PNNL-38273

GridLAB-D Technical Support Document: Residential Equivalent Thermal Parameter Model

September 2025

LE Hinkle CD Goodman RG Pratt

Prepared for the U.S. Department of Energy
Under contract DE-AC05-76RL01830

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1.0 Introduction

GridLAB-D is a power distribution systems simulation and analysis tool developed by Pacific Northwest National Laboratory (PNNL) (Chassin et al. (2008)) and has been used in various large scale simulation studies such as (Hansen et al. (2019)), (Reeve et al. (2022)), and (Mukherjee et al. (2023)). Residential thermal behavior is modeled using a thermal heat flow circuit, referred to as the equivalent thermal parameter (ETP) model in GridLAB-D's online documentation (*GridLAB-D* (2020)). It is a single zone model that lends itself well to residential buildings. As outlined in Goodman et al. (2022), the thermal dynamics of most homes are well represented by the ETP model. Although GridLAB-D and its underlying residential load model have been used in a variety of power systems analyses, comprehensive documentation of the derivation of the residential house model has not been formally published.

1.1 Available Documentation Resources and Limitations

Below is a list of published residential building model documentation for GridLAB-D, including a summary and description of limitations.

- GridLAB-D ShoutWiki (*GridLAB-D* (2020))

  The primary online documentation for GridLAB-D is located on ShoutWiki. The ”Residential module's user's guide” describes the ETP heat balance equations, initializing the room air temperature and the mass temperature, user-defined parameters and default values, design loads and HVAC sizing, thermostat control, and guidance on how to configure the house model. Figure 1 shows the relationship between the major variables that make up the ETP model. The derivation of the ETP model is also included on the Wiki with references to a handwritten derivation and accompanying Excel spreadsheet located on the GitHub repository. Although the Wiki includes important details on the ETP model and its usage, there are some consistency issues, missing units, inclusion of equations not currently implemented in the GridLAB-D code base, and compiling issues of the LaTeX equations. Details on modeling end-use loads are also included but some sections are incomplete.

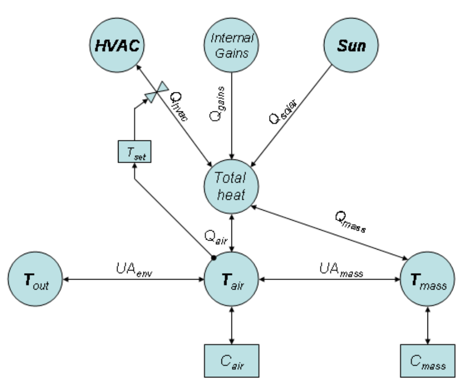

Figure 1. ETP representation of the typical residences in GridLAB-D (2020)

- GridLAB-D Technical Support Document: Residential End-Use Module Version 1.0 (Taylor et al. (2008))

  This documentation describes the modeling assumptions for the end use loads that can be implicitly defined when configuring the residential house model. Other than appliances and lights, this document also covers modeling assumptions for internal gains (plug loads) and heating and cooling loads. Many sections of the ShoutWiki match this technical support document. Some items in the document are not currently implemented in the GridLAB-D code which can be confusing for users. It also outlines a state space description of the ETP model which can help users understand the system of equations but does not describe how the solution is currently implemented in GridLAB-D. The state space representation does not include equations related to HVAC electric power consumption; it is focused only on the system of equations for the thermal dynamics of the home. This document only provides power consumption modeling details for the dishwasher, range, microwave, and internal gains. Details on the thermal models for refrigerators and water heaters are included.

- Notes on the GridLAB-D Household Equivalent Thermal Parameter Model (Tesfatsion and Battula (2020))

  Iowa State University researchers identified a need for comprehensive documentation of the GridLAB-D residential building model. Some examples of gaps identified by the Iowa State researchers include ambiguity on units of measure and unclear differentiation of structural elements versus data driven parameters. The house ETP model is presented as a complete analytic state space control representation including power consumption (not just thermal dynamics). An alternative solution method than the current GridLAB-D implementation is presented using simple forward finite-difference approximation. Tables of user-defined parameters, derived parameters, variables, and default values are also provided.

1.2 Scope of Technical Support Document

This document is to serve as a supplemental reference to the Wiki (*GridLAB-D* (2020)) and GitHub repository (`https://github.com/gridlab-d/gridlab-d`). Key documentation gaps that are addressed are listed below.

- Complete derivation of the closed-form implicit solution currently implemented in the GridLAB-D codebase.

- Step-by-step implementation of the ETP in the GridLAB-D “house_e.cpp” code with reference to the closed-form solution derivation. Implementation steps for the HVAC system operations are included as they relate to the thermal dynamics of the house model.

- Comprehensive definitions of the house parameters, including dependencies/relationships between parameters. GridLAB-D has several options for setting parameter values and it is easy for the user to unintentionally override a parameter value due to the complex relationships (user-defined parameters versus calculated parameters).

- Tables that outline default values for user-defined parameters.

- Excel parameter spreadsheet that describes every GridLAB-D house parameter and the variable name in the code.

- Calculation steps for estimating the mass heat capacity and the conductance between the indoor air and the mass if the user would like to modify from the defaults.

This document does not cover electrical power consumption modeling methods for HVAC or other end-use loads. The purpose of this technical support document is to serve as a comprehensive resource for the thermal dynamics modeling and house definition. Additional documentation updates are forthcoming for the GridLAB-D software suite. This document reflects the model as implemented in GridLAB-D version 5.3.0; this model has not been substantially changed for many versions and years and we expect both the structure of the model and the default parameter values of said model to be unchanged for the foreseeable future.

2.0 ETP Closed Form Solution

The ETP model in GridLAB-D simulates the behavior of a single zone. It is classified as a 2R2C resistance-capacitance (RC) model. It consists of two capacitors that account for the indoor air capacity, C_a, and mass capacity, C_m, and two resistors that represent the conductance between the outdoor air and indoor air, U_a, and the conductance between the mass and indoor air, H_m. With known outdoor air temperature T_o, heat gain delivered to the indoor air Q_a, and heat gain delivered to the mass Q_m, we can solve for the temperature of the indoor air T_a and mass T_m through a second-order differential equation derived from this model. Further, assuming constant T_o, Q_a, and Q_m over each timestep, we can find a closed-form solution, thus reducing the computational requirements. The following subsections detail the derivation of the closed-form solution implemented in GridLAB-D.

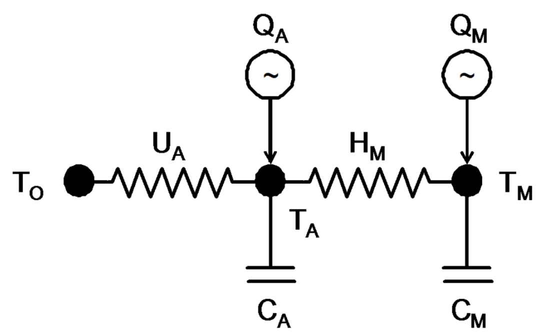

Figure 2. Equivalent Thermal Parameters Circuit Modeled by House-E in GridLAB-D (2020)

2.1 Derivation of the second-order differential equation

First, the heat balance on T_a is given as:

$$0 = Q_a - U_a(T_a - T_o) - H_m(T_a - T_m) - C_a\frac{dT_a}{dt} \tag{1}$$

Rearranging Equation 1 in the form for solving a differential equation:

$$0 = Q_a - (U_a + H_m)T_a + U_aT_o + H_mT_m - C_a\frac{dT_a}{dt} \tag{2}$$

$$\frac{dT_a}{dt} + \frac{U_a + H_m}{C_a}T_a - \frac{H_m}{C_a}T_m - \frac{U_a}{C_a}T_o - \frac{Q_a}{C_a} = 0 \tag{3}$$

Solving Equation 3 for T_m gives:

$$T_m = \frac{C_a}{H_m}\frac{dT_a}{dt} + \frac{U_a + H_m}{H_m}T_a - \frac{U_a}{H_m}T_o - \frac{Q_a}{H_m} \tag{4}$$

And differentiating Equation 4 with respect to time:

$$\frac{dT_m}{dt} = \frac{C_a}{H_m}\frac{d^2T_a}{dt^2} + \frac{U_a + H_m}{H_m}\frac{dT_a}{dt} \tag{5}$$

Next, the heat balance on T_m is given as:

$$0 = Q_m - H_m(T_m - T_a) - C_m \frac{dT_m}{dt} \tag{6}$$

Solving Equation 6 for T_a yields:

$$0 = Q_m - H_m T_m + H_m T_a - C_m \frac{dT_m}{dt} \tag{7}$$

$$T_a = \frac{C_m}{H_m} \frac{dT_m}{dt} + T_m - \frac{Q_m}{H_m} \tag{8}$$

Then, differentiating Equation 8 with respect to time:

$$\frac{dT_a}{dt} = \frac{C_m}{H_m} \frac{d^2 T_m}{dt^2} + \frac{dT_m}{dt} \tag{9}$$

