PRINCIPLES OF MODELING FOR CYBER PHYSICAL SYSTEMS

Assignment #3

Energy Plus and Model Parameters

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1 MODEL PARAMETERS

In this worksheet, you will encode the zone model structure (from Assignment 2) in `MATLAB`.

Problem 3-1: Assigning nominal values to model parameters using building construction details from the IDF file,

Problem 3-2: Encoding the model structure as a `MATLAB` function, and

Problem 3-3: Generating building operation data.

The following files are available on the course website and on UVA Collab for this assignment. `A03.zip`

1. `5ZoneAirCooled.idf`

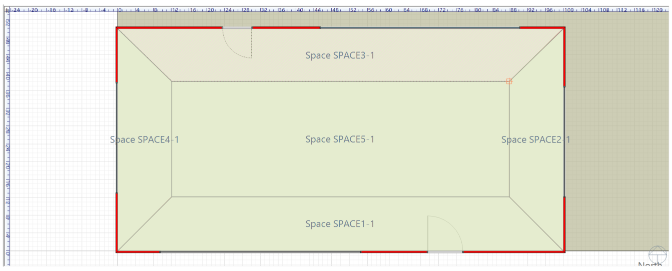

Figure 1.1: `SPACE3-1` is the north facing exterior zone of the building.

2. `model_structure.m`
3. `construction.m`

2 **PROBLEM 3-1:** NOMINAL PARAMETER VALUES

As discussed in the lectures, the parameter estimation problem for our state space model is non-linear in the parameters. Therefore, it is essential to compute nominal values of the parameter set in order to start the optimal parameter search during the estimation process. Much like the model structure design, the computation of the nominal values depends on the construction of the zone. The model structure contains two different types of lumped parameters describing the zone geometry.

- **Thermal resistance R** (in K/W): Thermal resistance is defined as the ratio of the temperature difference to the heat flow.
- **Conduction:** Under the one-dimensional steady-state heat flux conditions, the thermal resistance is given by:

$$R_{conduction} = \frac{L}{kA}$$

  where L is the thickness of the conduction plane (in m), A is the surface area (in m^2), and k is the thermal conductivity (in W/mK). The reciprocal of thermal resistance $1/R$ is referred to as thermal conductance (often denoted by U).

- **Convection:** Convective heat transfer is the transfer of energy between a surface and a fluid (such as air) in contact with the surface. Convection can be represented using thermal resistance similar to conduction. The thermal resistance for convection is given by:

$$R_{convection} = \frac{1}{h_c A}$$

  where, h_c (in W/m^2K) is the convection heat transfer coefficient of the fluid medium.

- **Thermal capacitance C** (in J/K): Thermal capacitance is the measure of temperature change in a material based on its volume. It is given by:

$$C = \rho L A c_p$$

  where ρ is the density of the material (in k/m^3), c_p is the specific heat capacity (in J/kK, and LxA is the volume (in m^3).

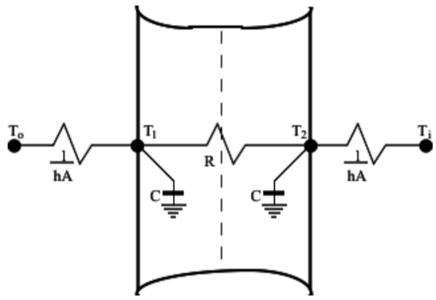

Figure 2.1: 3R2C lumped parameter configuration for a wall.

