HVAC DESIGN INFORMED BY ORGANIZATIONAL SIMULATION

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ABSTRACT

One of the major factors in HVAC design is the occupant load, both in terms of heat gains and fresh air needs. Internal heat gains that result from human occupancy, commonly use a predicted maximum occupancy and an estimated occupancy diversity factor. This may have two problems. First, the maximum number may be far away from true value, Secondly, in a dynamic organizational environment, it is not easy to get a good estimate of the occupancy diversity factor. This paper comes up with a new approach that informs the HVAC design process by organizational simulation. By augmenting the traditional load design procedure with organizational information, it is expected that a more accurate building load estimate can be achieved, resulting in more accurate HVAC sizing. This paper investigates this expectation.

MOTIVATION

HVAC design typically involves two processes, load calculation and system selection. The load calculation step involves calculation of the cooling load, heating load, and ventilation load. A typical human body emits a total of 119W (including sensible heat and latent heat) while sitting in a 20 °C still environment (Porges, 1982). The human emitted heat can be a significant part of the total load, especially in occupant-dense spaces, such as a theater or a conference room. Outdoor air ventilation requirement is another variable that depends on the number of occupants in a space. It can range from 60 cfm/person in a smoking lounge to 5 cfm/person in a lobby (Proges, 1982). It is quite common that a large portion of HVAC energy is devoted to conditioning the fresh air.

To calculate exactly the cooling load and heating load, one needs to know at each period how many people there are in each thermal zone. For some buildings, such as an office building, this information is usually well known in advance and specified in the design program. However, for special type buildings, like hospitals, this information is not known as accurately. The occupant flows in these buildings are dynamic because: (1) the customer arrival rate is changing at different times of the day and at different days during the week; (2) the availability of resources (processing stations) and possible queuing in front of resources makes the service time a varying number; (3) different customers have different needs and are hence part of different flow processes. Because of above reasons, it is difficult, and sometimes even impossible to get a good estimate of the occupancy numbers for special type buildings, in which complex processes are enacted.

The calculation of fresh air flow rate may require even deeper inspection of process information than the calculation of cooling and heating loads. This is because the fresh air flow rate depends on zoning and zone function, i.e., the designer needs to correlate occupancy patterns to each different function space in the thermal zones, which can be very difficult for a complex multi-zone building with varying functions in dedicated places.

A designer can choose the worst case situation to design a system, based on an estimate of the maximum occupancy that simultaneously appears in all zones. Designing for this worst case would presumably satisfy the needs in all situations. This, however, leads to unnecessarily large sizes of equipments, which in turn leads to a low efficiency of these equipments in average operation. A common practice is to multiply the calculated load by a diversity factor, which takes into account the variable nature of occupancy. In a dynamic building environment, the diversity factor is difficult to judge, hence our objective is to inspect the adequacy of this approach by comparing it to simulation generated occupancy patterns. To accomplish this, we propose to deploy organizational simulation to provide the information needed in the load calculation stage. In the next section, a brief review of organizational simulation is given. Then a new load calculation methodology is proposed, followed by a demo design case in which we show how to derive the necessary outdoor air intake flow rate. The conclusion is given in terms of when and how organizational simulation is important, reflecting on its benefits against its costs.

