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Conceptual Design Methods and Tools for Building Services with complex dynamics

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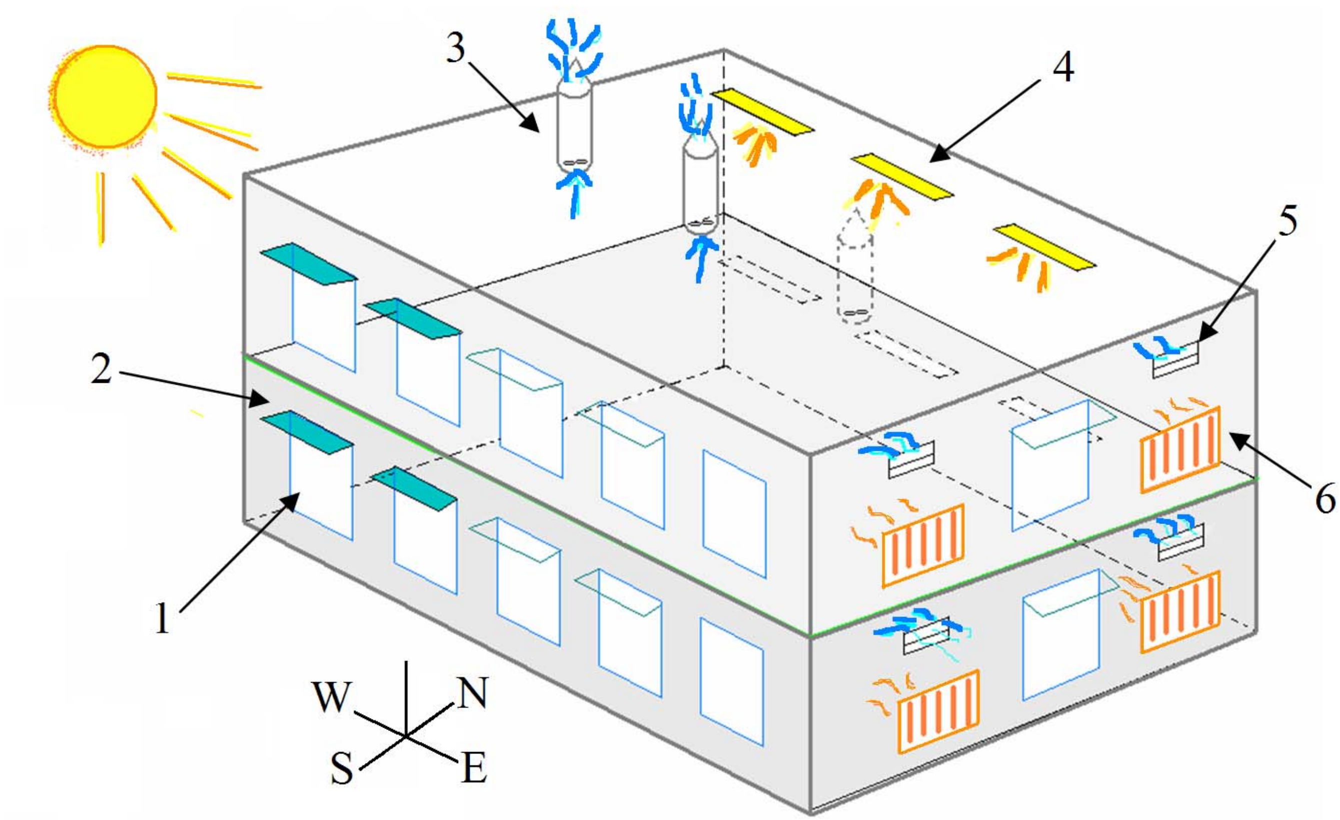
Conceptual design