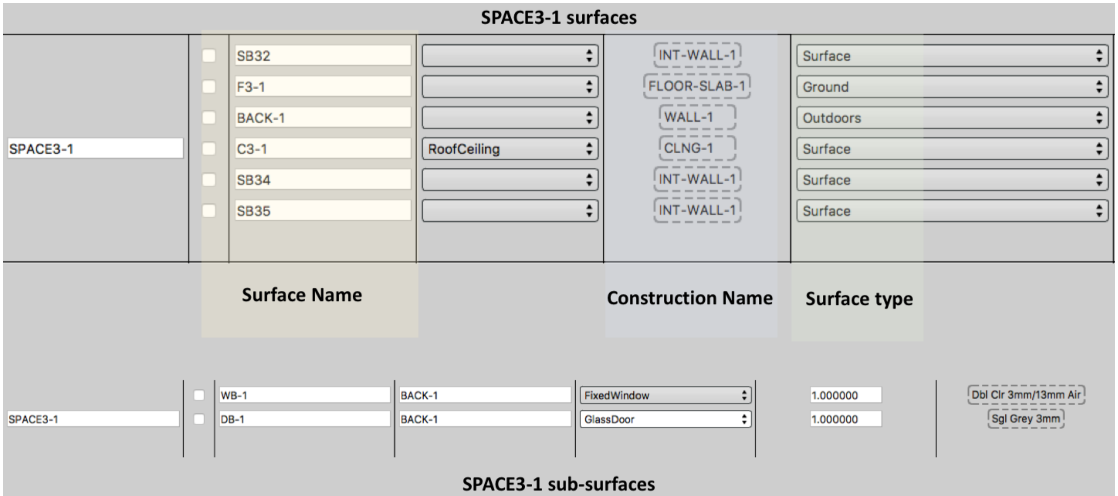

Figure 2.2: All surfaces and constructions of zone `SPACE3-1`

- Remember that in the popular **3R2C** parameter configuration as shown in Figue 2.1, each of the thermal capacitance coefficients C are considered equivalent. In which case:

$$C = \frac{\rho L A c_p}{2}$$

Each of these parameters, further depends on the characteristics of the material of construction, or the medium of heat transfer. For each surface, based on the material of construction, we will compute the nominal R and C values for that associated lumped parameter.
In EnergyPlus the building is described by its Input Data File or IDF file. This contains all the geometry, construction, operation, and equipment details about the building. Each zone is described by different surfaces, which are further described by different constructions, and each construction comprises of layers of one or often more materials.
So the zone layout is as follows: SURFACES » CONSTRUCTION » LAYERS » MATERIALS Figure 2.2 shows all the IDF variable names of the different surfaces and constructions for each

```
BuildingSurface:Detailed,
  BACK-1,                 !- Name
  WALL,                   !- Surface Type
  WALL-1,                 !- Construction Name
  SPACE3-1,               !- Zone Name
  Outdoors,               !- Outside Boundary Condition
  ,                       !- Outside Boundary Condition Object
  SunExposed,             !- Sun Exposure
  WindExposed,            !- Wind Exposure
  0.50000,                !- View Factor to Ground
  4,                      !- Number of Vertices
  30.5,15.2,2.4,  !- X,Y,Z ==> Vertex 1 {m}
  30.5,15.2,0.0,  !- X,Y,Z ==> Vertex 2 {m}
  0.0,15.2,0.0,  !- X,Y,Z ==> Vertex 3 {m}
  0.0,15.2,2.4;  !- X,Y,Z ==> Vertex 4 {m}
```

(a) BACK-1 surface (outdoor wall)

```
BuildingSurface:Detailed,
  C3-1,                   !- Name
  CEILING,                !- Surface Type
  CLNG-1,                 !- Construction Name
  SPACE3-1,               !- Zone Name
  Surface,                !- Outside Boundary Condition
  C3-1P,                  !- Outside Boundary Condition Object
  NoSun,                  !- Sun Exposure
  NoWind,                 !- Wind Exposure
  0.0,                    !- View Factor to Ground
  4,                      !- Number of Vertices
  30.5,15.2,2.4,  !- X,Y,Z ==> Vertex 1 {m}
  0.0,15.2,2.4,  !- X,Y,Z ==> Vertex 2 {m}
  3.7,11.6,2.4,  !- X,Y,Z ==> Vertex 3 {m}
  26.8,11.6,2.4;  !- X,Y,Z ==> Vertex 4 {m}
```

(b) C3-1 surface (ceiling)

Figure 2.3: IDF surface descriptions examples

surface. We can see that the zone `SPACE3-1` has a total of 6 different surfaces and 2 sub-surfaces. There are three internal walls, a floor, a ceiling, and an outdoor/external wall. The external wall surface (name `BACK-1`) has two sub-surfaces: one for the window (`WB-1`) and one for the door (`DB-1`).

Figure 2.3 shows two examples of how the surfaces are described in the IDF file. If you search the keyword 'BACK-1' in the IDF you will find that it the name of a 'BuildingSurface' , the surface type is a 'WALL', and the surface comprises of the construction WALL-1. The exact dimensions of the surface and its area can be computed using the 4 *(x,y,z)* vertices of the surface.

Having understood how surfaces are described, let us now look at constructions. Figure 2.4, shows the breakdown of the construction WALL-1. Remember that WALL-1 corresponds to the surface BACK-1 (which is the outdoor wall). We can see from the figure that the construction WALL-1 comprises of 4 layers of materials stacked together. The outermost material layer is called WD01 (exposed to the outside air), this is followed by 2 internal layers (PW03 and IN02) and lastly, the innermost layer (facing the inside of the zone) GP01. The IDF file describes the thermal properties of each layer in detail. We are interested in these thermal properties as we will use them to calculate the lumped thermal resistance and capacity of each surface.