Rearranging Equation 7 yields:

$$0 = C_m \frac{dT_m}{dt} + H_m T_m - Q_m - H_m T_a \tag{10}$$

Substituting Equation 4 and 5 into Equation 10 gives:

$$0 = \frac{C_m C_a}{H_m} \frac{d^2 T_a}{dt^2} + \frac{C_m(U_a + H_m)}{H_m} \frac{dT_a}{dt} + C_a \frac{dT_a}{dt} + (U_a + H_m) T_a - U_a T_o - Q_a - Q_m - H_m T_a \tag{11}$$

Rearranging Equation 11:

$$\frac{C_m C_a}{H_m} \frac{d^2 T_a}{dt^2} + \left(C_m \frac{U_a}{H_m} + C_m + C_a \right) \frac{dT_a}{dt} + U_a T_a = Q_m + Q_a + U_a T_o \tag{12}$$

Equation 12 is of the form:

$$a \frac{d^2 T_a}{dt^2} + b \frac{dT_a}{dt} + c T_a = d \tag{13}$$

a second-order linear differential equation where

$$a \equiv \frac{C_m C_a}{H_m} \tag{14}$$

$$b \equiv C_m \frac{U_a}{H_m} + C_m + C_a \tag{15}$$

$$c \equiv U_a \tag{16}$$

$$d \equiv Q_m + Q_a + U_a T_o \tag{17}$$

which assumes that d is constant over each timestep.

2.2 Solution

First, we solve the homogeneous equation to find the complementary solution $(T_a)_c$. Let $T_a = e^{rt}$:

$$\frac{dT_a}{dt} = re^{rt}$$

$$\frac{d^2T_a}{dt^2} = r^2e^{rt}$$

$$ar^2e^{rt} + bre^{rt} + ce^{rt} = d \tag{18}$$

The homogeneous solution to Equation 18 is given by:

$$ar^2 + br + c = 0$$

$$r_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{19}$$

$$r_2 = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \tag{20}$$

We can then show that $b^2 - 4ac > 0$ which indicates that r_1 and r_2 are real numbers. The complementary solution $(T_a)_c$ is formed by multiplying each solution by an arbitrary constant, A_1 and A_2

$$(T_a)_c = A_1e^{r_1t} + A_2e^{r_2t} \tag{21}$$

and the general solution is given by the sum of the complementary solution and particular solution $(T_a)_p$, which is assumed to be a constant

$$T_a = (T_a)_c + (T_a)_p = A_1e^{r_1t} + A_2e^{r_2t} + (T_a)_p \tag{22}$$

Then, taking the first and second derivative with respect to time:

$$\frac{dT_a}{dt} = A_1r_1e^{r_1t} + A_2r_2e^{r_2t} \tag{23}$$

$$\frac{d^2T_a}{dt^2} = A_1r_1^2e^{r_1t} + A_2r_2^2e^{r_2t} \tag{24}$$

Substituting Equations 22, 23, and 24 into Equation 13:

$$aA_1r_1^2e^{r_1t} + aA_2r_2^2e^{r_2t} + bA_1r_1e^{r_1t} + bA_2r_2e^{r_2t} + cA_1e^{r_1t} + cA_2e^{r_2t} + c(T_a)_p = d \tag{25}$$

Rearranging Equation 25:

$$A_1e^{r_1t}(ar_1^2 + br_1 + c) + A_2e^{r_2t}(ar_2^2 + br_2 + c) + c(T_a)_p = d$$

which reveals that the particular solution is:

$$(T_a)_p = \frac{d}{c} \tag{26}$$

So the general solution is given by:

$$T_a = A_1e^{r_1t} + A_2e^{r_2t} + \frac{d}{c} \tag{27}$$

$$T_a = A_1e^{r_1t} + A_2e^{r_2t} + \frac{Q_m + Q_a}{U_a} + T_o \tag{28}$$

2.3 Boundary conditions

With known boundary conditions T_{a_o} and $\frac{dT_{a_o}}{dt_o}$ at $t = 0$, we can solve for A_1 and A_2:

$$T_{a_o} = A_1 + A_2 + \frac{d}{c} \tag{29}$$

$$\frac{dT_{a_o}}{dt} = A_1 r_1 + A_2 r_2 \tag{30}$$

Multiplying Equation 29 by r_2 gives:

$$r_2 T_{a_o} = r_2 A_1 + r_2 A_2 + r_2 \frac{d}{c} \tag{31}$$

Then we subtract Equation 30 from 31 to eliminate A_2:

$$r_2 T_{a_o} - \frac{dT_{a_o}}{dt} = (r_2 - r_1) A_1 + r_2 \frac{d}{c} \tag{32}$$

$$A_1 = \frac{r_2 T_{a_o} - \frac{dT_{a_o}}{dt} - r_2 \frac{d}{c}}{r_2 - r_1} \tag{33}$$

From Equation 33 and Equation 29, A_2 is

$$A_2 = T_{a_o} - \frac{d}{c} - \frac{r_2 T_{a_o} - \frac{dT_{a_o}}{dt} - r_2 \frac{d}{c}}{r_2 - r_1} \tag{34}$$

$$A_2 = T_{a_o}\left(1 + \frac{r_2}{r_2 - r_1}\right) + \frac{d}{c}\left(\frac{r_2}{r_2 - r_1} - 1\right) - \left(\frac{r_2}{r_2 - r_1}\right)\frac{dT_{a_o}}{dt} \tag{35}$$

Substituting Equation 27 and 23 for T_a and $\frac{dT_a}{dt}$ in Equation 4 gives:

$$T_m = \frac{C_a}{H_m}(A_1 r_1 e^{r_1 t} + A_2 r_2 e^{r_2 t}) + \frac{U_a + H_m}{H_m}\left(A_1 e^{r_1 t} + A_2 e^{r_2 t} + \frac{Q_m + Q_a + U_a T_o}{U_a}\right) - \frac{U_a}{H_m} T_o - \frac{Q_a}{H_m} \tag{36}$$

Rearranging and simplifying Equation 36:

$$T_m = A_1\left(\frac{C_a}{H_m} r_1 + \frac{U_a + H_m}{H_m}\right) e^{r_1 t} + A_2\left(\frac{C_a}{H_m} r_2 + \frac{U_a + H_m}{H_m}\right) e^{r_2 t} + \frac{U_a + H_m}{H_m U_a} Q_m + \frac{Q_a}{U_a} + T_o \tag{37}$$

Let

$$T_m = A_1 A_3 e^{r_1 t} + A_2 A_4 e^{r_2 t} + \frac{Q_m}{H_m} + \frac{Q_m}{U_a} + \frac{Q_a}{U_a} + T_o \tag{38}$$

where

$$A_3 \equiv \frac{C_a}{H_m} r_1 + \frac{U_a + H_m}{H_m} \tag{39}$$

$$A_4 \equiv \frac{C_a}{H_m} r_2 + \frac{U_a + H_m}{H_m} \tag{40}$$

Equation 37 gives T_m for the next time step, i.e., at $t = t_o + \Delta t_o$. Note that the solution is discontinuous at any time t_s when Q_m, Q_a, or T_o change. At time t_s^+, the instant after Q_m, Q_a, or T_o changes, then Equation 4 can be solved for $\frac{dT_a}{dt}\big|_{t_s^+}$:

$$\left.\frac{dT_a}{dt}\right|_{t_s^+} = \frac{H_m}{C_a} T_{m_{t_s}} - \frac{U_a + H_m}{C_a} T_{a_{t_s}} + \frac{U_a}{C_a} T_{o_{t_s}} + \frac{Q_{a_{t_s^+}}}{C_a} \tag{41}$$

2.4 State-space form

Although not implemented in GridLAB-D, a state-space form of the ETP model can be derived by rearranging Equations 3 and 10:

$$\dot{x} = Ax + Bu \tag{42}$$

$$y = Cx + Du \tag{43}$$

$$\dot{x} = \begin{bmatrix} \dot{T_a} \\ \dot{T_m} \end{bmatrix}, \quad x = \begin{bmatrix} T_a \\ T_m \end{bmatrix}, \quad u = 1 \tag{44}$$

$$A = \begin{bmatrix} \frac{-U_a + H_m}{C_a} & \frac{H_m}{C_m} \\ \frac{H_m}{C_m} & \frac{-H_m}{C_m} \end{bmatrix} \tag{45}$$

$$B = \begin{bmatrix} \frac{U_a T_o}{C_a} + \frac{Q_a}{C_a} \\ \frac{Q_m}{C_m} \end{bmatrix} \tag{46}$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{47}$$

3.0 GridLAB-D House Parameter Definitions

The ETP model in Section 2.0 is implemented in the GridLAB-D house object. The ETP model parameters C_a, C_m, U_a and H_m are determined based on the house geometry, thermal mass characteristics, envelope, and HVAC design. Each category consists of user-defined parameters and calculated parameters, i.e., those involved in intermediate calculations of the ETP model parameters. This section classifies the parameters and maps their relationships to support users while setting up the house object(s). It also includes default values and references as appropriate. It is important to note calculated parameters and ETP parameters can be defined directly by the user but this is not commonly done. Instead, modelers define values for the more common house parameter values, allowing easier configuration of the models.

