INTRODUCTION OF BUILDING ENVIRONMENT DESIGNER'S SIMULATION TOOLKIT (DEST)

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ABSTRACT

This paper describes the methodology and the implementation of DEST, which is a simulation software developed to help the designer during design process. For each design phase, DEST provides corresponding method and program. Some new ideas about using simulation in design are introduced in the paper, with some examples that come from real projects. It is believed that the HVAC design should shift from single-point-design to whole process design in the new century. To achieve this goal, simulation plays an important role. In a sense, DEST is an attempt to "bring simulation into design".

INTRODUCTION

Building simulation and system simulation are widely used in academic fields. In the past 30 years, lots of simulation models, methodologies and tools have been developed. Although simulation technology in HVAC fields is a mature technology, simulation is not well adapted in the design world. Most of the designs are still based on critical conditions without considering the whole operation period. This causes problems such as oversizing the equipment, underestimation of the risk in transition season, etc. Recently, more efforts have been made to narrow the gap between design and simulation. In the IEA ANNEX 30 project, the analysis of design process is one of the major parts [1]. It's doubtless that simulation is an important and necessary technology to improve the quality of design. But the simulation tools cannot be well developed and used in practice unless the relationship between simulation and design process is clear.

The whole design process is consisted with preliminary phase (building characteristics), schematic phase (system type, zoning and operation manner), detailed phase (equipment selection, hydraulic systems and control) and post-design phases (Commissioning, Retrofit, etc) [2]. Is there any simulation software that can serve for the whole design process?

Nowadays, there are two main kinds of simulation software available: function-based (DOE [3]) and module-based (TRNSYS [4], HVACSIM+ [5], MATLAB).

When all the conditions are KNOWN, module-based software is very powerful to create a system and simulate it. It's suitable for research purpose to understand what will happen when each part the system has been chosen. But in design process, especially in early design phase, it's impossible to know all the conditions. Some conditions are to be determined by designer. They should be the outputs of simulation rather than the inputs. For example, in schematic design stage, when the designer want to compare different type of systems, he know nothing about the AHU because detail equipment selections should be carried out AFTER the schematic phase. To make the simulation run, DEFAULT equipment is introduced in module-type software. A very important feature of computer simulation program is that the outputs rely on inputs heavily. It doesn't make any sense to make decision according to the simulation results where many parts of the system are defaults, especially when the default parts are the targets of later phase. In a sense, module-based software is not so suitable for design purpose.

Compare with module-based system, function-based software is less flexible but closer to designer and easier to use. Users often use it to calculate the annual building energy consumption. In design process, it's important for the designer to understand the performance of the system and the requirement for equipment during the whole operation period. DOE includes building simulation, system simulation and plant simulation. "The HVAC simulation is designed around the idea that the supply air temperature is known. This works best for simple control schemes: scheduled or outdoor reset supply air temperature. For more complicated schemes, it doesn't work so well and previous time step data must be used, or the zones may have to be simulated twice (for warmest/coldest control)." [6] The designer has to re-start from the preliminary phase to calculate the building load again when he wants to compare different scheme options in schematic phase. Using zone load to establish the link between different phases makes all the programs too deeply coupled. Therefor, DOE is mostly used in building energy calculation and cannot be used in equipment selection or hydraulic system design.

Both the above two kinds of simulation software have some shortages to be applied into design procedure.

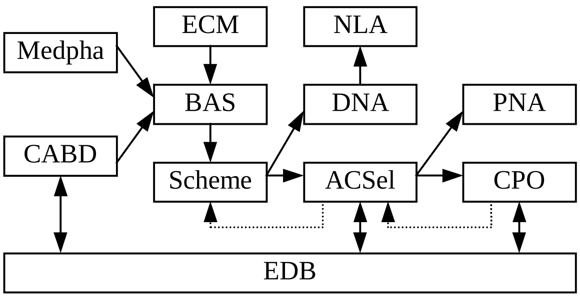
To build suitable simulation tools for design, three important factors should be considered:

- Phased design process.
- Treatment of known and unknown conditions in different design stage.
- Instead of using real control strategy under long time step, another kind of operation manner should be applied to reflect the system's response.