ORGANIZATIONAL SIMULATION

Organizational simulation is used to study the behavior of an organizational system. It is widely applied to manufacturing processes, healthcare processes, airports, supply chains, infrastructure operations, etc. In healthcare simulations there are many different system levels that lend themselves to simulation. At the highest level we can study healthcare as a complex adaptive social system (Rouse, 2008). At the meso level one can study the operation and management of a whole hospital with or without dispersed clinics. At the micro level, one typically studies single departments of a health care facility, such as the emergency department (ED) or intensive care unit (ICU). In an ED study, the typical goal is to reduce the patient length of stay in the ED and increase the staff utilization efficiency, which in fact may be conflicting goals. Using Arena, a general purpose organization simulation software, Guo (2004) established a model for an out-patient clinic, and compared the performance of several out-patient scheduling types. Blake (1996) used organizational simulation to analyze the emergency room of a children hospital, concluding that using 'fast track' processing and increasing physician hours can decrease the patient waiting time. This type of research focuses on improving the organization's overall performance by changing the number and allocation of resources (beds, nurses, doctors,etc), or by optimizing the flow process (e.g. changing appointment schedule, introducing a "quick treatment" option in the ED). Other related research uses organizational simulation to develop unprecedented systems, to advance the organization's ability to learn, and to simulate each individual's decision making behavior and the organization's aggregated behavior as a whole (Rouse, 2005).

The technique used in organizational simulation is typically discrete-event simulation (DES), since it is customary to assume that all observable actions of individuals in flow processes are discrete. The process logic is described at the system level, i.e., in a top-down fashion. If this assumption does not hold, one can resort to describing the actions at the individual level, typically leading to agent-based modeling, or bottom-up approach (Parunak, 1998). Developments in computer science have greatly enabled and pushed the popularity of these approaches, leading to tools such as MedModel (Charles, 2000), which is based on ProModel (Harrell, 2004), and Arena (Guo, 2004), all of which are used, although still sparingly, in the design of healthcare processes and facilities.

To summarize, organizational simulation has been accepted as a powerful tool to study the behavior of complex systems. Our objective is to verify whether the related techniques and tools are relevant to be front-ended to building design tasks, especially those performed by HVAC designers.

METHODOLOGY

The theoretical interdependence between organizational simulation and HVAC design is shown in Fig.1.

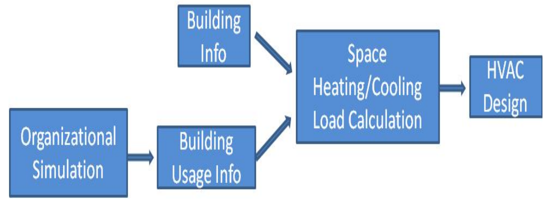


Figure1 Information Dependence

The HVAC designer is concerned with the number of occupants in each specific space at different times. This information can easily be generated by discrete simulation, usually in the form of time series or frequency distribution. It should be recognized that the generated information changes under different organizational operation modes, for example, full-load mode or partial-load mode. It is up to the HVAC designer to find the worst case situation, and conduct the load calculation accordingly.

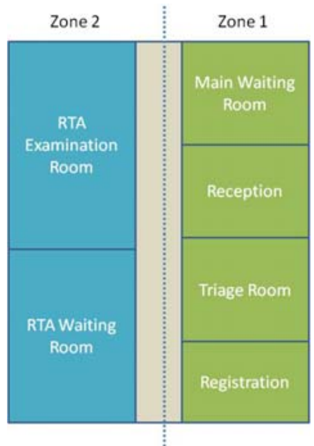
The principle of this approach is to use the information generated from organizational simulation to feed into the HVAC design procedure. Based on this principle, a 4 step procedure is proposed:

- Step1. Construct the organizational simulation model, with variables describing the pertinent organizational dynamics.
- Step2. Divide the building into thermal zones, and use the range of organizational parameters within acceptable ranges to find the most occupant dense cases for each zone.
- Step3. For each case found in step2, run coupled organizational simulation and building simulation to find the design load for each thermal zone.
- Step4. Based on the results of step3, adjust the thermal zone divisions, and repeat step 2, until an optimal outcome is found.

The next section introduces an ED case, for which the outdoor air intake flow rate is calculated following both the traditional procedure and the procedure advocated here, and then compared against each other.