Figure 2.4 also shows how the thermal characteristics of a material layer can be specified in `MATLAB`.

Figure 2.5 shows the layers for most of the constructions in the zone. However, it is highly advised that you navigate the IDF file by searching for the surface name, construction name, and then the layer name.

Remember the building elements are related in the following hierarchy SURFACES » CONSTRUCTION » LAYERS » MATERIALS

You should now be able to navigate to the thermal properties of any material, of any construction for the zone `SPACE3-1` in the IDF.

You can use the `MATLAB` function `construction.m` template provided to compute the nominal values of the parameters based on the material of construction details, as described in the input data file (IDF).

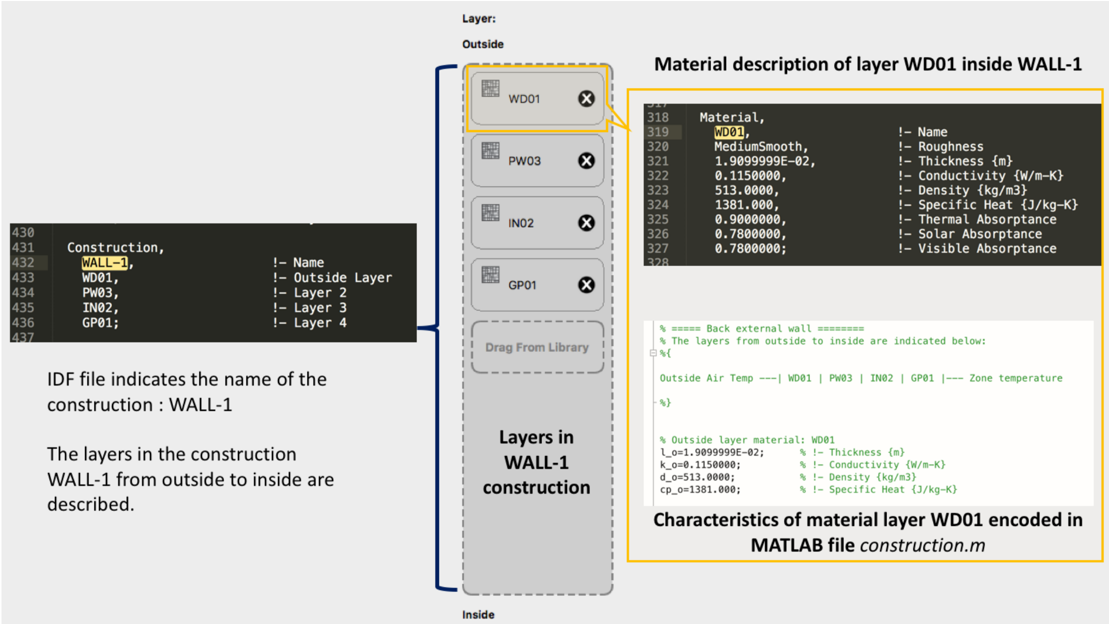

Figure 2.4: All surfaces and constructions of zone `SPACE3-1`

```
function [paranom,surfaces] = construction()

% Goal:
% Get familiar with zone construction
% Get familair with IDF files
% Parameter details and calclulation of the nominal values.

%{
Function Name: construction.m
Input arguments:
    - None
Outputs:
    paranom: A struct of nominal values with two fields
        - rvalues: thermal conductance nominal values.
        - cvalues: thermal capacity nominal values.
    surfaces: A struct with two fields:
        - areas: calculated areas of different zone surfaces
        - sol_abs: coefficient of irradiance absorpiton or ...
            transmission, where applicable.
%}
```

Here is an example of how the thermal properties can be specified in the `construction.m` function:

```
% ===== Back external wall ========
% The layers from outside to inside are indicated below:
%{
```