As a participant of ANNEX 30, Tsinghua University proposes the idea “Design by stage, simulate by stage”. With detail consideration of the above factors, a simulation software (DEST) has been developed and used in several real projects. It is function-based software with several parts corresponding to different design stages. Its job is to do the building/system/hydraulic/equipment simulation over the whole operation time period and provide vivid results to help designer make decision.

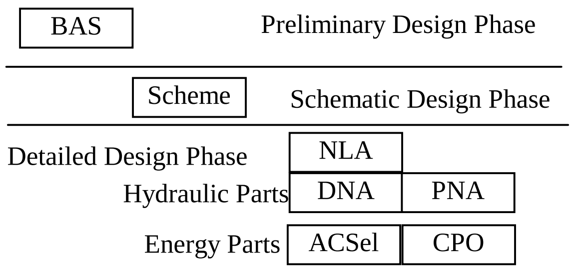
THE STRUCTURE OF DEST

The “phased design process” is fully considered in DEST and reflected from its structure. According to different phase of design, DEST is consisted with several programs and maintain the data flow between each program. Picture 1 shows the structure of DEST. The arrows represent the data flow between each component.



Picture 1: Structure of DEST

Based on twenty years measure data and stochastic model, Medpha produces hourly weather data of 193 cities in China. CABD is an ACAD-based building description program. It's the graphic interface to draw the building and define the thermal characters of enclosure and hourly scheduled casual gain. Some experiment coefficients are managed and provided by ECM. CABD transfers all the necessary data to BAS so that BAS can simulate the building's thermal performance automatically. Base on Space State + method [7,8], BAS is an accurate multi-zone building simulation program. It calculates each zone's room base temperature [9] (RBT, the zone's temperature without any HVAC system). Hourly RBT reflects the building's thermal character under passive heat disturbance. In preliminary design stage, architecture can compare different design options such as building shape, orientation as well as type of fabric by RBT. After the building is fixed, Scheme is carried out to simulate the building's performance and requirement for system under certain HVAC options (zoning, system type, operation manner, etc). The designer can compare the different HVAC system alternative in schematic phase from the simulation results. When HVAC scheme is determined, the requirements for AHU and supply duct network are clear. Based on hourly supply air volume/temperature/humidity, the designer could select equipment such as coil and humidifier and use ACSel to do the verification under all possible working conditions. The same procedure can be used in the selection of cooling plant by CPO. In hydraulic part, hourly required supply air volume could be used to determine the requirement for fan, which is the main task of DNA. The same method could be applied in pipe system by PNA. In ductwork simulation, the pressure drop over VAV terminal can be calculated to analyze the noise level of VAV terminal, which is the job of NLA. Picture 2 shows the correspondence between programs and design phases.



Picture 2: Relationship between DEST programs and Design Phases

In each design phase, the designer could interactive with the programs to calculate the system's performance and requirement for next step. The programs do the calculation according to designer's requirement, and the designer makes the decision by analyzing the simulation result.

THE TREATMENT OF KNOWN AND UNKNOWN CONDITIONS

Design process comprises several phases. In each phase, the known and unknown conditions are different. Through the designer's work, the unknown conditions in former stage become the known conditions in latter stage. For instance, in preliminary stage, the external and internal heat disturbances are known, the thermal behavior of the building is to be calculated. In schematic phase, the thermal character of the building is known. The detail information about the system is unknown. At this stage the designer's job is to compare possible HVAC system alternative based on detail information of the building and give instruction for further equipment selection. The bridge between preliminary and schematic phases is the thermal behavior of the building.

In each design phase, DEST uses detailed model to describe and simulate the known part, and considers the unknown part as an "ideal" component that can meet any requirement (energy, flowrate, etc). This treatment fits well with the design procedure and avoids the influence of default data. Because the unknown part is determined in further step, no matter what kind of default data is used, it must be different from what is final selected. There are two advantages calculating the current part with "ideal" component:

- ♦ The performances simulated are comparable because they have the same input and assumption.
- ♦ The requirement for further step is clear. The "output" of "ideal" component is the requirement for the "real" component. On the contrary, default data is not reliable to provide useful information for further determination.

