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Selection and evaluation of a thermal simulation method for a building simulator

by

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ABSTRACT

A network approach is chosen for a new building simulation program BUS, and a lumped capacitance method (LCM) is selected for the assessment of temperature levels and energy consumption of a building. An implicit solution algorithm is chosen to solve the energy balance equations and temperatures of network nodes. Both the simulation method and simulation parameters (number of thermal nodes and time-step) needed to simulate thermal behaviour of a single building structure reliably are tested by comparing the results of LCM with an analytical solution of a test case. LCM was found to be a reliable and effective sub-program for simulating building heat transfer processes when a material layer exposed to rapid changes is described with at least nine thermal nodes, and time-steps not longer than 5 min are used.

LIST OF SYMBOLS

A	coefficient matrix	-
$\mathbf{b}$	right hand side vector of a linear set of equations	-
Bi	Biot number ($Bi = h\,\Delta x\,k^{-1}$)	-
c	specific heat	J kg^{-1} K^{-1}
c_{pi}	specific heat of air	J kg^{-1} K^{-1}
c_{ph}	specific heat of steam	J kg^{-1} K^{-1}
C_i	heat capacity	J K^{-1}
Fo	Fourier number ($Fo = \alpha\,\Delta t/\Delta x^2$)	-
G_{ij}	conductance (heat transfer coefficient multiplied by heat transfer area) between nodes i and j	W °C^{-1}
h	heat transfer coefficient	W m^{-2} K^{-1}
h_i	enthalpy	J kg^{-1} K^{-1}
H_2	h/k	m^{-1}
k	conductivity	W m^{-1} K^{-1}
l_0	latent heat of water	J kg^{-1}
L	length	m
Q	heat flux	W m^{-2}
t	time	s
Δt	time-step	s
T	temperature	°C
Δx	length-step	m
x	distance from zero	m
x'	moisture content of air	kg H_20 (kg dry air)$^{-1}$
$\mathbf{x}$	unknown vector of a linear set of equations	-
α	thermal diffusivity ($\alpha = k\,\rho^{-1}\,c^{-1}$)	m^2 s^{-1}
β_m	positive root of the transcendental equation (3)	-
$\emptyset$	heat load	W
ρ	density	kg m^{-3}

1 INTRODUCTION

If a reliable building simulator was available, alternative construction and ventilation solutions of a building could be tested - and improved if necessary - before actual building and installation work. To achieve reliable simulation results, all the interacting physical phenomena ought to be calculated simultaneously. The aim of this study was selection and evaluation of a suitable thermal simulation method for combined building air flow(1) and heat transfer simulation program BUS.

The modelling principles of time-dependent building thermal analysis programs can be divided into two methods (Fig. 1). Firstly, a thermal process can be simulated by solving the transient heat balance equations. This is called the *heat balance* or *thermal balance method.* The other principle for simulating a thermal process for a time point is to sum up the effects of various load components (e.g. solar radiation, internal heat loads, exterior temperature) using weighting factors; this is called the *weighting factor method.* Most of the modern thermal models are based on the heat balance method (BLAST, SERIRES, HTB2, ESP, TASE), but there are also models based on the weighting factor method - e.g. DOE 2.1 (2).

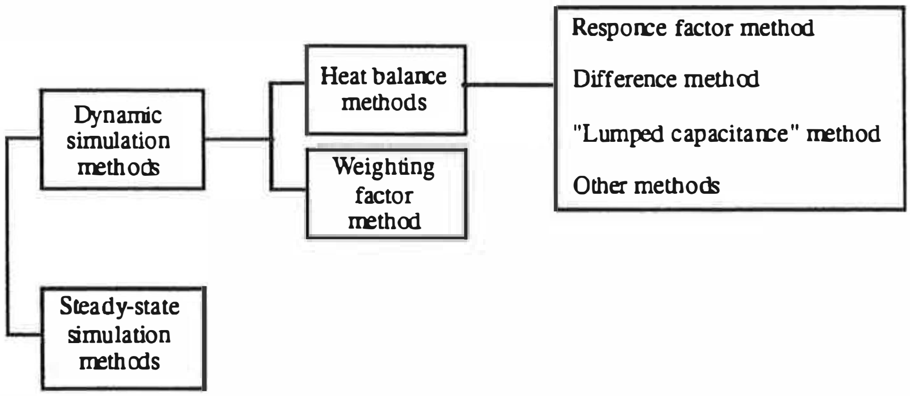

Figure 1. A classification of building thermal analysis methods.

The heat balance method gives more detailed output data than the weighting factor method because the former gives values for interior surface temperature and wall heat flux. The weighting factor method only gives an effective interior temperature, which includes the effects of both air and surface temperatures. In addition, the weighting factor method can only handle linear problems. This means that e.g. the interior heat transfer coefficients must be constant.(2) Because of uncertainties in defining weighting factors and non-physical features of the weighting method, it is rejected from a more detailed study in this context.