3.1 Geometry

The default house is roughly the size of the DOE prototypical residential home (Pacific Northwest National Laboratory (n.d.)) with notable geometric differences, including reducing the number of stories from two to one. The user-defined parameters that affect ETP parameter C_a is floor area and ceiling height. These are used to calculate the volumetric capacity of the interior air in Equation 48. Several geometric parameters also affect U_a which requires surface areas in its calculation. The relationships between geometric parameters are shown in Figure 3, and the default values are provided in Table 1. Note that some calculated parameters do not have an output. These parameters are referenced as inputs in later diagrams.

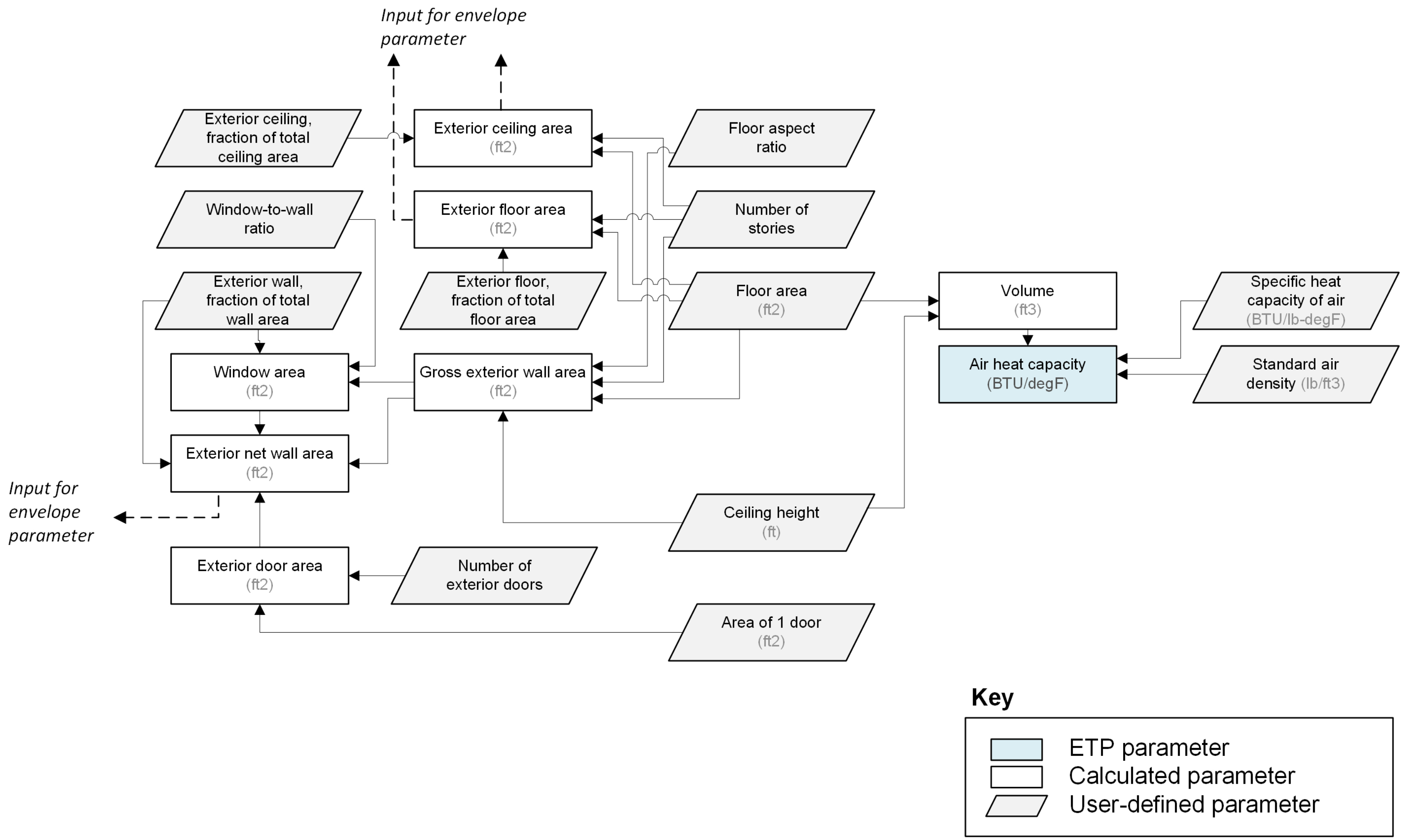

Figure 3. Dependency map of building geometry parameters in GridLAB-D residential model

Table 1. Geometry parameter defaults

Parameter	Default	Units	Notation
Floor area	2500	ft^2	A_f
Floor aspect ratio	1.5	-	-
Number of stories	1	-	n_s
Ceiling height	8	ft	-
Window-wall-ratio	0.15	-	-
Exterior floor, fraction of total floor area	1	-	-
Exterior ceiling, fraction of total ceiling area	1	-	ECR
Exterior wall, fraction of total wall area	1	-	-
Number of exterior doors	4	-	-
Area of 1 door	19.5	ft^2	$A_{ext\,door}$

The air capacity ETP parameter, C_a is calculated as shown in Equation 48.

$$C_a = 3c_p\rho v \tag{48}$$

where c_p is the specific heat capacity of air at constant pressure, ρ is standard air density, and v is the volume of the house. The default values for standard air density and specific heat capacity are given in Table 2. The multiplier of three is an engineering judgment estimate.

3.2 Envelope

The building envelope is specified by the modeler using a number of model parameters such as surface R-values, window characteristics, and infiltration rate. Alternatively, these values can be defined as a group by defining a single parameter called the “thermal integrity level”; this ensures a realistic combination of envelope parameters. For example, it is unlikely that a home with a low exterior wall R-value would have highly insulated windows with a high R-value. The default envelope values are provided in Table 3, and the relationship between envelope parameters is shown in Figure 4. The conductance between the outdoor air and indoor air, U_a, is defined by Equation 49.

Table 2. Constant defaults

Parameter	Default	Units	Notation
Standard air density	0.0735	lb/ft^3	ρ
Specific heat capacity of air at constant pressure	0.2402	BTU/lb-°F	c_p

Envelope

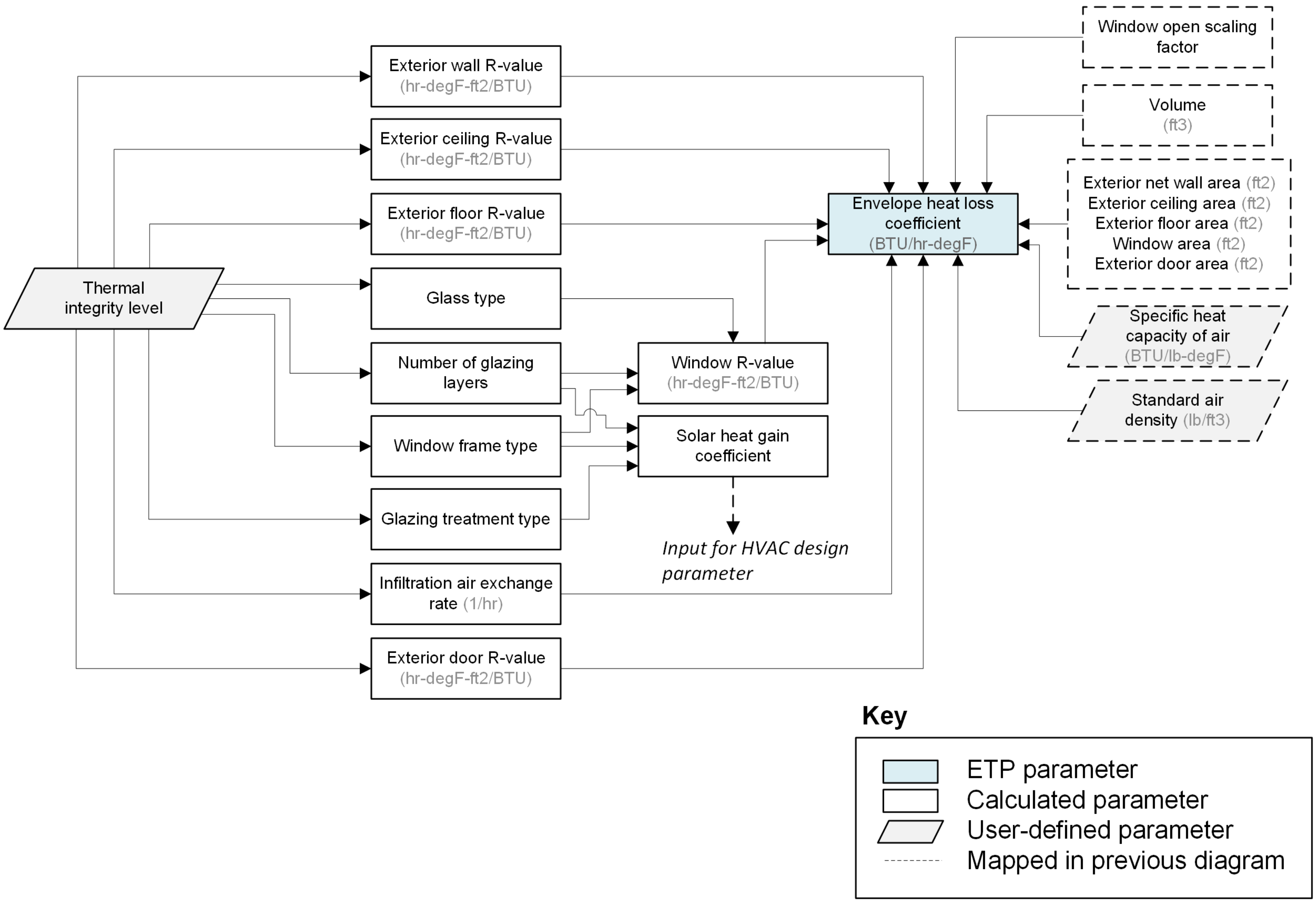

Figure 4. Dependency map of building envelope parameters in GridLAB-D residential model