Take schematic design phase as an example. The task of this stage, the known and unknown conditions is list in table 1.

Task	Determine suitable zoning or the rooms, HVAC system type (VAV, CAV, etc) and operation manner (Fresh air strategy, etc).
Known	Building's thermal characters (Room Base Temperature, response of heat disturbance on room temperature
Unknown	The supply air duct network The detail dimension of AHU The control

Table 1: The conditions of scheme simulation [9]

Equation 1: Mathematical model of scheme

$$\begin{cases} t_k(\tau) = t_{k,base}(\tau) + AQ_k(\tau) + AG_k(\tau)(t_{\text{supply}}(\tau) - t_k(\tau)) + \sum_{j,j\neq k} A_j(t_j(\tau) - t_{k,base}(\tau)) \\ d_k(\tau) = G_k(\tau)(d_{\text{supply}}(\tau) - d_k(\tau)) + W_k(\tau) + \sum_j B_j(d_j(\tau) - d_k(\tau)) \\ t_{k,set,\min} \le t_k(\tau) \le t_{k,set,\max} \\ \phi_{k,set,\min} \le \phi_k(\tau) \le \phi_{k,set,\max} \\ G_{k,\min} \le G_k(\tau) \le G_{k,\max} \\ Q_{k,\min} \le Q_k(\tau) \le Q_{k,\max} \\ MIN: J = f(t_{\text{supply}}, \mathrm{d}_{\text{supply}}, t_{out}, d_{out}, t_{return}, d_{return}, AHUType) + \sum_k Q_k \\ k = 1,2,\ldots, for\ each\ time\ step \end{cases}$$

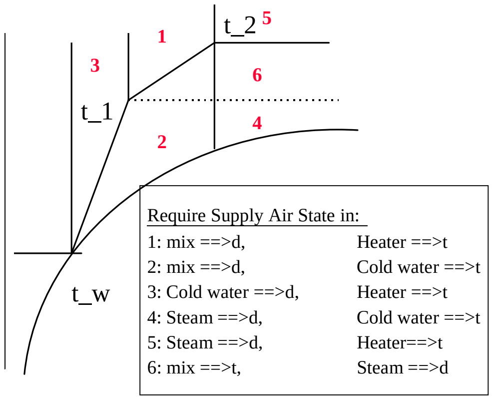
simulation

Equation 1 shows the scheme simulation model. From detail building simulation, room base temperature $t_{k,base}$ and response of heating (cooling) released by the HVAC system on room temperature A and A_j are calculated. They are known conditions at this stage. Supply air volume (G_k), supply air state (t_{supply},d_{supply}) and the output of FCU or heat terminal (Q_k, if used) are to be determined during simulation in this stage. All the values must obey the bounds in equation 1. Through the following steps, the performance of the scheme could be obtained.

1. Calculate required air supply state range (SSR_k) or each room.
2. Because at each time only one supply air state could be produced by AHU, so the common part (CSSR) of all SSR_k are calculated.
3. As far as the supplied air stage is inside of the CSSR, the required air state of each zone can be satisfied. However, the energy required to produce air to different points within the CCSR may be different. Therefor, an optimization can then be carried out to find the optimal supply air point in CSSR. At the same time, the air handling process of AHU is determined.
4. After optimal supply air state is found, the supply air volume and output of terminals (FCU, heat terminal) could be determined.
5. At last, each zone's temperature and humidity can be obtained.

From hourly zone's temperature and humidity, the performance of such HVAC scheme can be evaluated by satisfaction ratio. If all the zones' state can be controlled inside their setpoint ranges, the performance of such scheme can be compared by the energy required for AHU.