When the heat balance method is used, an important point is how the transient heat flux through walls is calculated. BLAST, DOE 2.1 and TASE use the *response factor method* [3]; SERIRES, HTB2, and ESP utilize the *difference method* (Fig. 1). The *response factor method* is a time-series method[4]. A time series of responses - caused by one triangular thermal pulse (usually the base is two hours and height is 1 K) - is calculated for a specific structure. The calculated values of the time series are called response factors, and they can be defined, e.g. by subroutines developed by Mitalas and Arsenault[3]. In this study, the response factor method is excluded from deeper investigation due to the complexity of time series, response factor definition, and transformation of the response factors.

The difference methods are most commonly used with constant increments between thermal network nodes across solid material layers. This causes waste of computation resources in cases with highly non-linear temperature gradients within building structures. Therefore, it would be reasonable to have a possibility to locate more thermal nodes freely in areas with highly non-linear temperature gradients, in order to obtain reliable simulation results without consuming unnecessary calculation resources. A method that allows free placement of thermal nodes is a *lumped capacitance method*. This is a typical approximative network method, where adjacent thermal nodes are connected to each other by thermal conductances, and node temperatures are calculated by solving energy balance equations of the nodes. Inside a single node a temperature gradient is neglected, and that is why such an approach may be used when the dimensionless Biot number (i.e. thermal resistance to conduction within the material divided by thermal resistance to convection across the fluid boundary layer) is small enough.

The lumped capacitance method (LCM) is selected because, as a method, it is extremely straight-forward and very flexible. These are important features when combining building air flow and heat transfer simulations. Since the lumped capacitance method neglects the internal temperature gradients of single nodes, the validity of this method needs to be evaluated. Accordingly, this paper presents an analytical solution of a test case for evaluation of a heat transfer simulation sub-program based on the lumped capacitance method.

2 METHODS

As mentioned above, the *lumped capacitance method* (LCM) was selected for calculating the transient heat transfer process of a building and building structures. Perhaps the main disadvantage of LCM is lack of defining temperature gradient inside a single thermal node. This can lead to severe problems in cases where too few nodes try to describe a highly non-linear temperature gradient inside a building structure, e.g. within conjunction of two insulated external walls. Also discretization can become a problem. Namely, if a non-implicit discretization method was chosen, selection of too long time-step for time-dependent simulations can cause oscillation in a solution, or the whole solution can even diverge. In addition to this, errors will always occur due to discretization itself.

One of the main advantages of the LCM is free description of a thermal process, i.e. definition of thermal capacitances of network nodes. Nevertheless, this very freedom leads us into a problem of smart network generation. Namely, in order to use computation resources effectively, more thermal nodes ought to be placed in areas with highly non-linear temperature gradients; whereas less nodes are needed within areas with modest temperature gradients. Because of this, an optimal number of nodes ought to be defined inside single building structures, in order to obtain reliable simulation results using a reasonable amount of computer resources. This number of thermal nodes within a single material layer is studied later in this paper for a test case.

In order to evaluate the accuracy and reliability of LCM, a severe building wall structure test case, with a step change in outdoor air temperature, was adopted. This test case is solved both analytically and using LCM. When testing the main principles of LCM, this first version of the program neglects heat radiation, and only heat conduction and convection are included. In the near future, both long- and short-wave radiation will be added to the building simulation program BUS.

2.1 An analytical solution method

The general, one-dimensional Fourier heat transfer equation, without internal heat generation, can be written as:

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial x^2}. \tag{1}$$

By separating the variables, a solution of this differential equation (with boundary conditions $\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0$ and $\left.\frac{\partial T}{\partial x}\right|_{x=L} + H_2 T = 0$, and uniform initial temperature of T_0) can be expressed as[5]:

$$T(x,t) = 2T_0 \sum_{m=1}^{\infty} e^{-\alpha\beta_m^2 t} \frac{H_2}{L(\beta_m^2 + H_2^2) + H_2} \frac{\cos(\beta_m x)}{\cos(\beta_m L)}, \tag{2}$$

where β_m are positive roots of the transcendental equation[5]:

$$\beta_m \tan(\beta_m L) = H_2. \tag{3}$$

For time $t = 0$, equation (2) simplifies to[5]:

$$1 = 2\sum_{m=1}^{\infty} e^{-\alpha\beta_m^2 t} \frac{H_2}{L(\beta_m^2 + H_2^2) + H_2} \frac{\cos(\beta_m x)}{\cos(\beta_m L)}, \tag{4}$$

which is a formal representation of unity in the interval $0 < x < L$ in terms of the eigenfunctions cos $(\beta_m x)$ of the considered heat-conduction problem.[5]

2.2 The lumped capacitance method

Building thermal response can be estimated by a network model (i.e. *lumped capacitance method*, Fig. 1). In such a model, heat loads and casual gains are applied to nodes, and heat in the process is either stored in the thermal capacities (C_i) of the nodes or transferred via a connection path with conductance G_{ij} between nodes i and j. System identification consists of defining a network approximation of the building and assigning numerical values to every conductance and capacitance[6]. This kind of model can be used with reasonable confidence when the Biot number is smaller than 0.1[7].

The time derivate of the general heat transfer equation (1) can be approximated by a linearization:

$$\left.\frac{\partial T}{\partial t}\right|_j = \frac{T_j^{p+1} - T_j^p}{\Delta t}, \tag{5}$$

where $(p+1)$ denotes the next time-step and (p) the present time. Different approaches can be selected for a linearization of the term $\partial^2 T(t,x)/\partial x^2$. The three most common discretization methods are the explicit method (Euler method), the implicit method and a combination of these (for example Crank-Nicholson).