Table 3. Thermal integrity level 5 defaults

Parameter	Default	Units	Notation
Exterior wall R-value	19	hr-°F-ft^2/BTU	$R_{ext\,wall}$
Exterior ceiling R-value	30	hr-°F-ft^2/BTU	$R_{ext\,ceiling}$
Exterior floor R-value	22	hr-°F-ft^2/BTU	$R_{ext\,floor}$
Glass type	Low-E	-	-
Number of glazing layers	2	-	-
Window frame type	Thermal break	-	-
Glazing treatment type	Clear	-	-
Infiltration air exchange rate	0.5	hr-°F-ft^2/BTU	ACH
Exterior door R-value	5	hr-°F-ft^2/BTU	$R_{ext\,door}$

$$U_a = \frac{A_{ext\,net\,wall}}{R_{ext\,wall}} + \frac{A_{ext\,ceiling}}{R_{ext\,ceiling}} + \frac{A_{ext\,floor}}{R_{ext\,floor}} + \frac{A_{window}}{R_{window}} + \frac{A_{ext\,door}}{R_{ext\,door}} + (ACH * C_p * \rho v) \tag{49}$$

where A is the area of the surface, R is the R-value of the surface, ACH is the infiltration air exchange rate, C_p is the specific heat capacity of air at constant pressure, ρ is standard air density, and v is the volume of the house.

3.3 Thermal Mass

Calculating the mass heat capacity C_m requires estimating the house thermal mass. In the current GridLAB-D implementation, the total thermal mass per unit floor area is a user-defined parameter. The default value is based on residential wood-frame construction including furnishings. In the Appendix, we provide a detailed calculation for total thermal mass per unit to help guide users if they wish to adjust it. Similarly, the mass-air conductance H_m is calculated using two aggregate parameters, interior/exterior wall surface ratio IWR and interior surface heat transfer coefficient h_i. These values can also be adjusted using the detailed calculations in the Appendix. The relationships between thermal mass parameters are depicted in Figure 5, and the default values are given in Table 4. C_m and H_m are defined by Equations 50 and 51, respectively.

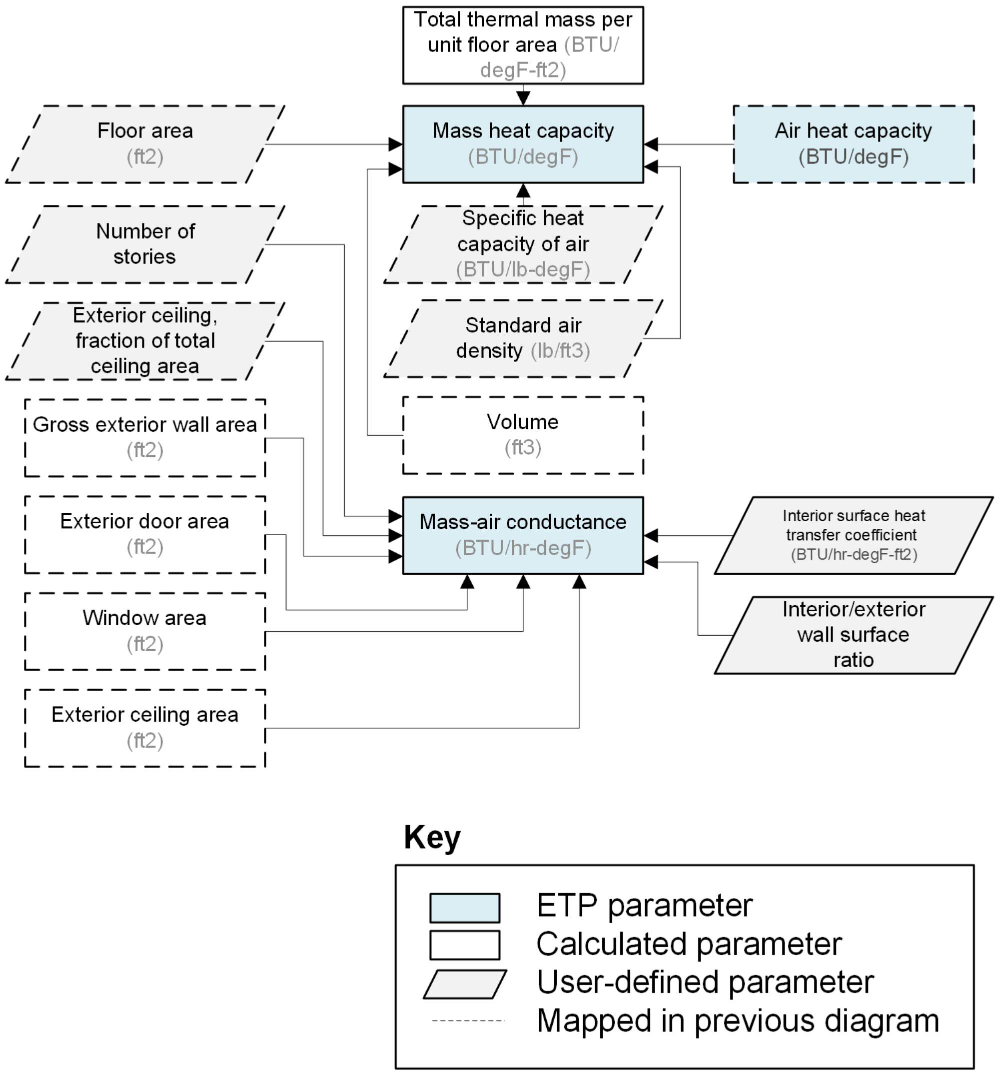

Figure 5. Dependency map of building thermal mass parameters in GridLAB-D residential model

$$C_m = A_f m_f - (C_a - C_p \rho v) \tag{50}$$

where A_f is the total floor area, m_f is total thermal mass per floor area, C_a is the house air heat capacity, C_p is the specific heat capacity of air at constant pressure, ρ is standard air density, and v is the volume of the house. The default value for m_f (total thermal mass per floor area, see Table 4) is based on a survey of moving companies to estimate a typical furnishings weight.

$$H_m = h_i \left((A_{gross\,ext\,wall} - A_{window} - A_{ext\,door}) + A_{gross\,ext\,wall} IWR + n_s \left(\frac{A_{ext\,ceiling}}{ECR} \right) \right) \tag{51}$$

where h_i is interior surface heat transfer coefficient, A is the area of the surface, IWR is the interior/exterior wall ratio, n_s is the number of stories, and ECR is the exterior ceiling, fraction of total ceiling area.

Table 4. Thermal mass parameter defaults

Parameter	Default	Units	Notation
Total thermal mass per unit floor area	2	BTU/°F-ft^2	m_f
Interior surface heat transfer coefficient	1.46	BTU/hr-°F-ft^2	h_i
Interior/exterior wall surface ratio	1.5	-	IWR

3.4 HVAC Design

Although the HVAC design parameters do not inform the ETP model parameters, ETP model parameter U_a is required to calculate the design cooling and heating loads. The heating and cooling loads are used to determine the capacity of the system and are discussed further in Section 3.4.1. The relationships between HVAC design parameters are shown in Figure 6, and the default values are provided in Table 5.