CASE STUDY

The demo case is part of an ED. It has a main waiting area (where patients wait for reception, triage and registration), a reception area, triage rooms, registration blocks, a RTA (rapid treatment area) pod, and a RTA waiting area. It can be divided into two thermal zones: Zone 1 and Zone 2 (as illustrated in Fig.2). Zone 1 is used by almost all patients, and is referred to as the front area in hospitals. To distinguish the severity level of patients, the Emergency Severity Index (ESI) is used. ESI is a five-level stratification of patients into five groups from 1 (most urgent) to 5 (least urgent) on the basis of acuity and resource needs. After all patients have gone through processes in zone 1, less severe patients (typically ESI level 4 and 5) go to the RTA area for treatment, while high severity patients (typically ESI level 2 and 3) go to areas with more equipments and laboratories (the process flow chart is illustrated in Fig.3). The patient arrival data as well as ESI level distribution data is provided by the hospital owner or operator organization (as illustrated in Fig.4 and Table 1). It is assumed that the patient arrival rate follows a Poisson distribution, the mean value changes at different hours during the day, and the typical day distribution of arriving patients is usually assumed to stay the same during the whole year unless compelling evidence says differently.



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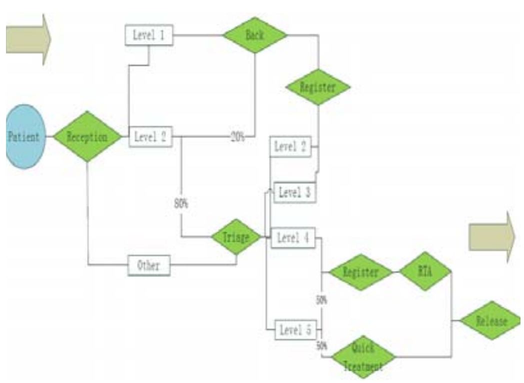

Figure3 Patient Flow Process Chart

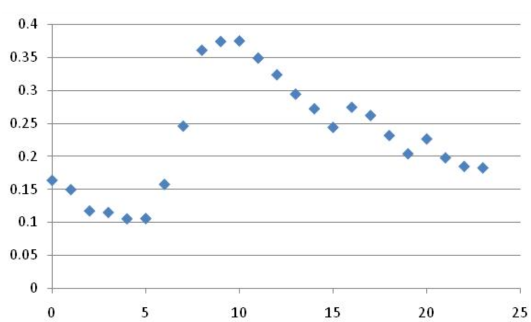

Figure4 Total Patient Arrival Rate (unit: per/min)

Table 1: Patient ESL Level Distribution

ESI LEVEL	WALK-IN	AMBULANCE
1	0	0.005
2	0	0.295
3	0.107	0.7
4	0.763	0
5	0.13	0

Traditional Procedure

Following ASHRAE standard 62-2001 and Addendum 62n, the calculation is conducted as following;

- Look up the minimum people outdoor air rate (R_p) and minimum area outdoor air rate (R_a),
- Estimate the maximum zone population (P_z) and zone floor area (A_z), using the following equation to calculate the breathing zone outdoor airflow:
$$V_{bz}= R_p * P_z + R_a * A_z$$
- Look up the air distribution effectiveness (E_z) based on the air distribution configuration (Overhead diffusers are used in this case)
- Use the following equation to calculate the zone outdoor air flow rate (V_{oz}) for both cooling mode and heating mode, and pick the larger one.
$$V_{oz}= V_{bz}/ E_z$$
- Based on design cooling load and primary temperature, determine the design zone primary air flow (V_{pz}). Considering the occupant/ equipment density and usual cooling standard, it is assumed that the primary zone air flow for Zone 1 is 4140 cfm (1.8cfm/sqft), and the primary zone air flow for Zone 2 is 5400cfm (2.7cfm/sqft).
- Establish a minimum primary zone air setting; in this case it is set to be 0.3 for Zone 1 and Zone 2.
- Find the primary zone outdoor air fraction using the zone outdoor air flow V_{oz} and zone primary air flow V_{pz} based on the equation below:
$$Z_p= V_{oz}/ V_{pz}$$
- Look up system ventilation efficiency E_v based on Z_p; it is found to be 0.64 and 0.6 respectively for Zone 1 and Zone 2.
- Calculate occupant diversity D, and find the uncorrected outdoor air intake V_{ou} flow rate using the following equation:
$$V_{ou}=D*\sum(R_p * P_z)+ \sum(R_a * A_z)$$
- Finally, the design outdoor air intake flow rate V_{ot} is calculated using the following equation:
$$V_{ot}=V_{ou} / E_v$$
The result is 698 cfm for Zone 1 and 978cfm for Zone 2.