In the explicit method, the new temperature of a node can be calculated from present known values of a node and its neighbours. A stability criterion for internal nodes can be defined: for pure (one-dimensional) finite-difference method (with constant Δx) the time-step and the length between nodes have to be selected in such a way that the Fourier number ($Fo = \alpha \Delta t / \Delta x^2$)becomes smaller than 0.5 - otherwise there will be oscillation in the solution. If the Fourier number exceeds 1.0, the solution becomes unstable and will diverge. The benefit of the explicit method is the simplicity of the solution.

In the fully implicit method, the new temperature of a node is calculated by new temperature values of all nodes. In this case, heat balance equations of every node have to be solved simultaneously, and this way the solution becomes far more difficult compared with the explicit method. The main advantage of this method is stability, in other words there will be no oscillation.

The Crank-Nicholson method is a combination of the methods mentioned above. The new temperature is calculated as an average of the known present value and the new values of temperatures of nodes. In this case, longer time-steps can be selected than in the explicit method, because the Fourier number has to be larger than 1.0 in the pure (one-dimensional) finite-difference method before there will be oscillation in the solution. In addition to this, the solution always converges, though the solution can be physically wrong when large Fourier numbers are used.(7)

There are two basic error sources when the difference method is used, namely round-off errors and errors due to discretization. Round-off errors occur when there are not enough significant numbers. Accumulation of round-off errors can become critical in the simulation of large processes when a great number of mathematical operations are needed to reach the solution. Such errors can be avoided by careful planning of the solution method, by using the double expression if possible, and by using numerical methods higher than first order. Errors in discretization are due to replacing the exact derivatives by approximative differences. This kind of error cannot be totally avoided, but it can be minimized by reducing the time-step in the solution, by selecting the nodes in the structure, and by planning the discretization method carefully. In order to achieve an acceptable accuracy in transient heat flux modelling, three nodes ought to be used to describe each element of the whole structure(8).

Where the stability of a numerical solution of a heat balance in a building is concerned, the surface node of the structure is the most critical point which determines the time-step. For example, the stability criteria of the explicit (one-dimensional) finite-difference method become $Fo\ (1 + Bi) \leq 0.5$, where $Bi = \alpha\ \Delta x/\lambda$ is the Biot number. The higher the Biot number is, the smaller the Fourier number has to be.

In the lumped capacitance method (LCM) a fully-implicit discretization has been chosen. This is done to avoid oscillation, and to achieve coherent formulation with an earlier developed air flow simulation method(1). Therefore, a general energy balance equation for a single node, where the mass transfer between nodes is also included, can be written as:

$$C_i \frac{T_i^{(p+1)} - T_i^{(p)}}{\Delta t} + \sum_j G_{ij}\left(T_i^{(p+1)} - T_j^{(p+1)}\right) + \sum_j \dot{m}_{ij}^{(p+1)}\, h_{ij}^{(p+1)} = \emptyset_i^{(p+1)} \quad , \tag{6}$$

$$\text{where } h_{ij}^{(p+1)} = \begin{cases} c_{pi}\ T_i^{(p+1)} + x_i\left(l_0 + c_{ph}\ T_i^{(p+1)}\right);\ \dot{m}_{ij}^{(p+1)} \geq 0 \\ c_{pi}\ T_j^{(p+1)} + x_j\left(l_0 + c_{ph}\ T_j^{(p+1)}\right);\ \dot{m}_{ij}^{(p+1)} < 0 \end{cases} \quad . \tag{7}$$

A heat balance matrix for a whole process (i.e. heat balance equation for every node) can then be expressed as:

$$A\ \mathbf{x} = \mathbf{b}\ , \tag{8}$$

where matrix A defines all the connections between different nodes. (Connection coefficients A_{ij} are defined by time-step Δt, conductances G_{ij} and heat capacitances C_i : $A_{ij} = \Delta t \cdot G_{ij}\ / C_i$.) Vector **x** consists of the unknown temperatures (of the next iteration loop p+1), and vector **b** includes all the known heat capacitances and temperatures (of the previous iteration loop p) and the rest of the heat load parameter values.

3 RESULTS AND DISCUSSIONS

3.1 Definition of a slab test case

Figure 2 presents a simple, transient building slab test case used by Bland(9). The wall is uniform with one material layer, and no internal heat generation exists. In the beginning, the whole system is at the uniform temperature of 293.15 K (20 °C), and suddenly, at time $t = 0$, the outdoor air temperature increases to 343.15 K (70 °C). Selected boundary conditions for the internal and external surfaces are

$$\frac{\partial T}{\partial x} = 0 \ (x = 0) \text{ and } \frac{\partial T}{\partial x} + H_2 T = 0 \ (x = L), \qquad (9)$$

respectively, where $H_2 = h / k$, and the external heat transfer coefficient is $h = 20$ W K^{-1} m^{-2}. This is a case near to a real situation, in which the internal surface ($x = 0$) is faced with an insulation material, and the external surface ($x = L$) is exposed to forced convection due to wind. In this test case, a high temperature gradient near the outdoor surface is introduced in order to test the lumped capacitance method properly.

