and compare the hours of dissatifing the indoor design conditions. In this stage, the calculation is based on hourly cooling and heating loads and hourly air flow rates to predict the initial and operating costs.

Detail Design Stage: it is concentrated on various parts of the system, including central plant, terminal unit, duct network, pipe network. In this stage, economic analysis is focused on individual component of the system.

Pro-design Economic Analysis: simulations have been carried out for almost every part of the building and systems. Lots of information is obtained and a very accurate initial and operating costs model is established. These calculations also help to train the neural network for predicting economic analysis for other systems.

APPLICATIONS

DeST aids to assist building environment and system design. Its major areas of applications include:

Building and HVAC system design aid

1. Refinement of building envelope design

Building envelope includes building elements, selection of materials and external shading systems, etc. The thermal effect of building can be affected greatly by the thermal properties of the building envelope, therefore to optimize the building envelope will have an important effect of the whole building energy conservations.

DeST can based on users defined building envelope to carry out hourly temperature and system energy consumption calculations. At the same time, economic analysis of the building envelope can also be done, the designers can compare both the thermal and economical aspects to make decisions.

DeST supports all types of complicated building elements (eg, multiple buildings, multiple boundary, skylight, inclined wall, underground floor, etc) calculations. It can also analyse building orientations and window-wall ratio; and to allow simulations of different building materials, combination and insulation. It also supports the definition of internal gains and ventilation. For all the above, building simulation can be used to compare with different building envelope in terms of energy consumption.

2. HVAC scheme and zoning

The building operation temperature and the degree of satisfaction of occupant comfort are very senstitive to system and zoning design. Current system design is still very much based on experience and unfortunately this may not be appropriate for modern buildings that are so complex.

Based on hourly simulation for the building and systems, DeST can predict the temperatures for each room, its level of satisfaction and its HVAC capacity. Economic analysis can also be carried out, designers can then evaluate the building and systems based on both technical and economical analysis.

3. Air Handling Unit equipment verification

Upon the decision made on scheme and zoning, designers can determine the equipment in DeST, eg heat recovery + cooling coil + humidifier. From the scheme results of DeST, it is to choose equipment type and capacity to carry out hourly simulation based on AHU, DeST can calculate very accurate economical analysis of the whole system. Repeating the same procedure for different systems, a parametric analysis of different system and equipment can be done.

In DeST, it is clear that designers can understand the operating conditions of each equipment at very early stage. Undue equipment sizing at a later stage can be avoided.

4. Chiller plants and pumping station design

Chiller plant is the heart of the HVAC system design. Chiller capacity and the number of unit have an important effect on initial cost and operating cost of the HVAC systems. DeST used the hourly cooling capacity data from AHU module to compute the hourly optimal chiller set combinations for users.

5. Distribution system design

From scheme module and AHU module, the water and air flow rates for each terminal are obtained. It is then used to calculate AHU system, water system, to confirm fan and water pump models, valid design schemes and to estimate the energy consumption for all possible working conditions

Building Energy Conservation Assessment

Environmental issues, energy crisis, etc; bring building energy conservation measures on the very top of the world agenda. Relevant building energy efficiency regulations, standards, codes of practices and guidelines are now a common language for many countries of the world. In 2001, the Ministry of Construction of China approved the 《Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone》 [JGJ 134-2001] and in 2003, the Ministry approved the 《Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone》 [JGJ 75-2003]. Both standards endorsed the use of dynamic simulations to calculate energy consumption indices and related energy standards for buildings in difference zones of China. Both standards indicate that if the building envelope can not meet the requirements of the standards, simulation can be used to predict annual energy consumption and to judge whether the calculated results can meet the requirements of the local standards. As one of the slogan for the 2008 Beijing Olympic is "Green Olympic", scholars from China has published a Green Olympic building assessment series [Green Olympic Building Research Special Group 2003]. For the energy assessment of Olympic buildings, it includes residential buildings for athlete and commercial buildings that adopted the "reference building" [ASHRAE 1999] approach, simulation tools are required to use for predicting the annual energy consumption.

DeST has a special version for the HVAC energy assessment of residential buildings called "DeST-e". This version is specially developed to comply with the requirements of the energy conservation standard for residential buildings issued by the Ministry of Construction, China. Apart from that, the 《China Eco-Residential Building Technical Assessment Guide》 [Nie et al 2003] has a section on 《Energy and Environment》 about the grading scheme and method, DeST would be an important tool for assessing eco-residential buildings in China.

Areas of Scientific Research

Apart from being a practical dynamic building simulation tool, DeST can also be used as a major tool for research into many areas relating to HVAC systems. In the history of research and development of DeST, a number of researchers have been using DeST to obtain the following research results:

- The effect of building window-wall ratio for cooling energy consumption;
- The effect of night ventilation purging on indoor environment;
- Effect of building internal and external insulations on indoor thermal environment [Jian et al 2001];
- Effect of HVAC system and internal heat gains scheduling on building energy consumption [Jian et al 2002];
- Effect of ventilation scheduling on residential building energy consumption [Yang et al 2002];
- Analysis of energy consumption on various building envelope materials of residential buildings [Chen et al 2001][Song et al 2003];
- HVAC System performance validation analysis [Pan et al 2003][Yan et al 2003].

CONCLUSION

DeST has been widely used nationally in China for various prestige large structures such as the State Grand Theatre [Sun et al 2003], the State Swimming Centre, etc. DeST also used for the following renovation projects: CCTV HVAC systems, Beijing Development Building, Military Museum HVAC systems.

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