At this phase, the AHU is assumed to be an "ideal" component. It can produce any air temperature and humidity needed. Only its type is determinate at this phase. Picture 3 shows the idea of an "Ideal" AHU, which is consisted with a mixing box, a cooling coil and a steam humidifier. t_1 and t_2 refer to either outside or return air state. t_w is the cold water temperature. When AHU type has been selected, the psychometric divisions like picture 3 are determined. The direction of each air handling process is restricted by component's type. For instance, heating process must be a vertical line in psychometric graph. The ability of the component is unlimited. The length of the air handling process line could be as long as needed. The "ideal" AHU is useful to determine the requirement for each component during the whole working period. After the schematic design finished, the demands for AHU component are clear. Detailed dimension of AHU component (heating coil, cooling coil, and humidifier) will be carried out in next design stage.



Picture 3:An “Ideal” AHU

The same assumption is applied in supply air ductwork. It’s assumed that the ductwork could achieve the required supply air distribution during the whole operation time. When designer is satisfied with his schematic design, he can then have the very detailed data (hourly-required supply volume) to design the ductwork.

CONTROL & INVERSE CALCULATION

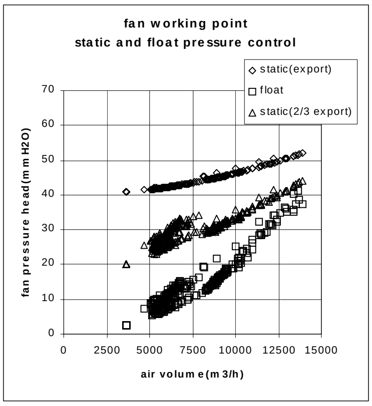
Usually control is a short time step process, while the HVAC system design should consider the operation over the whole year. How to combine or integrate these two different kinds of processes? Here, design could be divided into two parts: HVAC system design and control design. DEST focus on the first part. No matter what kind of system, what kind of equipment is selected, the purpose of system design is to produce a totally controllable system that can meet the user’s demand. Based on this idea, DEST simulates the system with one-hour time step to calculate the system performance and requirement over a long time period. Instead of using short time step control, an inverse calculation method is introduced.

For instance, in detailed design phase, when analyzing the supply air ductwork of a VAV system, the designer’s work is to verify if the required supply air distribution could be reached and to select a suitable fan.

To solve the above problem, the procedures of simulation with normal control method are:

1. Select a fan and set control property (PID parameters, etc)
2. Calculate the flowrate of network
3. If the flowrate calculated is different from the required, adjust the VAV terminals based on some control rule.
4. Go to 2. for the next time step

As the inertia of the duct is very small, this simulation has to be carried out with very small time step (1 second). As an ideal control, every VAV box can be assumed to be working at the desired air volume. Therefrom, the air flowrate through the main trunk of ducts can be calculated. Assuming the pressure at each room space is zero, the required pressure drop by each VAV box can then be calculated if the pressure on the reference point of the network is maintained. The pressure head and flowrate for the fan can also be determined Picture 4 shows the fan working points under two types of static pressure control strategy and float pressure control. Based on the points, fan’s efficiency and energy consumption can be easily calculated. The pressure drop over each VAV terminal can also be determined. With the manufacture catalog, noise level of VAV terminal can be calculated.



Picture 4: Working points of fan under different pressure control strategy

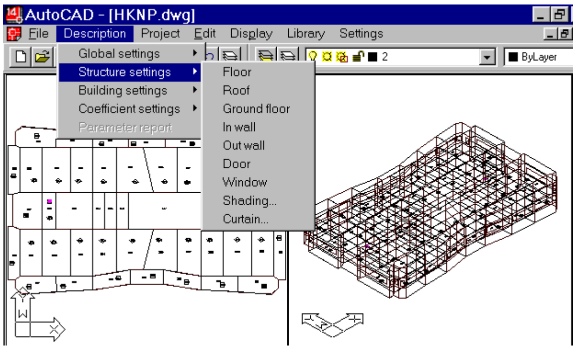
Short time step feedback control is avoided by using inverse calculation method. Inverse calculation can be considered as an “ideal” open-loop control method. In AHU equipment selection, this method is used to calculate the coil water temperature or flowrate when the inlet and outlet parameters are known. If the system requirement could not be meet under inverse calculation, the system cannot be controlled to the demanded state no matter using what kinds of control. In a sense, DEST investigate the system’s controllability by inverse calculation and answer the following two questions:

1. Can the system be controlled to meet the requirement?
2. If can, what’s the best performance of the system under “ideal” control.