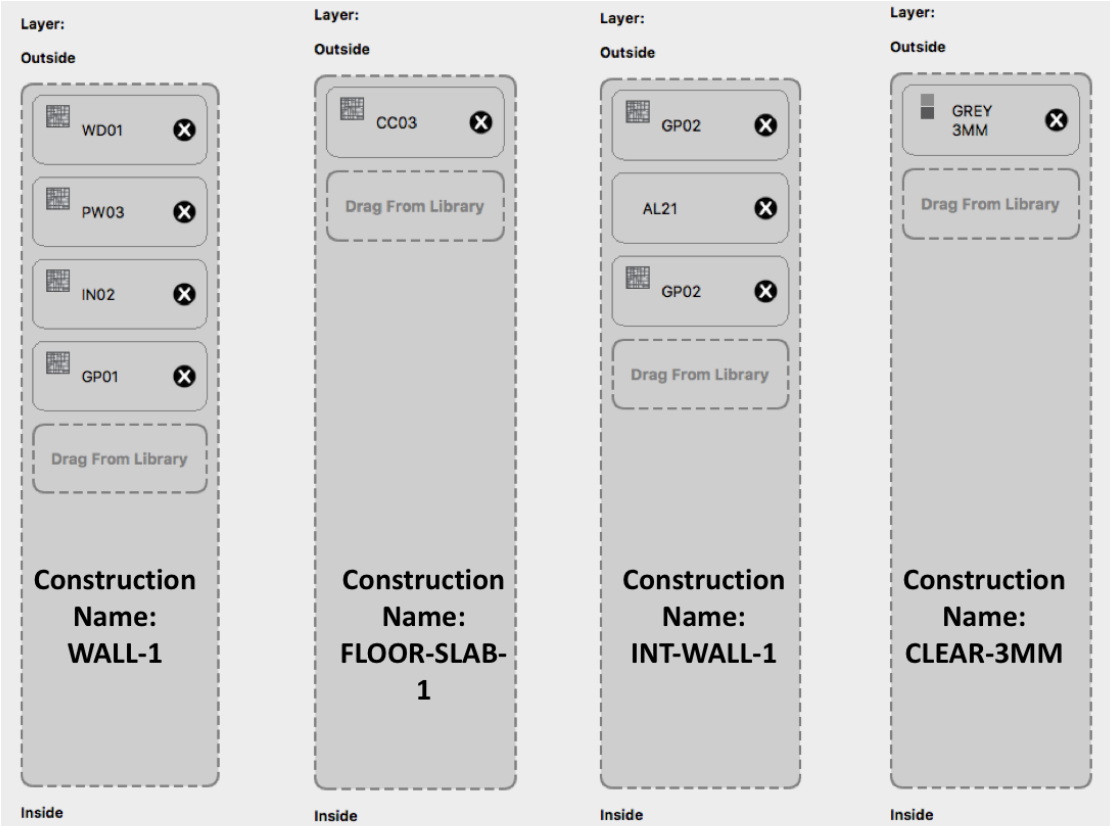

Figure 2.5: Layers element within different zone constructions

```

Outside Air Temp ---| WD01 | PW03 | IN02 | GP01 |--- Zone temperature

%}


% Outside layer material: WD01
l_o=1.9099999E-02;       % !- Thickness {m}
k_o=0.1150000;           % !- Conductivity {W/m-K}
d_o=513.0000;            % !- Density {kg/m3}
cp_o=1381.000;           % !- Specific Heat {J/kg-K}
```

Majority of the parameters have been initialized to zero, but some parameter have been pre-computed for assistance. Follow the instructions in the `construction.m` template and fill in all the missing values.

Submit the following: (50 points)

- **[P3-1.a] (40)** Submit your `construction.m` solution file. Do not change the format or the fields of the output structures `paranom`, and `surfaces`, although you may edit/add the number of elements in the structures based on your model. Be sure to comment your code and edits and describe the parameters, should you make any changes.

- **[P3-1.b] (10)** Submit a CSV file `nominal.csv` where the first column contains the parameter variable name, and the second column contains the computed value of the parameter, and the thrid column contains a breif description of the parameter. For e.g. an entry in this file could be: `Ue, value, Thermal conductance external wall`