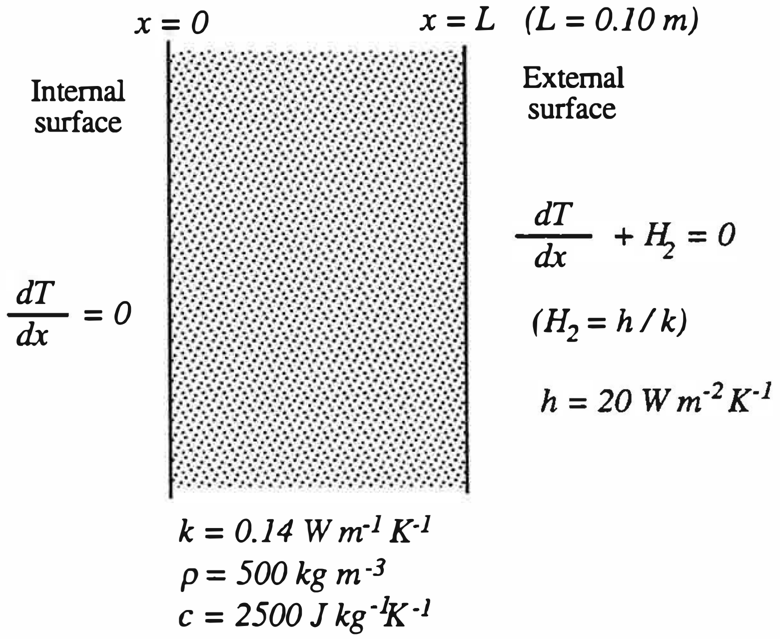

Figure 2. A building slab test case.

3.2 An analytical solution of the slab test case

Most commonly, four or six first positive roots of the transcendental equation (3) are given in traditional heat transfer reference books. In this study, the first hundred positive roots were computed (with increment of 1.0e-15 for each β_m). Table 1 shows analytically solved surface temperatures and heat flux of the test case at different time values during the first hundred hours after the step increase of outdoor air temperature. After the step change of 50 K in outdoor air temperature, the outdoor surface temperature begins to rise more rapidly than other parts of the slab. This causes a non-linear temperature gradient into the slab for the first hours after the step change.

Table 1. Analytically solved surface temperatures and heat flux of the slab test case at different time values during the first hundred hours.

Time [h]	T_i (°C)	T_e (°C)	Q [W m^{-2}]
1.0	20.022	60.678	186.4340
2.0	20.847	63.241	135.1854
3.0	23.102	64.432	111.3584
4.0	26.130	65.164	96.7202
5.0	29.379	65.687	86.2601
6.0	32.576	66.101	77.9846
7.0	35.608	66.450	70.9933
8.0	38.433	66.757	64.8551
9.0	41.044	67.032	59.3515
10.0	43.447	67.282	54.3625
20.0	58.865	68.861	22.7706
30.0	65.332	69.523	9.5460
40.0	68.043	69.800	4.0020
50.0	69.180	69.916	1.6777
60.0	69.656	69.965	0.7033
70.0	69.856	69.985	0.2949
80.0	69.940	69.994	0.1236
90.0	69.975	69.997	0.0518
100.0	69.989	69.999	0.0217

This analytically calculated data (presented in Table 1) is almost identical to data defined by Bland in an earlier study(9). In the beginning of the test period, some minor deviation occurs between these analytically calculated results, which is most likely due to a different number of terms adopted in a solution of series equation (2).

3.3 A solution of the slab test case by LCM

The slab test case defined above was also solved by the lumped capacitance method (LCM). Four different definitions of the same slab were used: in the first case (a), the slab was defined by two equal thermal capacitances; in the second case (b) by three equal thermal capacities; in the third case (c) with four equal thermal capacities; and in the fourth case (d) with five equal thermal capacitances. Heat conductances were defined from the boundary conditions and other properties of the test case (Appendix A). A time-step of 1,800 s (30 min) was used.

In the second LCM test, the same slab test case was used. In order to improve accuracy, the number of thermal nodes was increased. In addition, near the external surface a thicker node network was defined. Namely, thickness of the first thermal node exposed to the step change was selected according to Biot number criterion 0.05. (This criterion gave thickness of 0.00035 m for the first thermal node on the surface.) Thicknesses of the subsequent nodes through the slab were selected according to a geometric series with a ratio of two. This algorithm gave the following increments between the nodes: 0.0007 m, 0.0014 m, 0.0028 m, 0.0056 m, 0.0112 m, 0.0224 m, 0.448 m, and 0.0111 m. The first and the last nodes were located on the external and internal surfaces, accordingly. The conductances of this test were defined from the boundary conditions and thermal resistances within the slab. The thermal capacitances of the nodes were calculated by dividing the mass between adjacent nodes into two equal proportions. This test was performed using three different time-steps: 1,800 s (30 min), 900 s (15 min), and 300 s (5 min).