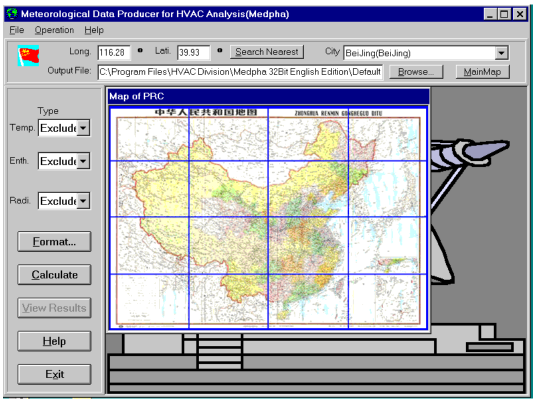
From that on, the designer can go further to develop his control rules and compare the performance of his control strategy with the "best" one.

INTERFACE OF DEST[10]

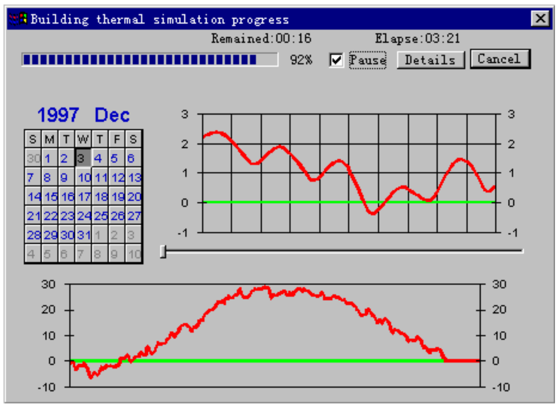
DEST runs on Windows 95/98/NT. All the programs are integrated with CABD. CABD (Picture 5) is an interface based on AutoCAD R14. Users describe the building and launch other program from it. An database includes all the information about the buildings (materials, geographic data, internal heat disturbance, etc) is behind the graphic interface It takes about 1~3 hours to finish all the definition of a building shown in picture 5 in CABD. To get weather data, the user picks the city name from Chinese map in Medpha (Picture 6) and sets the output format. Medhpa will produce the hourly weather data and establish the link between the data and building simulation program.



Picture 5: Outlook of CABD

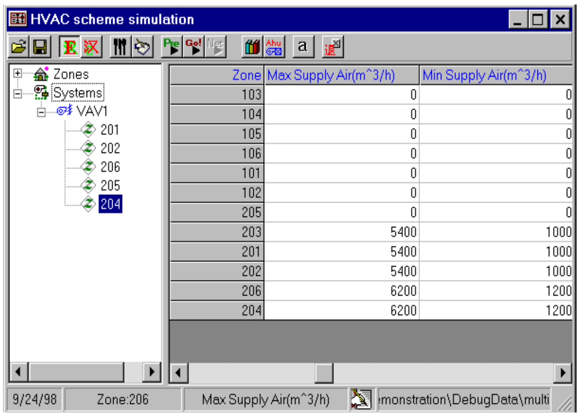


Picture 6: Medpha (Meteorological Data Producer for HVAC analysis)

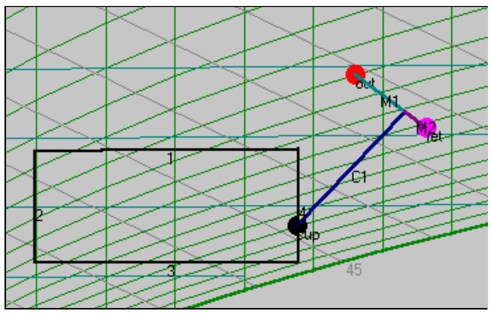


Picture 7:BAS (Building Analysis and Simulation)

When doing the building simulation, the hourly room base temperature calculated is shown in the BAS simultaneously (Picture 7). Interface of scheme simulation is shown in picture 8. All the parameters (system options) can be adjusted here easily. When scheme simulation is running, dynamic air handling process is drawn in the psychometric chart (picture 9) so that the designer can understand why and how the supply air state and optimal air handling process are selected.