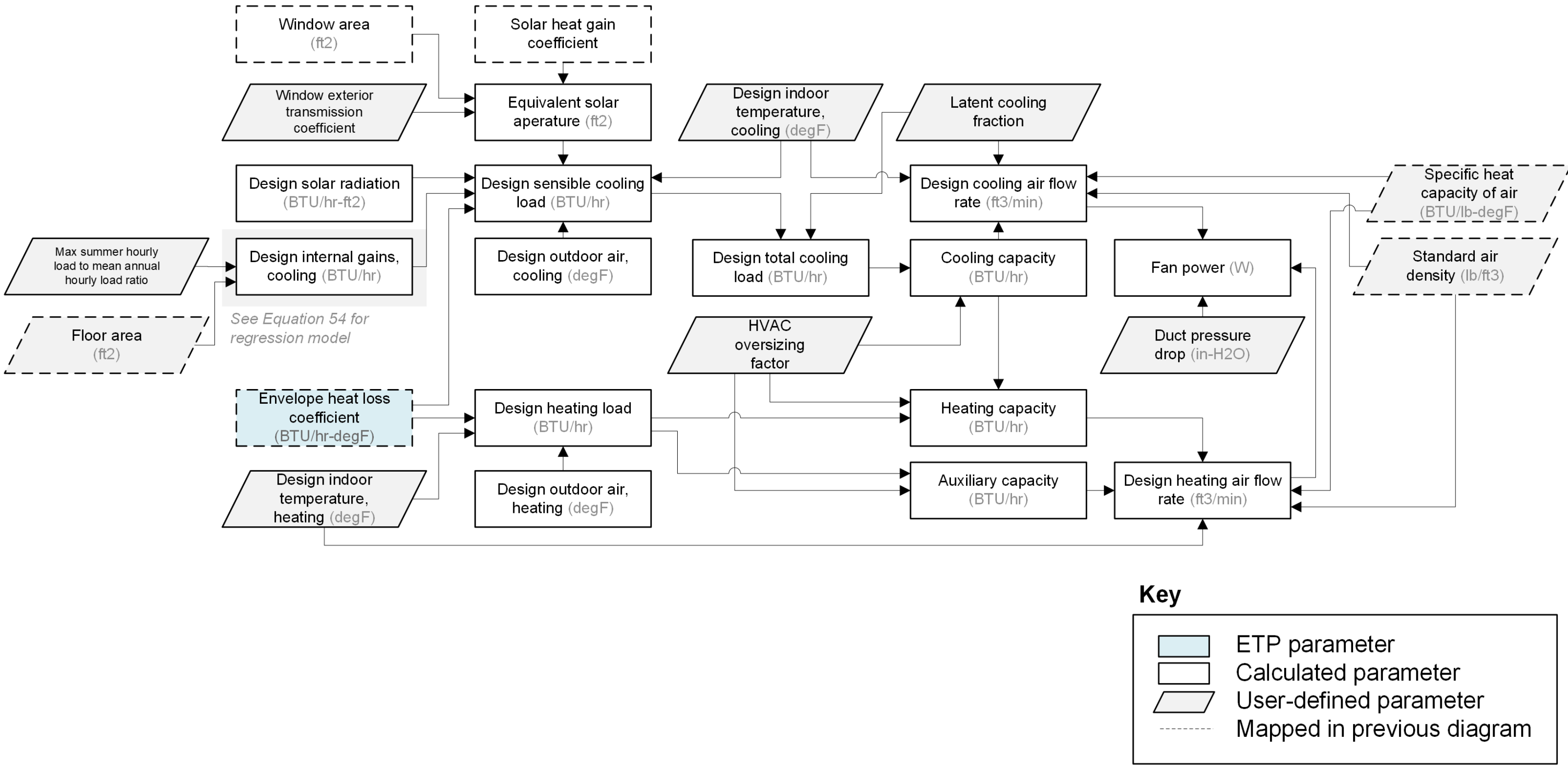

Figure 6. Dependency map of building HVAC design parameters in GridLAB-D residential model

Table 5. HVAC design parameter defaults

Parameter	Default	Units	Notation
Design indoor temperature, cooling	75	°F	T_{cool}
Design indoor temperature, heating	70	°F	T_{heat}
Latent cooling fraction	0.30	-	f_{latent}
HVAC oversizing factor	0	-	-
Duct pressure drop	0.50	in-H_2O	-
Window exterior transmission coefficient	0.60	-	WET
Max summer hourly load to mean annual hourly load ratio	1.32	-	-

3.4.1 Sizing

As mentioned previously, U_a is required to calculate the design heating and cooling loads, which are given as:

$$Q_{heat} = U_a(T_{heat} - T_{out_{heat}}) \tag{52}$$

where T_{heat} is the design indoor temperature for heating and $T_{out_{heat}}$ is the design outdoor temperature for heating.

$$Q_{cool_{sensible}} = U_a(T_{out_{cool}} - T_{cool}) + 3.413\frac{BTU}{hr}Q_{i_{design}} + Q_{s_{design}}A_{window}SHGC * WET \tag{53}$$

where $T_{out_{cool}}$ is the design outdoor temperature for cooling, T_{cool} is the design indoor temperature for cooling, 3.413 is a conversion factor, $Q_{i_{design}}$ is the design internal gains, $Q_{s_{design}}$ is the design solar radiation, A_{window} the surface area of the windows, $SHGC$ is the solar heat gain coefficient of the windows, and WET is the window exterior transmission coefficient.

3.4.2 Internal Gains

The design internal gains account for heat gains from non-HVAC equipment. The equation is based on a regression model that was developed using End-Use Load and Consumer Assessment Program (ELCAP) “Other” category data collected in 1990 (Pratt et al. (1993)). It was fit to an equation of the form $y = ax^b$ where y is the design end usage, $a = 324.9$, x is the floor area A_f, and $b = 0.442$. Then, the estimated end usage is scaled by the maximum hourly load of the summer average load shape to the mean load of the year ratio, which is also from ELCAP. Finally, the design internal gains is given as:

$$Q_{i_{design}} = a\,A_f^b\,1.32\,\frac{3413\frac{BTU/hr}{kW}}{8760\frac{hr}{yr}} \tag{54}$$

where 1.32 is ratio of the maximum hourly load of the summer average load shape to the mean hourly load of the year. The value $3413\frac{BTU/hr}{kW}$ is a conversion factor.

4.0 HVAC Models

The user-defined HVAC model parameter defaults are provided in Table 6.

4.1 Thermostat Control

This section covers the heating and cooling system controls in GridLAB-D.

1. Thermostat control types

   - Full control: The thermostat adjusts $T_{cool,ON}$, $T_{cool,OFF}$, $T_{heat,ON}$, and $T_{heat,OFF}$ to create a hysteresis band around the heating and cooling setpoints. The default deadband is 2.0 °F. There are auxiliary heating controls using $T_{aux,ON}$. The control model checks for overlapping deadbands ($T_{cool,OFF} < T_{heat,OFF}$) and throws an error indicating the setpoint deadband (DB) needs to be reduced or the difference between the heating and cooling setpoints needs to be increased. This measure prevents simultaneous heating and cooling.

$$\begin{aligned} T_{cool,ON} &= T_{cool} + \frac{DB}{2} \\ T_{cool,OFF} &= T_{cool} - \frac{DB}{2} \\ T_{heat,ON} &= T_{heat} - \frac{DB}{2} \\ T_{heat,OFF} &= T_{heat} + \frac{DB}{2} \\ T_{aux,ON} &= T_{heat} - DB_{aux} \end{aligned} \quad (55)$$

   - No control: No thermostat control. The system mode controls the HVAC system and control logic for determining system mode (HEAT, COOL, OFF, AUX) is ignored. An external input can be used to change the system mode.
   - Band control: $T_{cool,ON}$, $T_{cool,OFF}$, $T_{heat,ON}$, and $T_{heat,OFF}$ are set by the user and are not dynamically adjusted directly in the GridLAB-D house model around the heating and cooling setpoints.

2. System modes: There are four different system modes with their activation described in Table 7. $T_{aux,LO}$ is the lockout temperature compared against the outside air temperature to enable the auxiliary heat when temperatures drop. Note, in AUX mode the heat pump is shut down.

3. Overrides: There are override controls to ignore the deadbands with heating and cooling control or to force the systems off regardless of normal setpoint triggers. During window opening (described in Section 4.3), the HVAC system is disabled.

4. Cycle time control: There are controls to minimize cycling on and off of the equipment. The logic prevents the transition of system modes before the cycle time has been reached.