New Approach

After running the organizational simulation, the following targets are expected to be achieved:

(1) More accurate Peak zone population Pz.; It is quite possible that the number of patients in each zone is different from their design value.

Table 2. Outdoor Air Flow Calculation (Traditional procedure)

						Cooling		Heating		
Variable	R_p (cfm/p)	R_a (cfm/sqft)	P_z (p)	A_z (sqft)	V_{bz} (cfm)	E_z	V_{oz} (cfm)	E_z	V_{oz} (cfm)	V_{ot} (cfm)
Zone1				2300	503		503		628.75	698
Waiting area & Reception	5	.06	25	500	155	1.0	155	0.8	193.75	
Triage Area	10	0.16	10	1000	260	1.0	260	0.8	325.00	
Registration	5	0.06	8	800	88	1.0	88	0.8	110.00	
Zone2				2000	722		722		902.50	978
RTA Exam Room	25	0.25	6	800	350	1.0	350	0.8	437.50	
RTA Waiting	5	0.06	60	1200	372	1.0	372	0.8	465.00	

(2) More accurate Occupancy Diversity; the estimated number of occupants in the system is assumed to be 2/3 of the peak population, and organizational simulation results will shed light on this assumption and allow a more accurate estimate.

(3) As a consequence of above results, a more accurate design outdoor air intake flow rate emerges.

- Step1. Build the organizational simulation model

The organizational simulation model is built using Anylogic 6.3. A run time screen can be viewed in Fig.5. All the staff variables can be changed as process variables. A corresponding flow process implementation can be viewed in Fig.6.

Feeding the organizational model with the assumptions made in terms of patient ESI-level distribution and patient arrival rate table, as well as various resource utilization time, the simulation model was run for a relatively long time (3 months). The information of concern was averaged over the simulation period. The resulting organizational simulation output can be viewed in Table 4.

It is important to note that we not only get the peak zone population and occupancy diversity from the organizational simulation, but also calculate the required ASHRAE standard compliant ventilation rate directly in the organizational simulation. In this sense, organizational simulation and ventilation rate calculation are integrated with each other.

- Step2. Divide the building into thermal zones, and then vary the relevant dynamic factors in their allowable range to find the most occupant dense case for each zone.

As shown in Table 3, four operational scenarios are considered in this study. To illustrate the importance of organizational simulation, we first assume the total number of staff is fixed, whereas the number of staff in the other scenarios is allowed to vary at each process step, in line with different organizational procedures that are commonly deployed in practice.