Picture 8: Scheme simulation

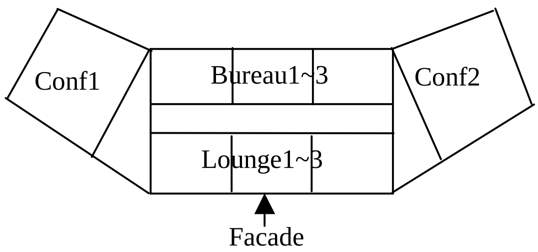


Picture 9: Air handling process in psychometric chart

ActiveX, DLLs and ARX modules are developed to integrate all the programs into one system. The purpose is to reduce the time on preparing input data so that the designer can put all his attention on analyzing the simulation results. The results are in plain text format and could be easily imported into powerful data analysis tools such as EXCEL. When the use are familiar with the interface, the time spent on preparing data and running the program is about ¼ or less of the time consumed on analyzing.

WHAT CAN BE PRODUCED BY DEST?

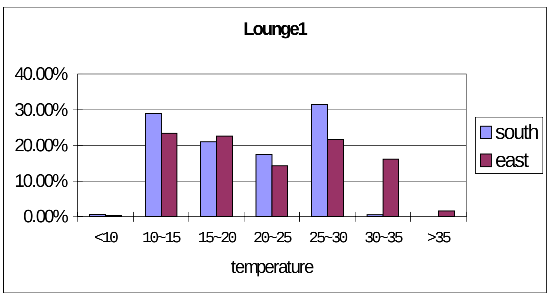
In this section, Two examples are introduced to demonstrate how to use DEST in different design phases. One is ANNEX 30 Case study 1, which is a nine-floor office building in German. The Belgium weather data is used in simulation. Each room should be controlled to 22~26C, RH 40~60%. Detail information can be found in [11]. Picture 10 is the sketch map of the building. The other one is a commercial building (picture 13) in TIANJING, China



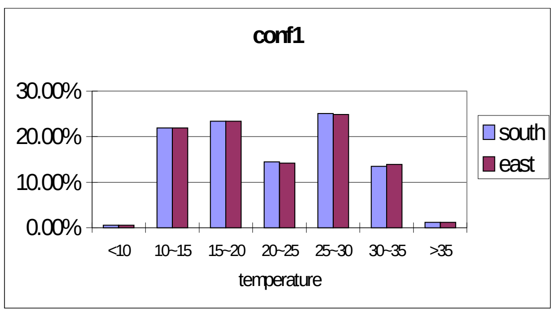
Picture 10: Sketch map of case study 1 building

- Preliminary design

In this phase, two different building orientations are compared by RBT distribution. The following two chart show two rooms' RBT distribution under different facade orientation (south and east).



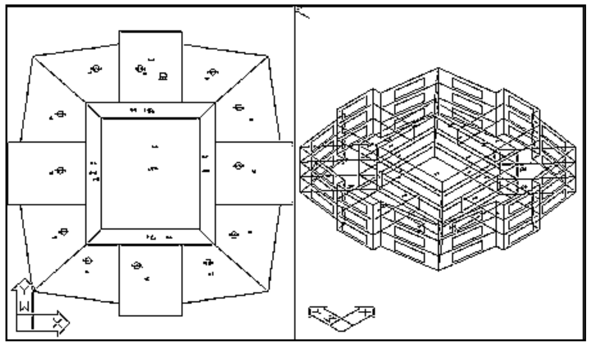
Picture 11: RBT distribution of Lounge1



Picture 12: RBT distribution of Conf1

From the results, the designer can know very well the influence of orientation. For rooms like Conf1, facade is not a sensitive factor. But the orientation has very strong influence on rooms like Lounge1 because the solar radiation.