4.2 Outdoor air temperature adjustments to capacity and COP

The effects of outdoor air temperature on COP and capacity for heat pumps and air conditioning units are captured in the equations below. The 95°F and 47°F values, used in

Table 6. HVAC equipment parameter defaults

Parameter	Default	Units
Cool system type	electric	-
Heat system type	heat pump	-
Heating COP	2.50	-
Cooling COP	3.50	-
Thermostat setpoint, heating	schedule	°F
Thermostat setpoint, cooling	schedule	°F
Thermostat deadband	2	°F
Thermostat cycle time, minimum	2	min
Auxiliary heat type	electric	-
Auxiliary heat deadband	2	°F
Auxiliary heat outdoor lockout temp	10	°F
Auxiliary heat time delay	5	min
Fan type	1-speed	-
Fan power, low-speed, fraction of high-speed	0.50	-

Table 7. HVAC System Modes and Activation

Mode	Activation Condition	Description
HEAT	$T_a < T_{heat,ON}$	heating system is “on”
COOL	$T_a > T_{cool,ON}$	cooling system is “on”
AUX	Deadband strategy: $T_a < T_{aux,ON}$ Lockout strategy: $T_o < T_{aux,LO}$ Timer strategy: ON when recovery timer exceeded	auxiliary heating system is “on” heating and cooling systems “off”
OFF	$T_a > T_{heat,OFF}$ $T_a < T_{cool,OFF}$	all systems “off”

$COP_{cool\,adj}$ and $COP_{heat\,adj}$ respectively, represent the rated outdoor air temperature for cooling and heating mode. Those values are not adjustable.

$$COP_{cool\,adj}(\text{curve type}) = \begin{cases} \frac{COP_{cool}}{k_0+k_1T_{out}}, & \text{if curve type=DEFAULT} \\ COP_{cool}, & \text{if curve type=FLAT} \\ COP_{cool}\frac{95°F}{T_{out}}, & \text{if curve type=LINEAR} \end{cases} \tag{56}$$

where $k_0 = -0.01363961$ and $k_1 = 0.01066989$.

$$COP_{heat\,adj}(\text{curve type}) = \begin{cases} \frac{COP_{heat}}{k_0+k_1T'_{out}+k_2T'^2_{out}+k_3T'^3_{out}}, & \text{if curve type=DEFAULT} \\ COP_{heat}, & \text{if curve type=FLAT} \\ COP_{heat}max(1, \frac{T_{out}}{47°F}), & \text{if curve type=LINEAR} \end{cases} \tag{57}$$

where $k_0 = 2.03914613$, $k_1 = -0.03906753$, $k_2 = 0.00045617$, $k_3 = -0.00000203$, T'_{out} is $min(T_{out}, 80)$.

$$C_{cool\,adj}(\text{curve type}) = \begin{cases} C_{cool\,design}(k_0 + k_1T_{out}), & \text{if curve type=DEFAULT} \\ C_{cool\,design}, & \text{if curve type=FLAT} \end{cases} \tag{58}$$

where $k_0 = 1.48924533$ and $k_1 = -0.00514995$.

$$C_{heat\,adj}(\text{curve type}) = \begin{cases} C_{heat\,design}(k_0 + k_1T_{out} + k_2T^2_{out}), & \text{if curve type=DEFAULT} \\ C_{heat\,design}, & \text{if curve type=FLAT} \end{cases} \tag{59}$$

where $k_0 = 0.34148808$, $k_1 = 0.00894102$, and $k_2 = 0.00010787$.

4.3 Window opening model

If the window opening model is enabled, and the outdoor air temperature is between the low temperature cutoff T_{low} and high temperature cutoff T_{high}, there is some probability occupants will open the windows $0 \leq p_{open} \leq 1$ which is calculated using Equation 60. In order to simulate the occupant behavior, a random value is drawn from a uniform distribution $rand_{val} \sim \mathcal{U}(0, 1)$. If $rand_{val} \leq p_{open}$, then the windows are opened. In this case, the HVAC system is overridden to OFF and U_a is multiplied by 10 (window open scaling factor shown in Figure 4) for all ETP model calculations to simulate an increase in heat transfer. There is no source mentioned for the factor of 10 increase for U_a so it is assumed to be engineering judgment. If the windows are closed, the HVAC system operates normally. Lastly, if the outdoor air temperature changes by more than window temperature delta from the previous state, the model is updated to determine if the windows will remain opened or closed.

$$p_{open} = a_{win}T_o^2 + b_{win}T_o + c_{win} \tag{60}$$

where a_{win} is the window quadratic coefficient, b_{win} is the window linear coefficient, and c_{win} is the constant coefficient. Defaults for the window opening model are provided in Table 8.

Table 8. Window opening model parameter defaults

Parameter	Default	Units	Notation
Low temperature cutoff	60	°F	T_{low}
High temperature cutoff	80	°F	T_{high}
Window quadratic coefficient	0	-	a_{win}
Window linear coefficient	0	-	b_{win}
Window constant coefficient	1	-	c_{win}
Window temperature delta	5	°F	-

Table 9. Fraction of heat gain delivered to mass defaults

Parameter	Default	Units	Notation
HVAC gains delivered to mass	0	-	Q_h
Internal gains delivered to mass	0.5	-	Q_i
Solar gains delivered to mass	0.5	-	Q_s

5.0 Implementation in GridLAB-D

As stated in Section 2.0, solving the ETP model requires known outdoor air temperature, T_o, heat gain delivered to the indoor air Q_a, and heat gain delivered to the mass Q_m at each timestep. T_o is read from the weather file (top of the hour), or linearly interpolated if specified. Q_a and Q_m are given by the following equations:

$$Q_a = (1 - f_h)Q_h + (1 - f_i)Q_i + (1 - f_s)Q_s \tag{61}$$

$$Q_m = (f_h)Q_h + (f_i)Q_i + (f_s)Q_s \tag{62}$$

where f_h is the fraction of HVAC heat gains delivered to the mass, Q_h is the heat gains from the HVAC system, f_i is the fraction of internal gains delivered to the mass, Q_i is the internal heat gains, f_s is the fraction of solar gains delivered to the mass, and Q_s is the solar heat gains. The default f_i and f_s is set to 0.5 to represent that not all heat gains are delivered directly to the air (Table 9). In order to appropriately model the heat transfer to the air and dampen the response of T_a, half the heat gain is assumed to be delivered to the mass. T_m and T_a are coupled through H_m (see Figure 2). Q_i is determined based on probabilistic models built with ELCAP data (Pratt et al. (1993)). For the current end uses and occupants, Q_i for each timestep is given by:

$$Q_i = 3.412\frac{BTU}{hr}\sum_{eu=1}^{N} p_{eu} f_{I_{eu}} + n_{occ} f_{occ} Q_{occ} \tag{63}$$

where N is the number of end uses, p_{eu} is the current real power, $f_{I_{eu}}$ is the fraction of load that is internal to the house, n_{occ} is the number of occupants, f_{occ} is the occupancy fraction, and Q_{occ} is the sensible heat per occupant.

Q_s is calculated using the equivalent solar aperture and incident solar radiation. Incident solar radiation is based on solar radiation from the weather file, where solar radiation is the total over the hour ending at the time of the observation and is not interpolated. Q_s is given as:

$$Q_s = \sum_{d=1}^{8} I_d A_{window_d} SHGC_d \tag{64}$$

where I is the incident solar radiation, A_{window} is the window area, and $SHGC$ is the window solar heat gain coefficient.

5.1 Initialization

The model is initialized by calculating all ETP constants: C_a, C_m, H_m, U_a, a, b, c, r_1, r_2, A_3 and A_4. The initial T_{a_o} is a random value drawn from a uniform distribution between T_{low} and T_{high}:

$$T_{a_o} \sim \mathcal{U}(T_{low}, T_{high}) \tag{65}$$

where

$$T_{low} = \text{clip}\left(\frac{T_{cool} + T_{deadband}}{2},\ 60,\ 140\right) \tag{66}$$

$$T_{high} = \text{clip}\left(\frac{T_{heat} - T_{deadband}}{2},\ 60,\ 140\right) \tag{67}$$

where T_{cool} is the cooling setpoint, T_{heat} is the heating setpoint, and $T_{deadband}$ is the thermostat deadband. We also assume that $T_{m_o} = T_{a_o}$.

5.2 Model Update

After the initial timestep, T_a and T_m are solved using the ETP model equations. For each timestep:

1. Solve for air and mass temperatures and determine window opening (if used).
   a. Compute T_a using Equation 28
   b. Compute T_m using Equation 38
   c. Determine probability of window opening from Equation 60 and compare it with a random value (described in Section 4.3).