3.4 Comparison of the slab test case results

Figure 3 presents internal and external surface temperatures during the simulation period of 10 hours, using both analytic and lumped capacitance (with two, three, four, and five thermal nodes) methods. The biggest differences between the results, given by the analytic and the lumped capacitance methods, occur in the beginning of the simulation period. In addition to this, the fewer thermal nodes are used to describe a single material layer, the greater deviations are obtained. In other words, according to this test case, LCM gives reasonable and logical results for transient heat transfer problems.

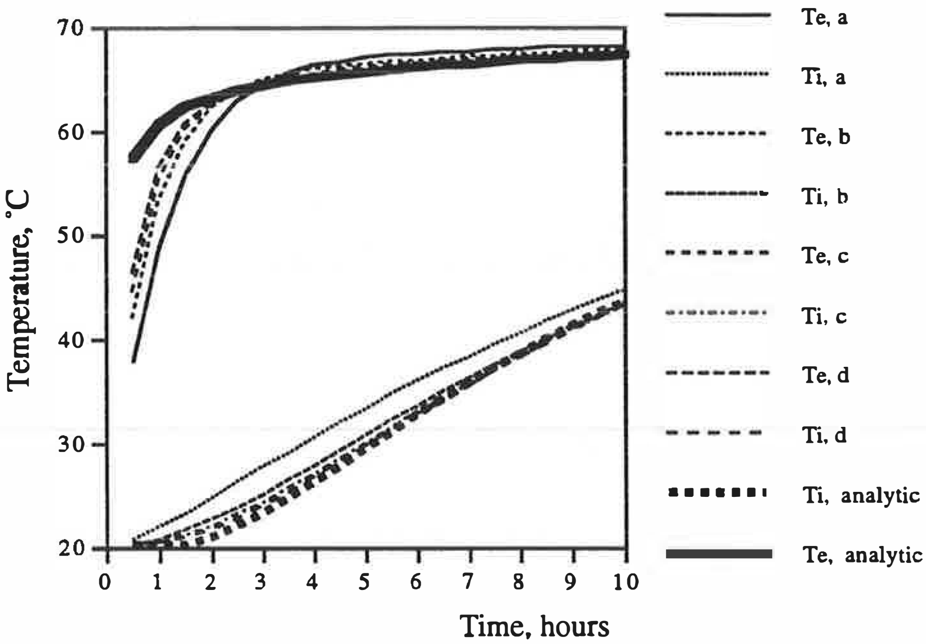

Figure 3. Internal and external surface temperatures of the slab test case during the simulation period of 10 hours, using both analytic and lumped capacitance methods.

Table 2. Analytically calculated time-dependent heat fluxes, and simulated heat fluxes with three and five thermal nodes (and relative differences compared with analytical calculation) of the slab test case.

Time [h]	$Q_{analytic}$ [W m^{-2}]	Q_a (3 nodes) [W m^{-2}]	r.d. [%]	Q_d (5 nodes) [W m^{-2}]	r.d. [%]
1	186.44	337.98	81.28	274.16	47.05
2	135.18	159.38	17.90	148.32	9.72
3	111.36	104.98	-5.73	111.38	0.02
4	96.72	83.92	-13.23	93.36	-3.47
5	86.26	72.72	-15.70	81.70	-5.29
6	77.98	65.04	-16.59	73.02	-6.36
7	71.00	58.94	-16.99	66.02	-7.01
8	64.86	53.78	-17.08	60.10	-7.34
9	59.36	49.26	-17.01	54.92	-7.48
10	54.36	45.22	-16.81	50.32	-7.43

Table 2 presents analytically calculated heat fluxes, as well as simulated heat fluxes (and relative differences) when three and five thermal nodes are used in LCM. After one hour, the relative difference was 47 % between analytically solved external heat flux and the heat flux given by the LCM method even when five equal thermal nodes were used. According to this severe slab test case, the previously suggested three thermal nodes for each material layer of a building structure(8), is not enough to simulate a dynamic heat conduction problem of a building in the tested conditions. In the case of rapid changes in a process, even more thermal nodes are required to predict reliably time-dependent temperature levels and energy consumption of a building. In particular, more thermal nodes ought to be used near surfaces which are exposed to thermal variations.

Table 3 shows calculated external surface temperatures and relative heat flux differences in the second LCM slab test case. As defined earlier, nine thermal nodes (according to a geometric series) were used, and the simulations were performed using three different time steps (30 min, 15 min, and 5 min). According to this second test case, the relative heat flux difference after one hour dropped from 47 % to 21 % when the number of thermal nodes increased from five to nine — the time-step was 30 min in both cases. When the time-step was also decreased to values of 15 min and 5 min, the relative heat flux differences after one hour decreased to 11.2 % and 5.4 %, respectively. In other words, reliable simulation results can be obtained by defining a thicker node network near a surface, and selection of a time-step small enough.

Table 3. Analytically solved and simulated external surface temperatures and relative heat flux differences after one hour in the second LCM slab test case.