- Schematic design, system type comparison



Picture 13: Standard layer of office building in Tianjin

This building in picture 13 is a hotel in Tianjin. FCU system is planed to used to condition the rooms in different orientation. The requirement for room temperature varies from 22C to 28C. According to different required precision, the demand for FCU system is different. Especially in transition season, the higher control precision needed, the longer period is required for the plant to supply both hot and cold water at the same time.

Three kinds of precision are considered, the corresponding room setpoint temperatures are shown in table 2.

Precision	Setpoint of some rooms
±1°C	21±1,23±1,25±1
±2°C	22±2,24±2,26±2
±3°C	23±3,24±3,25±3

Table 2: Three kinds of precision to simulate

Scheme simulation are carried out under different precision and the requirement for plant to supply hot water and cold water simultaneous are counted, table 3 is the results.

Month	Mar		Apr		May	
precision	Hot	Cold	Hot	Cold	Hot	Cold
±1°C	744	304	604	450	345	709
±2°C	744	175	579	204	272	525
±3°C	665	13	315	47	9	288

Month	Sept		Oct		Nov	
precision	Hot	Cold	Hot	Cold	Hot	Cold
±1°C	256	684	589	544	720	149
±2°C	169	569	571	323	720	75
±3°C	5	366	366	53	668	11

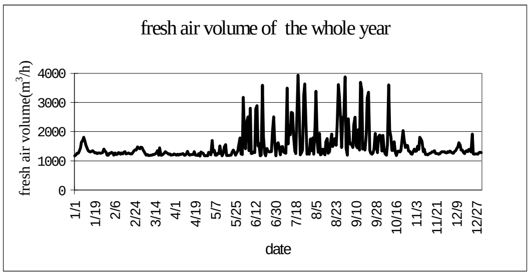
Table 3: Hours required to use four pipe system

In table 3, Hot means hot water is required. Cold means cold water is need in the month.

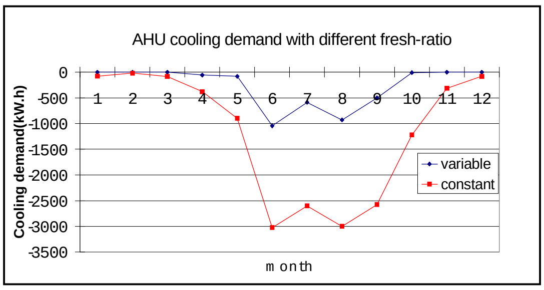
From the results it's quite obviously that four-pipe FCU system is needed when the precision is high. The plant has to supply both hot and cold water in transition season. If lower precision (±3°C) could be accepted, two-pipe FCU can meet the requirement with only 138 hours unsatisfied in six months (13 hours in March, 47 hours in April, 9 hours in May, 69 hours in September, October and November). In the 4th, 5th, 10th and 11th month only hot water is supplied. From 6th to 9th month only cold water is needed.

- Schematic design, system operation manner comparison

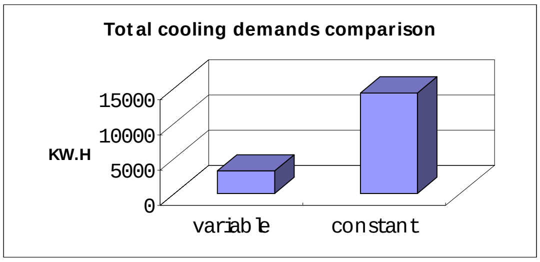
In case study 1, a VAV system is selected to condition all the eight rooms. Because the weather in Belgium is not so hot in summer, fresh air strategy affects the energy required of AHU significantly. Two fresh air strategies are compared: 30~100% variable and 30% fixed. Picture 14 and 16 show the results.