2. Run HVAC system based on the updated temperatures
   a. Update climate parameters, including T_o and solar radiation. These are either fixed constants or, more commonly, are updated using time-series data such as in a TMY3 weather file that is defined by the modeler.
   b. Update $COP_{cool\,adj}$, $COP_{heat\,adj}$, $C_{cool\,adj}$, and $C_{heat\,adj}$ using Equations 56, 57, 58, and 59, respectively. Then update cooling demand Q_{cool} and heating demand Q_{heat} using the following equations (where s_t is system type):

$$Q_{cool} = \frac{C_{cool\,adj}}{COP_{cool\,adj}} \frac{0.001W}{3.4120Whr} \tag{68}$$

$$Q_{heat}(C_{heat\,adj}, COP_{heat\,adj}, s_t) = \begin{cases} \frac{C_{heat\,adj}}{COP_{heat\,adj}} \frac{0.001W}{3.4120Whr}, & \text{if } s_t\text{=heat pump} \\ 0, & \text{if } s_t\text{=gas} \\ C_{heat\,design} \frac{0.001W}{3.4120Whr}, & \text{if } s_t\text{=resistance} \end{cases} \tag{69}$$

   c. Compute system capacity based on the system type (s_t) and system mode (s_m):

$$Q_h = \begin{cases} C_{heat\,adj} + P_{fan} f_{fan\,heat\,gain} 3412 \frac{BTU}{kWhr} & \text{if } s_m = \text{HEAT} \ \&\ s_t = \text{heat pump} \\ C_{heat\,design} + P_{fan} f_{fan\,heat\,gain} 3412 \frac{BTU}{kWhr} & \text{if } s_m = \text{HEAT} \ \&\ s_t = \text{gas} \\ C_{heat\,design} + P_{fan} f_{fan\,heat\,gain} 3412 \frac{BTU}{kWhr} & \text{if } s_m = \text{HEAT} \ \&\ s_t = \text{resistance} \\ -Cool_{on} \frac{C_{cool\,adj}}{1 + f_{latent\,RH\,adj}} + P_{fan} f_{fan\,heat\,gain} 3412 \frac{BTU}{kWhr} & \text{if } s_m = \text{COOL} \ \&\ s_t = \text{electric} \\ C_{aux} + P_{fan} f_{fan\,heat\,gain} 3412 \frac{BTU}{kWhr} & \text{if } s_m = \text{AUX} \end{cases} \tag{70}$$

   where C_{aux} is the auxiliary heat capacity, $f_{latent\,RH\,adj}$ is defined by Equation 71 below, P_{fan} is the fan power, and $f_{fan\,heat\,gain}$ is the fraction of heat gain from the fan power. If fan heat gain is included, the default fraction is 1. The system modes $COOL$, $HEAT$, and AUX are defined in Table 7.

$$f_{latent\,RH\,adj} = 0.1 + \frac{f_{latent}}{1 + exp(4 - 10RH)} \tag{71}$$

where f_{latent} is the latent cooling fraction and RH is the outdoor relative humidity.

d. Update electric power consumption of customer end uses. The modeling of these devices is not covered in this paper.
e. Compute Q_i using Equation 63
f. Update $T_{cool,On}$, $T_{cool,Off}$, $T_{heat,On}$, $T_{heat,Off}$, and $T_{aux,On}$ for current setpoints.
g. If window is open, enable off override on HVAC system.
h. Determine the system mode using the thermostat logic and updated T_a.

3. Compute the initial conditions for the next timestep

a. Compute Q_s using Equation 64
b. Compute heat gains Q_a and Q_m, using Equation 61 and 62, respectively
c. Compute d using Equation 17
d. Compute $\left.\frac{dT_a}{dt}\right|_{t_s^+}$ using Equation 41.
e. Compute A_1 and A_2 using Equation 33 and 34, respectively
f. Update T_{event} using Table 10 and calculate when T_{event} will occur. This step is detailed in the next section.

5.3 Event-driven timestep

GridLAB-D uses an event-driven timestep approach, advancing the simulation to the time the next HVAC operation is predicted to occur. This results in variable length timesteps. First, the next indoor air temperature threshold T_{event} at which the HVAC system should change its state based on the current thermal conditions and thermostat settings is calculated using the logic outlined in Table 10. The various event temperatures (e.g., $T_{cool,ON}$) are outlined in Section 4.1. Note that $\frac{dT_a}{dt}$ is solved for in Equation 41.

After T_{event} is determined from the current system mode and air temperature gradient, the time interval required to reach T_{event} is calculated by solving Equation 28 for t and adding it to the current timestamp, which determines when the next update will occur. There is a minimum off cycle time to prevent short cycling of the HVAC equipment. If the time interval required to reach T_{event} is less than the minimum cycle time, the next timestep is set to the last cycle time plus the minimum cycle time.

It is important to note that there may be small discrepancies in the solution when comparing an independent run of GridLAB-D versus one conducted in co-simulation using Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS). The outdoor temperature is assumed constant over the timestep period. When running GridLAB-D with a co-simulation, the simulation may be interrupted prior to reaching the calculated next timestep. At that time, GridLAB-D reads the new T_o, updates T_a, and recalculates T_{event} and therefore when the next timestep will be for the GridLAB-D ETP model. Because the outdoor air temperature may not be constant during the timestep, this could result in a different thermal response than running GridLAB-D as a standalone simulation.

Table 10. Determining T_{event} in order to calculate next timestemp

Current System Mode	Condition (if applicable)	T_{event}
HEAT	$\frac{dT_a}{dt} > 0$	$T_{heat,OFF}$
HEAT	$\frac{dT_a}{dt} \leq 0$ AUX deadband strategy selected	$T_{aux,ON}$
AUX	n/a	$T_{heat,OFF}$
COOL	n/a	$T_{cool,OFF}$
OFF	$\frac{dT_a}{dt} < 0$	$T_{heat,ON}$
OFF	$\frac{dT_a}{dt} > 0$	$T_{cool,ON}$
OFF	$\frac{dT_a}{dt} = 0$	T_a

6.0 Conclusion

This technical support documentation provides a comprehensive review of the ETP model and its implementation in GridLAB-D, including implementation steps for HVAC operation. The intent of this document was to improve the existing residential building model documentation, focusing on the current implementation in GridLAB-D. The accompanying Excel spreadsheet is intended to provide users with a comprehensive library of the modeling parameters and a testbed for the ETP model. The inclusion of the ETP model closed-form solution in the companion Excel spreadsheet has the added benefit of demonstrating the efficiency/simplicity of the modeling method. Updates to the documentation of the GridLAB-D software suite are forthcoming.

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Appendix A – Guidance on user-defined parameters calculation

This section provides detailed calculations that can be used to inform user-defined parameters. Specifically, it is intended to help users define the interior/exterior wall ratio IWR, interior surface heat transfer coefficient h_i, and total thermal mass per floor area m_f. Figure A.1 shows additional user-defined geometric parameters required to calculate the interior wall area, which is used in the calculation of m_f and IWR. Defaults are provided in Table A.1.

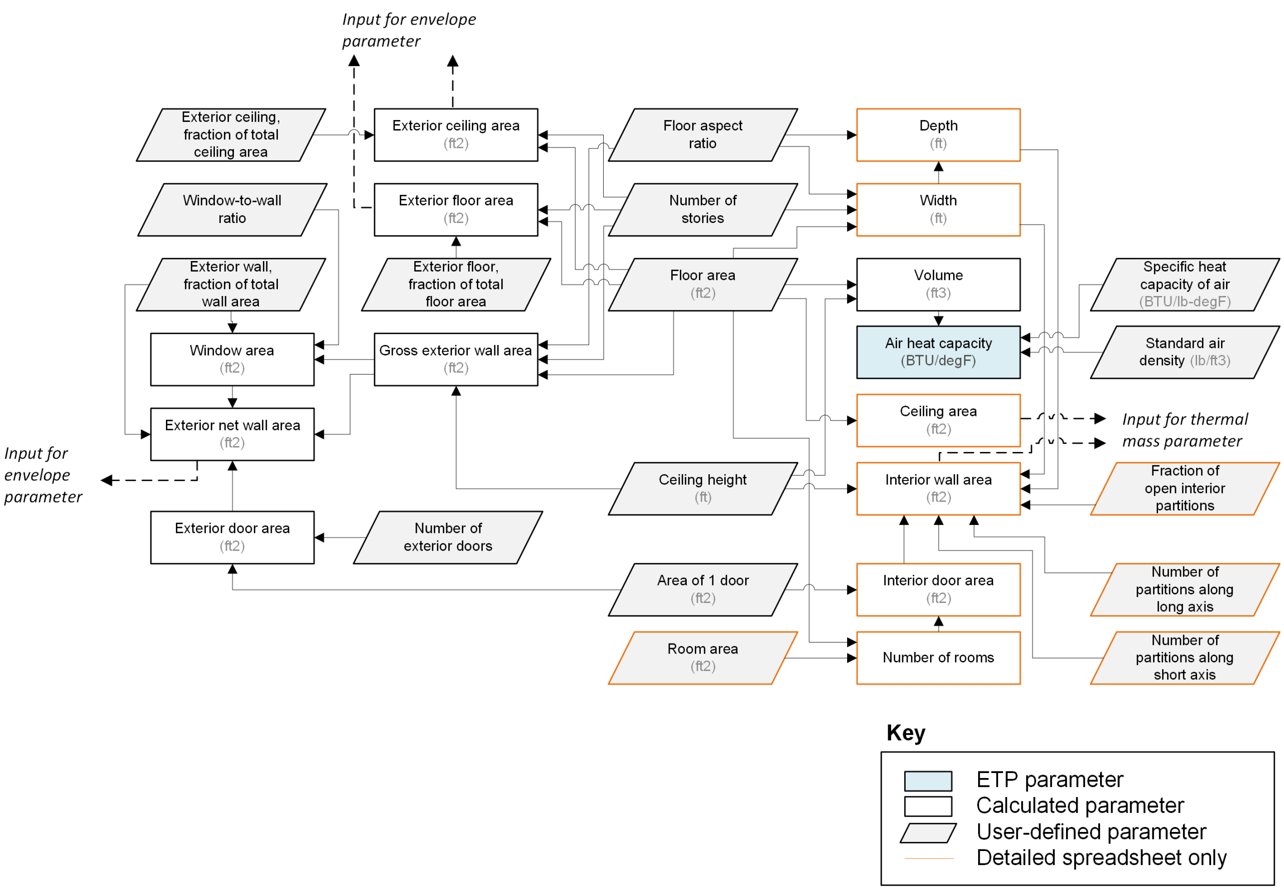

Figure A.1. Dependency map of building geometry parameters in GridLAB-D residential model with detailed calculations

Table A.1. Detailed geometry parameter defaults

Parameter	Default	Units
Room area	250	ft^2
Fraction of open interior partitions	0.2	-
Number of partitions along long axis	2	-
Number of partitions along short axis	3	-

Furthermore, there is an additional set of user-defined parameters required to calculate m_f regarding the furnishings and appliances. The defaults are provided in Table A.2 and their relationships described in Figure A.2. Figure A.3 shows an updated version of Figure 5 with m_f, IWR, and h_i as calculated parameters.