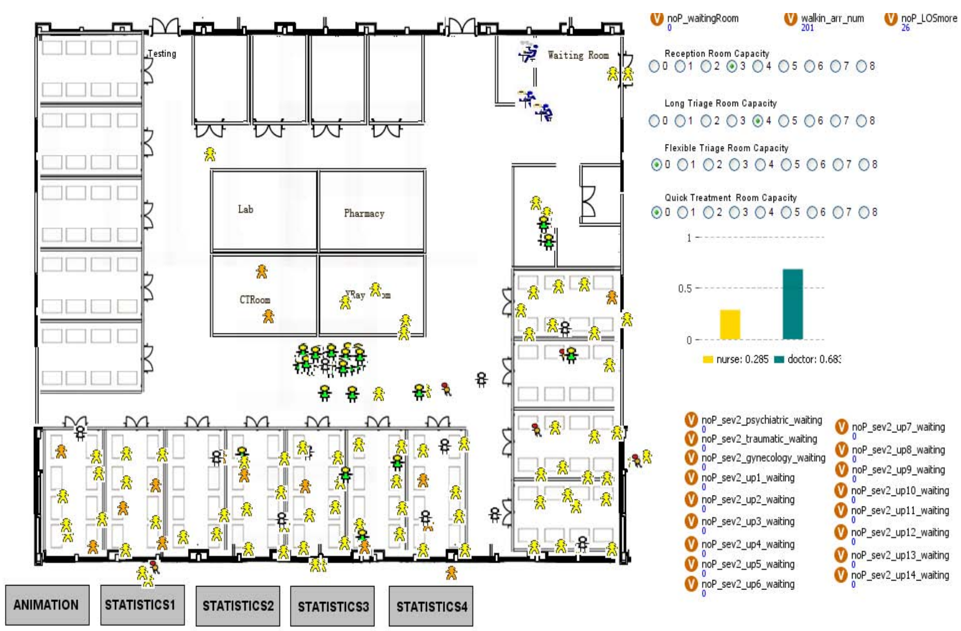

Figure5 Model Runtime Screenshot

The simulation outcomes for each scenario are listed in the table. It can be seen that the peak load in zone 1 and zone 2 happens in scenario III and scenario I respectively. Therefore, these two scenarios are chosen as the worst (design) scenarios for further calculation.

Table3 Simulation Scenarios and Results

	I	II	IV	IV
Reception Clerk	3	3	3	3
Triage Nurse	4	5	4	3
Registration Clerk	4	3	3	4
RTA Doctor	3	3	4	4
Zone1 Avg Population	20	51	55	31
Zone2 Avg Population	21	16	14	15

- Step3. For each case found in step2, and organizational simulation and a building simulation are run to find the best estimate of the design load for each thermal zone.

The simulation run period is set to be 3 months. Every minute, the number of occupancy in the system is automatically updated and the required outdoor air flow rate at each time step is calculated based on following equation:

$$V_{bz}= R_p * P_z + R_a * A_z$$

R_p, R_a stand for ventilation rate per person, per area, respectively. P_z , A_z stand for number of occupancy at each time step, zone area respectively.

After the required uncorrected ventilation rate is recorded for each time step, the design ventilation rate is found based on the 80% principle: the system needs to meet the need 80% of the time. The number 80% is a rule of thumb. It should be driven by the requirement of clients. For example, if the client is very sensitive to fresh air, then we can adjust the number to 90%. The result is showed in Table 4.

It should be noted that because the calculation of design outdoor ventilation rate is relatively simple (compared to thermal simulation), it can be embedded in the organizational simulation software. For more complex simulation (dynamic all year thermal simulation), it is recommended to use a loose coupling strategy to combine organizational simulation tool with building simulation software. Wetter's approach (2008) to accomplish this in a generic API is a good example of how this can be accomplished with for instance the use of EnergyPlus.

- Step4. Based on the results of step3, adjust the thermal zone division, repeat step 2, until the optimal case is found.

This step is not executed in our test case since the thermal zone is considered as appropriate. So the final result of this case study is that the design outdoor air ventilation rate of zone 1 is 638 cfm; for zone 2 it is 510 cfm.

DISCUSSION

Ventilation requirement is not satisfied

It is quickly found from routine use of organizational simulation that the patient flow is affected a lot by adjusting the quantity of resources, even by only a small value. In this case study, after moving one staff from the registration block to the RTA pod, the patient flow that leaves zone 1 and goes to zone 2 is slowed down significantly, therefore the main waiting room gets much more crowded in scenario III than in scenario I. This shows that, although the ASHRAE design load can meet the need in scenario I, it can only meet the need in 20% of the time in scenario III.