Picture 14: Required fresh air volume in the whole year (30~100%)



Picture 15: Monthly cooling demand under different fresh air strategy

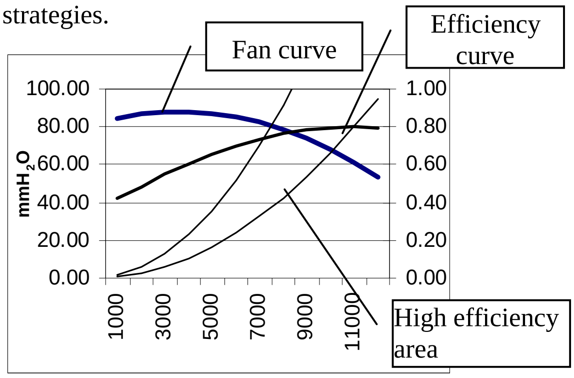


Picture 16: Total cooling demand comparison

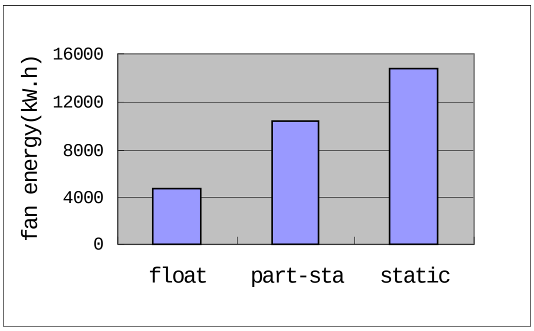
Picture 14 shows the evolution of required fresh air volume. In winter, the less fresh air, the more energy saved. From May to October, system could benefit from using more fresh air. During this period, more fresh air volume are required to reduce the cooling demand for AHU. Because the Belgian weather is rather cool in summer, about ¾ cooling energy could be saved by using more fresh air. Thanks to inverse calculation, this kind of simulation doesn't consume much time and the designer can know very well about difference between two strategies from the results.

- Detailed phase, fan selection

In case study 1, after all the fan working points are calculated (picture 4), the designer could use DEST to calculate the fan energy consumption during the whole year. Picture 17 is the fan curve provided by manufacture and picture 18 shows the different energy consumption under different pressure control strategies.



Picture 17: fan performance curve



Picture 18: Fan energy consumption under different pressure control strategy

Three kinds of pressure control strategies are compared: float pressure point, keep static pressure point at the export of fan and keep the static point at 2/3 distance to the fan. Using float pressure control could save about 2/3 fan consumption during the whole year because most the working points are located in high efficiency area. This comparison is useful either in the detailed design phase to chose suitable pressure control strategy, or in the retrofit phase when the building owner want to reform his HVAC system.

- DEST could also be applied in selecting AHU component under whole working points, determine the proper (optimal) operation of cooling plant, etc. The key point here is to produce reasonable all working conditions based on detailed consideration of known part then use them as the input (requirement) for designing the unknown part.

CONCLUSIONS

- Compare with "traditional" simulation software, the simulation methodology of DEST is different. Inverse calculation method, using detail model for known components and "ideal" process to describe unknown component, using different program in different design stage and integrate them into one system, all these treatments make DEST closer to realistic design process. Designer can use it to compare different design options in each design stage.

- It's more reliable to design under all possible working conditions. DEST can calculated annual hourly requirement at each stage (required supply air volume, required supply cold water flowrate, etc) so that the design can be expanded to whole process design rather than single point design.

- In design process, it's very important to reduce the time consumed on preparing input data. Thanks to the well integration and friendly interface, DEST is very convenient for design purpose. Till now, DEST has been used in about 20 commercial projects in China successfully.

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NOMENCLATURE

t_k: Air temperature of room k

d_k: Air humidity of room k

Q_k Heating or cooling energy put into room by FCU or heat terminal

G_k:upply air volume for room k

$t_{k,base}$:Room base temperature of room k

A,A_j,B_j: Coefficients

t_{supply}: Supply air temperature of AHU

d_{supply}: Supply air humidity of AHU

$t_{k,set,min},t_{k,set,max}$: Room k's temperature setpoint range

$\phi_{k,set,min},\phi_{k,set,max}$: Room k's relative humidity setpoint range

$G_{k,min},G_{k,max}$: Supply air volume range to room k (VAV system)

$Q_{k,min},Q_{k,max}$: Capacity range of FCU or heat terminal of room k

t_{out},d_{out}: Outside air temperature and humidity

t_{return},d_{return}: Returned air temperature and humidity of AHU