Time-step [s]	T_e [°C]	$\Delta Q/Q$ [%]
analytic	60.678	-
1,800	58.741	20.78
900	59.634	11.2
300	60.171	5.4

3.5 A thermal simulation of an artifical building by LCM

An artificial building - presented in Figure 4 - is used in this qualitative building heat transfer test simulation. Figure 5 presents all thermal nodes of the process. The time-dependent effects of a step decrease of 20 K in outdoor air temperature, and the step increase of heating loads in indoor air nodes were studied by the lumped capacitance method. Heating loads (1200 W in nodes 7 and 9, and 2100 W in nodes 6 and 8) were selected in such a way that the steady-state room air temperature levels become close to the inital values before the changes in the process. Tables 4 and 5 show the thermal connections and parameter values used in this building test case. In the beginning the whole system was at a uniform temperature of 293.15 K, and first all air flow rates between the air nodes were assumed to be equal to zero.

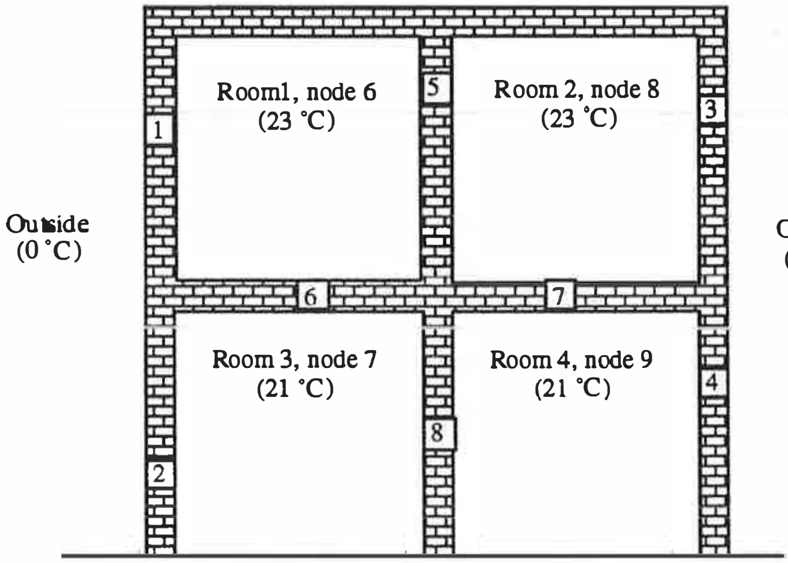

Figure 4. A schematic section of the building test case.

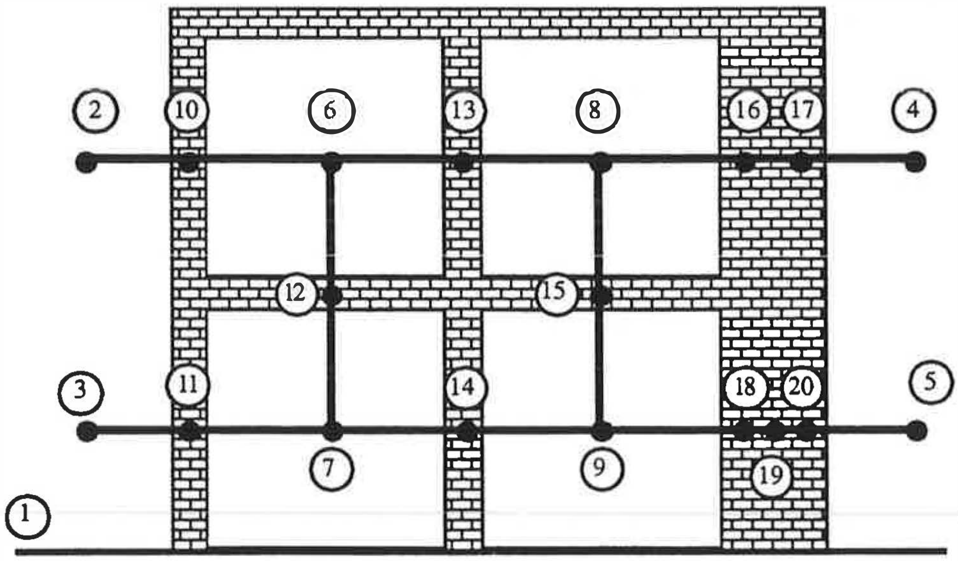

Figure 5. The thermal network of the thermal test case.

Figure 6 presents the calculated air node temperatures during a simulation period of 5 days (120 hours). The maximum temperature levels were achieved in 18 hours. After that the temperatures began to fall because of the transient heat transfer through the building envelope. The temperature deviation between the ground floor rooms (and the first floor rooms) was caused by different structures in envelope network definitions. In this test case, the deviation was as large as 0.40 K between the first floor room air temperatures (nodes numbers 6 and 8) and 0.33 K between the ground floor rooms (nodes 7 and 9) after 12 hours. These deviations decrease with time, and they disappear in the steady-state situation. This test case, as well as a previous study[8], shows the importance of careful planning of network structure in order to achieve reliable simulation results.