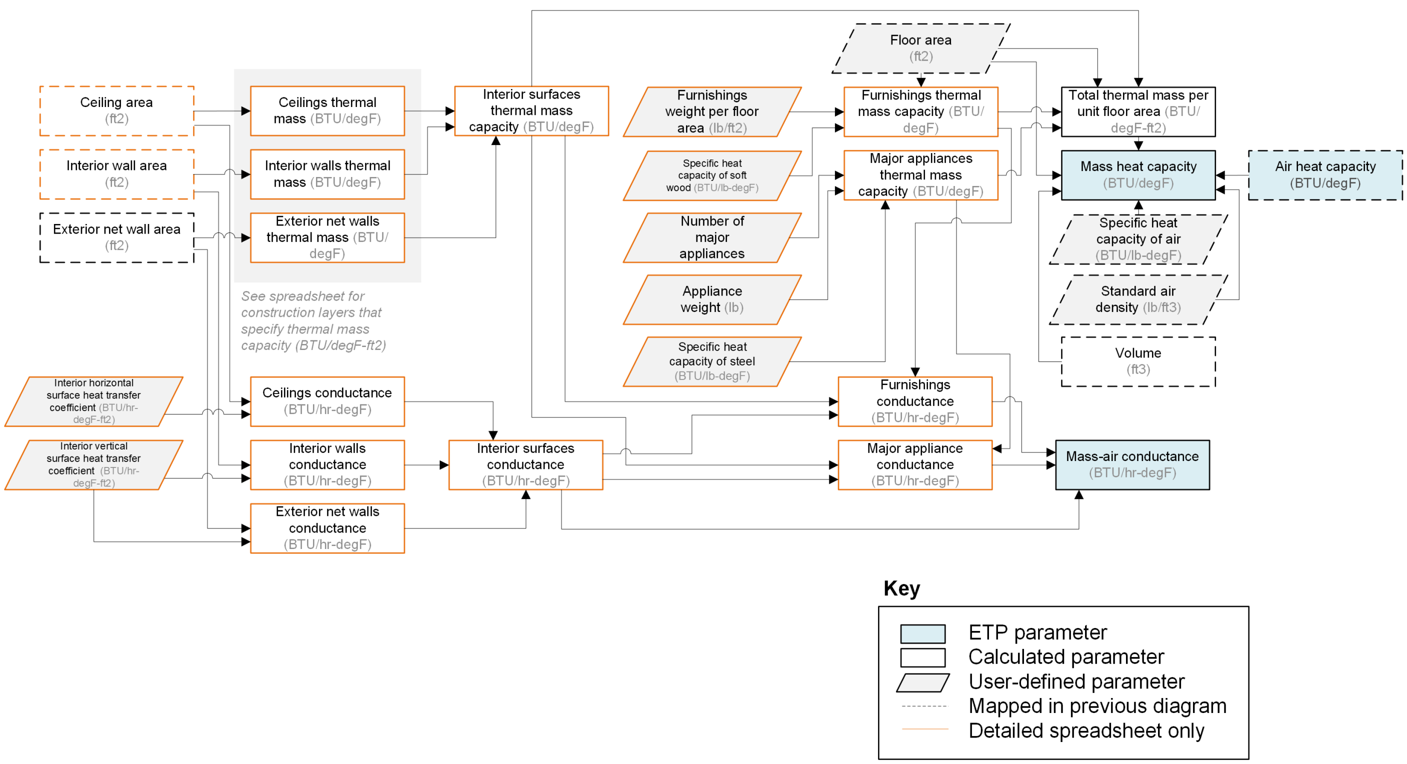

Figure A.2. Dependency map of building thermal mass parameters in GridLAB-D residential model with detailed calculations

Table A.2. Detailed thermal mass parameter defaults

Parameter	Default	Units
Furnishings weight per floor area	3.4	lb/ft^2
Number of major appliances	5	-
Appliance weight	200	lb
Interior horizontal surface heat transfer coefficient	0.49	BTU/hr-°F-ft^2
Interior vertical surface heat transfer coefficient	0.49	BTU/hr-°F-ft^2

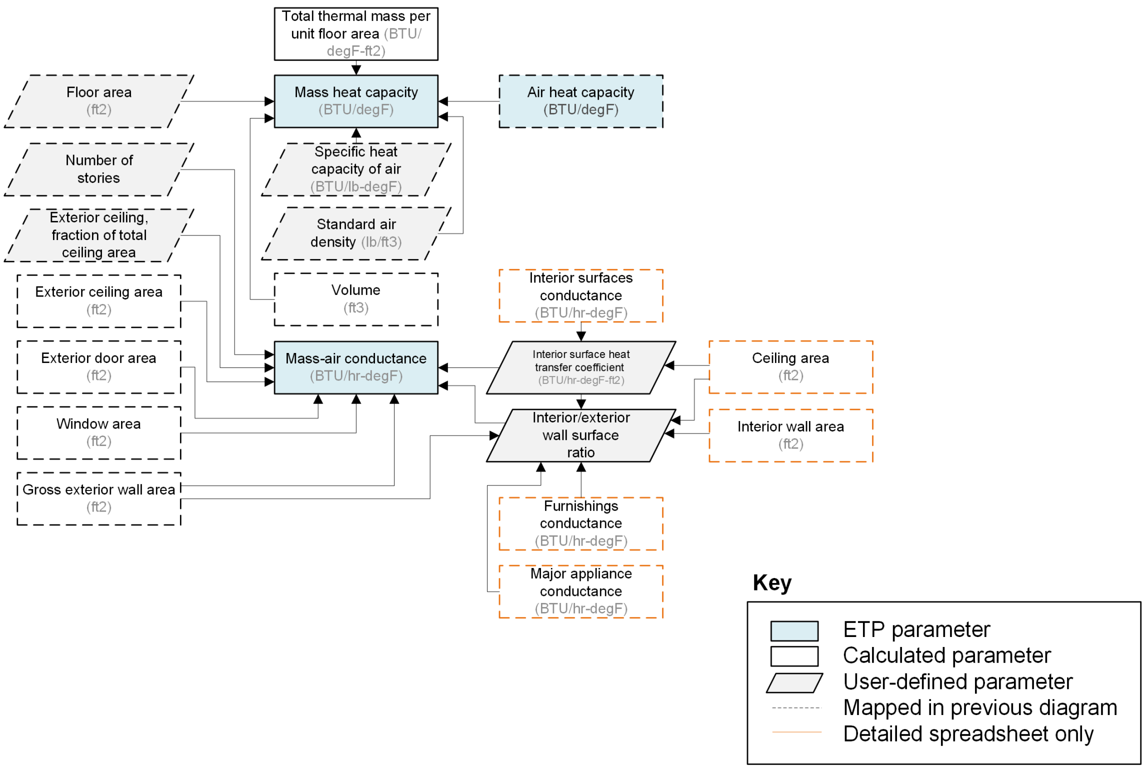

Figure A.3. Dependency map of building thermal mass parameters in GridLAB-D residential model with detailed calculations

$$IWR = \frac{(A_{int\,wall} + A_{ceiling}) + \left(\frac{H_{appliances}}{h_i}\right) + \left(\frac{H_{furnishings}}{h_i}\right)}{A_{gross\,ext\,wall}} \quad \text{(A.1)}$$

where $H_{appliances}$ is the thermal conductance of the major appliances and $H_{furnishings}$ is the thermal conductance of the furnishings.

$$h_i = \frac{H_{int\,surfaces}}{(A_{int\,wall} + A_{ceiling})} \quad \text{(A.2)}$$

where $H_{int\,surfaces}$ is the thermal conductance of the interior surfaces.

$$m_f = \frac{C_{int\,surfaces} + C_{furnishings} + C_{applicances}}{A_f} \tag{A.3}$$

where $C_{int\,surfaces}$ is the thermal mass capacity of the interior surfaces, $C_{furnishings}$ is the thermal mass capacity of the furnishings, and $C_{appliances}$ is the thermal mass capacity of the major appliances.

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