If we study the CO_2 concentration in the zones, we expect to find significant differences per scenario. The concentration is calculated based on the assumption that zone 1 is always ventilated under the ASHRAE design load, and that all humans emit CO_2 at a rate of 0.0105cfm. The result in Fig.7 shows that the mean CO_2 concentration is 1800 ppm, and that during 90% of the time it is above the acceptable value of 1000ppm. This is clearly unacceptable. Note that this is calculated under the assumption that the system is always running at the peak load. In reality

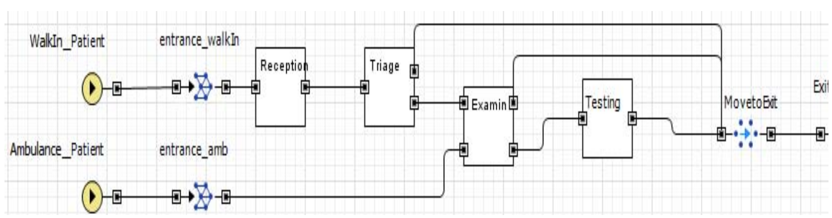

Figure6 Process Flowcharts in Anylogic

Table 4. Organizational Simulation Result

	Scenario I(3-4-4-3)			Scenario III(3-4-3-4)			ASHRAE Design	
	Peak Zone Population (p)	Expected Occupancy in system (p)	Required outdoor flow 80% of the time (cfm)	Peak Zone Population (p)	Occupancy in system 80% of the time (p)	Required outdoor flow 80% of the time (cfm)	Outdoor Airflow Rate (cfm)	Percentage of time that need is not satisfied (%)
Zone1	76	20	413	132	72	638	447	79.5
Zone2	48	21	582	22	16	510	587	0

this may not be the case so the resulting CO_2 concentrations may be worse.

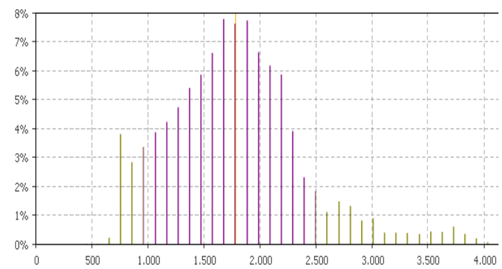

Fig7. CO_2 Concentration in Scenario III

Use of Organizational Simulation

The importance of organizational simulation is obvious. It is easy to verify other options. For instance, after considering the worst case scenario in zone 1, the time that the ventilation load is not met is decreased to 20%, whereas the required capacity of the ventilation system changes by as much as 43%.

In this example, the use of organizational simulation to size the system is critical. This is because the occupancy numbers prove to be very sensitive to different operational scenarios. This is typical when the process environment is very 'dynamic'. Furthermore, we can infer that the more 'dynamic' the environment to be served is, the more important it is to consider different operational scenarios.

Cost/Benefit Analysis

It is difficult to give a quantitative analysis, so let's attempt a general qualitative analysis. On the cost side, the initial software license cost can be assumed to be marginal. The time needed to conduct an organizational simulation is 2-3 days for an experienced worker (if input data is available), so the total cost is 2-3 workdays. On the benefit side, the uncertainty related with HVAC design is reduced by a lot. The costs and damages that may result from the uncertainty in the system sizing is hard to quantify, but intuitively it is clear that the risk of costly refurbishments and eventual litigation far outweighs the modest investment in performing organizational simulation.

CONCLUSION

HVAC system sizing in a dynamic organizational environment should be treated as an organization responsive task. To make sure that the designed HVAC system meets the service needs, each operational scenario needs to be considered and satisfied. Organizational simulation can be used to provide HVAC designers with the information that is needed. The implementation can take different approaches; (1) directly calculate HVAC load in the organizational simulation model, (2) feed dynamic occupancy information into a dynamic building simulation tool, and (3) check how HVAC system performs in different operational situation.

A general load calculation procedure is proposed in this paper. A case study demonstrates how organizational simulation can be used to reduce the risk that HVAC system is poorly designed. The cost/benefit analysis shows that this approach is attractive and potentially mandatory in dynamic organizational processes.

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