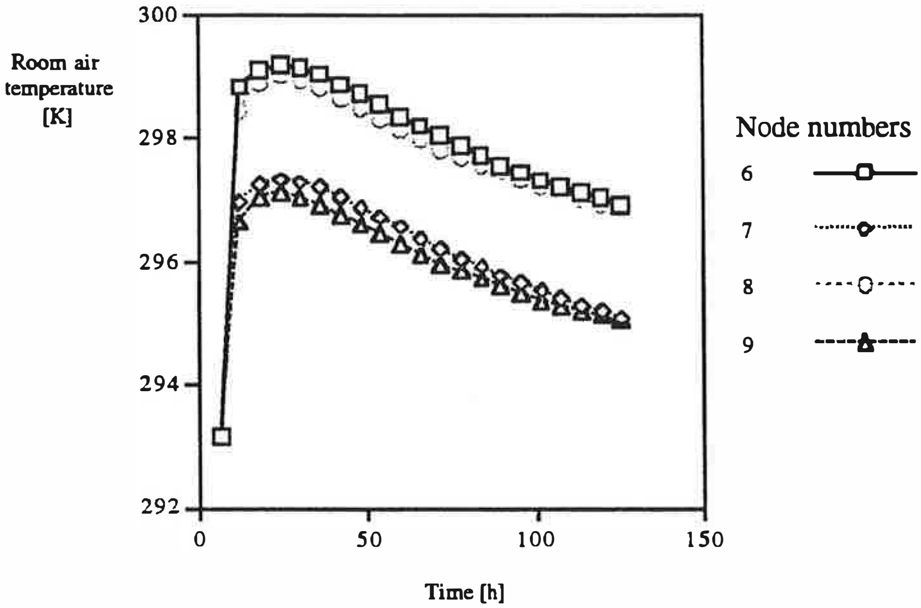

Figure 6. Calculated room air node temperatures of the heat transfer simulation during a simulation period of 5 days (120 h) in the thermal test case.

In the second building test case of this study, air infiltration was included in the heat transfer simulation. A similar heat transfer test - with step decrease of 20 K in outdoor air temperature, and step increase in room air heating loads - was simulated. Tables 4, 5, and 6 show the input parameter values also used in this combined air flow and thermal test case.

Table 4. Thermal conductances used in the building test case.

Thermal connection nodes from	to	Conductance [W K^{-1}]
2	10	175.0
10	6	175.0
3	11	125.0
11	7	125.0
4	17	262.5
17	16	262.5
16	8	262.5
5	20	250.0
20	19	250.0
19	18	250.0
18	9	250.0
6	12	110.0
12	7	110.0
6	13	110.0
13	8	110.0
7	14	110.0
14	9	110.0
8	15	110.0
15	9	110.0

Table 5. Initial temperatures, thermal capacities, and heat loads of the nodes used in the building test case.

Node number	Temperature [K]	Capacitance [J K^{-1}]	Heat load [W]
1	273.15	1.0e32	0.0
2	273.15	1.0e32	0.0
3	273.15	1.0e32	0.0
4	273.15	1.0e32	0.0
5	273.15	1.0e32	0.0
6	293.15	90540.0	2100.0
7	293.15	90540.0	1200.0
8	293.15	90540.0	2100.0
9	293.15	90540.0	1200.0
10	293.15	28336000.0	0.0
11	293.15	20240000.0	0.0
12	293.15	10120000.0	0.0
13	293.15	6072000.0	0.0
14	293.15	6072000.0	0.0
15	293.15	10120000.0	0.0
16	293.15	14168000.0	0.0
17	293.15	14168000.0	0.0
18	293.15	6746666.7	0.0
19	293.15	6746666.7	0.0
20	293.15	6746666.7	0.0

Table 6. Air mass flow rates of the second building test case.

Flow element	Mass flow rate [kg/s]
1	0.029599
2	0.027480
3	-0.032348
4	-0.024730
5	0.028513
6	0.00108
7	-0.003837
8	0.028567

Figure 7 presents the simulated room air tempratures during a simulation period of 120 h (5 days). Compared with Figure 6 (in which the infiltration process was ignored), these temperature levels were totally different. This was due to cold outdoor air (273 K, 0 °C) entering rooms 1 and 3 (node numbers 6 and 7). The temperature level increased only in room 2 (node number 8); in the rest of the rooms temperature levels decreased. This phenomenon is caused by increased heat losses due to air infiltration.

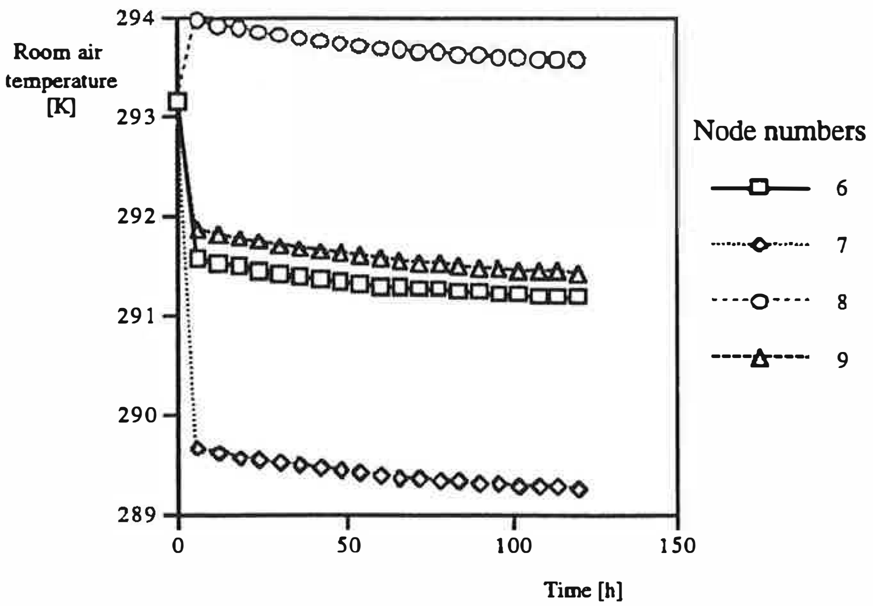

Figure 7. Calculated room air node temperatures of the combined air flow and thermal simulation test case during a simulation period of 5 days (120 h).