3 Problem 3-2: Model structure in MATLAB

Now that the nominal values of the parameters have been computed, the next step is to import the structure of the state-space model from the previous worksheet into MATLAB. This implies, creating the A,B,C, and D in MATLAB with the correct elements which depend on the values of the different R and C parameters of the model. This step should be straight forward since you submitted the A, B, C, and D matrices as the solutions to Worksheet #2. All we need to do is create the same matrices as the output of a function.
Feel free to use the `model_structure.m` function template provided.

```
function [A,B,C,D] = model_structure(p,nstates,ninputs)
%{
Input the A, B, C and D matrices for the state space model in terms of ...
    the parameters specified in paranom.

Function Name: model_structure.m
Function Description: Given a vector of parameters, the function creates
the state transition (A), input (B), output (C), and feedforward (D)
matrices by specifying the non-zero elements in these matrices.
Input arguments: 3
    - p: This is a vector of all the unknown parameters. For parameter ...
        identification we initialize the vector p using the nominal
    values computed in the paranom structure.
    - nstates: Number of states in the model (from Worksheet 2)
    - ninputs: Number of inputs in the model (from Worksheet 2)

Outputs:
    Matrices A,B,C, and D with the correct dimentsions:
    dim(A) = nstates x nstates
    dim(B) = nstates x ninputs
    dim(C) = nstates x nstates
    dim(D) = nstates x ninputs
```

As can be seen, the input to the function is a vector,

$$\vec{p}$$

of parameters to be estimated. Let us briefly review how the parameter estimation works: Therefore, we need to specify the elements of the A,B,C, and D matrices in terms of the parameter vector $\vec{p}$ Refer to the example in the `model_structure.m` template file for details on how to define the vector $\vec{p}$ of unknown parameters.

Algorithm 1 How parameter estimation will be setup later.

```
procedure PARAMETER ESTIMATION PSEUDO-CODE
    Compute nominal values
    Initialize parameter vector p⃗ with nominal values
    Define model structure (A,B,C,D) in terms of p⃗
    while Repeat until convergence do
        Estimate new value of p⃗ using data and non-linear least squares.
        Update elements of A,B,C,D with new p⃗
    return best estimate of p⃗
```

Submit the following: (50 POINTS)

- Submit your $model\_structure.m$ solution file.

4 **PROBLEM 3-3:** GENERATING BUILDING OPERATION DATA

```
RunPeriod,
  ,                            !- Name
  1,                           !- Begin Month
  1,                           !- Begin Day of Month
  12,                          !- End Month
  31,                          !- End Day of Month
  Tuesday,                     !- Day of Week for Start Day
  Yes,                         !- Use Weather File Holidays and Special Days
  Yes,                         !- Use Weather File Daylight Saving Period
  No,                          !- Apply Weekend Holiday Rule
  Yes,                         !- Use Weather File Rain Indicators
  Yes;                         !- Use Weather File Snow Indicators
```

Figure 4.1: Run Period is specified in the IDF.

- Run the `5ZoneAirCooled.idf` file for the entire month of July with a **time-step of 5 mins.** Assume the first day of the month is Monday. You will need to change the Run-Period specified in the IDF as well as the timestep.

- You will notice that the simulation output creates a directory will multiple files. Import the following columns from the *correct* csv file into `MATLAB`. Write a matlab script to read the data from the CSV file and arrange it in a matrix with **columns in the order specified below**. Save this matrix as `<Your_Name>_Building_Data.mat`

  1. Ground Temperature, T_g (°C)
  2. Outside ambient temperature, T_a (°C)
  3. Return air plenum temperature, T_p (°C)
  4. Total external solar heat gain, $Q_{sol,e}$ (W)

5. Total internal heat gain, Q_{gain} (W)
6. Total sensible cooling load, Q_{cool} (W)
7. Neighboring zone temperatures for `SPACE2-1` T_2, `SPACE4-1` T_4, `SPACE5-1` T_5 (°C) [in this order]
8. SPACE3-1 zone temperature, T_z (°C)

Please adhere to the order of the columns specified above as we will grade the extra credit below based on that.

Submit the following: (EXTRA CREDIT(1): 20 POINTS)

- For each of the above inputs/states (1-8) report the minimum value, maximum value, and average value of the input for the period of the simulation.
- Submit the entries of row 141 from your mat file.

Submit the following: (EXTRA CREDIT(2): 20 POINTS) You are now the building facilities manager for this building. On July 17, you know there will be a demand response event from 2:00-4:00pm in the afternoon. You know you have notified the occupants of SPACE3-1 about this event and expect that during the event the occupancy of the SPACE3-1 will remain constant at 0.4 fraction of the maximum occupancy.
You now want to use EnergyPlus to simulate the effect of the changed occupancy schedule. Modify your IDF file such that:

- On July 17, between 2-3pm the occupancy of SPACE3-1 will be at 0.4 fraction of the maximum occupancy.
- Occupancy outside of the demand response event can remain as usual.
- Note that we only want the occupancy of SPACE3-1 to change and not affect any other zones.

Submit all the edits you made to the IDF file for this. You may need to define custom schedules and make other changes to link that schedule to SPACE3-1.