As shown in the test case presented above, time-dependent thermal behaviour of a building can become quite complicated. This is due to the capability of heavy and middle weight structures to store heat. For this reason, temperatures in a simulated building process cannot be assumed to be constant if reliable simulation results are desired.

3.6 General remarks

If the common criteria for Biot number ($Bi \leq 0.1$) were used for the slab test case, thickness of a single thermal capacitance in the slab test case would become $\Delta x = 0.0007$ m. This means that the number of thermal capacitances for 0.10 m thick wood slab ought to be 143 (NB). If each material layer of every building structure were described by more than 100 thermal nodes, a lot of both input data generation and calculation resources would be consumed.

According to the tests, good results can be obtained by LCM. However, the method is sensitive to description of building structures, especially to number of thermal nodes. The more rapid transient heat transfer processes are simulated, the more thermal nodes and the shorter time-steps need to be used in order to simulate a process accurately. Under normal conditions, for highly time-dependent cases, a time-step not longer than 5 min and at least nine thermal nodes (with small increment near surface) for a material layer exposed to rapid changes are recommended.

From the energy consumption point of view, accurate thermal simulation seems to be most important. Particularly surface temperatures need to be simulated accurately in order to define heat fluxes reliably. This can be done by careful planning of thermal networks, i.e. by defining several small thermal capacities near to the surfaces, in order to be able to investigate effects of even rapid changes in environmental conditions to whole processes.

From the pure air flow simulation point of view, the effect of even rapid changes in outdoor air temperatures seems to have a relatively slow and modest effect on indoor surface temperatures. For this reason, in future, more attention ought to be paid, for example, to reliable evaluation of internal heat loads, which means simulation of both heating and cooling devices and networks.

Practical problems when using the present version of LCM are both generation of (quite often complicated) thermal network, and selection of parameter values for network nodes and connections. Therefore, special attention needs to be paid in future work to developing more effective interfaces for building simulation programs. Another problem with LCM is exclusion of thermal radiation, but in the near future both short- and long-wave thermal radiation will be included in this thermal simulation model of the building simulation program BUS.

4 CONCLUSIONS

A new thermal network simulation model, based on the lumped capacitance method (LCM), has been developed for the assessment of temperature levels and energy consumption of a building. This building thermal simulation model has been programmed and tested in order to combine it with an existing air infiltration and ventilation simulation model(1). The thermal simulation program was found to be effective in solving the energy balance equations and temperatures of a transient building structure heat transfer process. This is extremely important when developing a reliable building simulation program in which the interacting physical processes are simulated simultaneously.

Several assumptions are made when evaluating the thermal behaviour of a building by this new simulation model. The main assumption is that no temperature gradient exists inside single thermal nodes. This can lead to considerable errors if large temperature gradients occur in a heat transfer process. On the other hand, this effect can be reduced by dividing simulated structures into several thermal nodes (which are connected in series). Still, the temperature gradient caused by changes in complex shapes, for example in corners of a building, remains. Secondly, heat radiation is neglected, and only heat conduction inside material layers and heat convection on surfaces are included in the present version of LCM. Therefore, in the near future both short- and long-wave radiation will be included to this model of the building simulation program BUS.

According to the test cases, reliable dynamical thermal behaviour is very important when evaluating temperature levels and heat losses of a building. As a result, temperatures in different parts of a simulated building process cannot be assumed to be constant if reliable building simulation results in realistic, time-dependent conditions are desired. The new thermal simulation model was found to be a reliable and effective program for simulating building heat transfer processes when a material layer exposed to rapid changes is described with at least nine thermal nodes, and time-steps not longer than 5 min are used.

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Appendix A: Parameter values used in calculation of the slab test case by the lumped capacitance method.

Node number	Initial temperature [°C]	Heat capacity [J K^{-1} m^{-2}]
1	70.0	1.0e32
2	20.0	31250.0
3	20.0	31250.0
4	20.0	20833.3
5	20.0	20833.3
6	20.0	20833.3
7	20.0	15625.0
8	20.0	15625.0
9	20.0	15625.0
10	20.0	15625.0
11	20.0	12500.0
12	20.0	12500.0
13	20.0	12500.0
14	20.0	12500.0
15	20.0	12500.0
16	20.0	1.0e32

From node number	To node number	Conductance [W K^{-1}]
1	2	20.0
2	3	0.7
3	16	1.0e-32
1	4	20.0
4	5	1.4
5	6	1.4
6	16	1.0e-32
1	7	20.0
7	8	2.1
8	9	2.1
9	10	2.1
10	16	1.0e-32
1	11	20.0
11	12	2.8
12	13	2.8
13	14	2.8
14	15	2.8
15	16	1.0e-32