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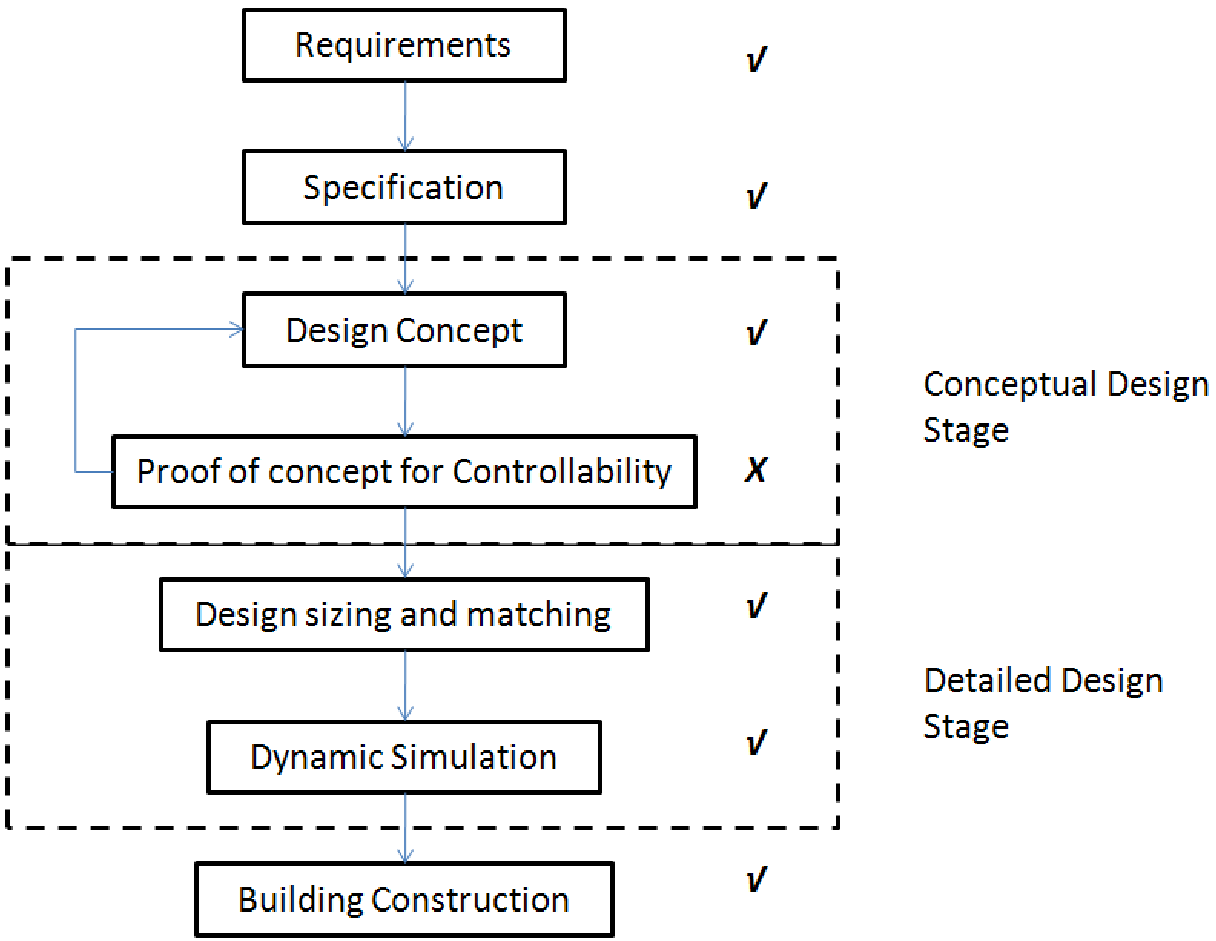
Design Process

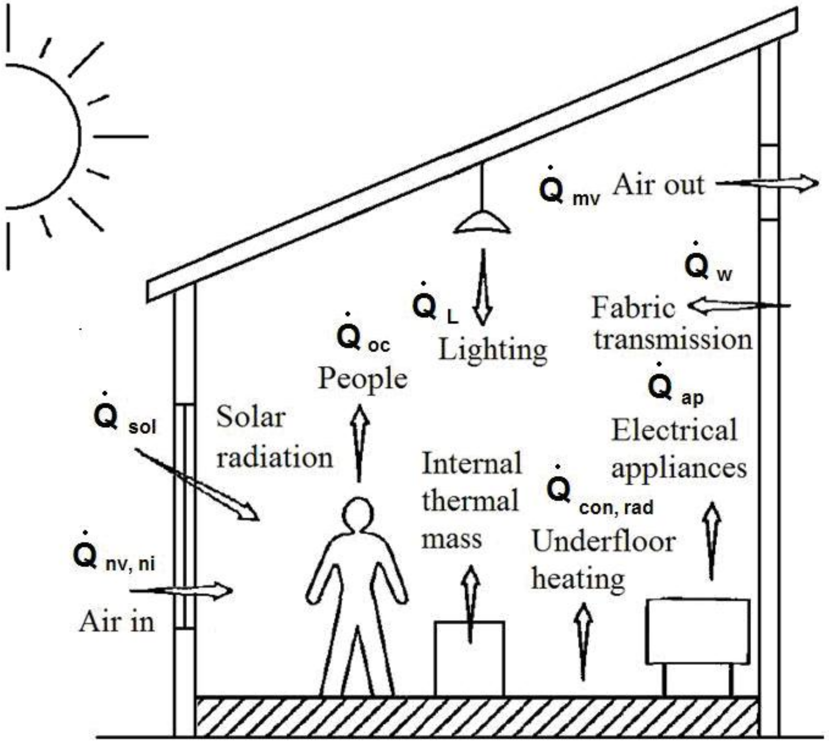


Dynamics

- Complex Building Physics
  - Natural ventilation (Bouncy and wind)
  - Dynamic internal and external disturbances

- Simultaneous control of Fast and Slow Actuators
  - Under Floor heating
  - Mechanical Ventilation

- Actuator Rate limits
- Physical Power limits



Holistic Design Method

Modelling — Building physics & Systems

Symbolic Analysis — Controllability

Simulation — Results Verification

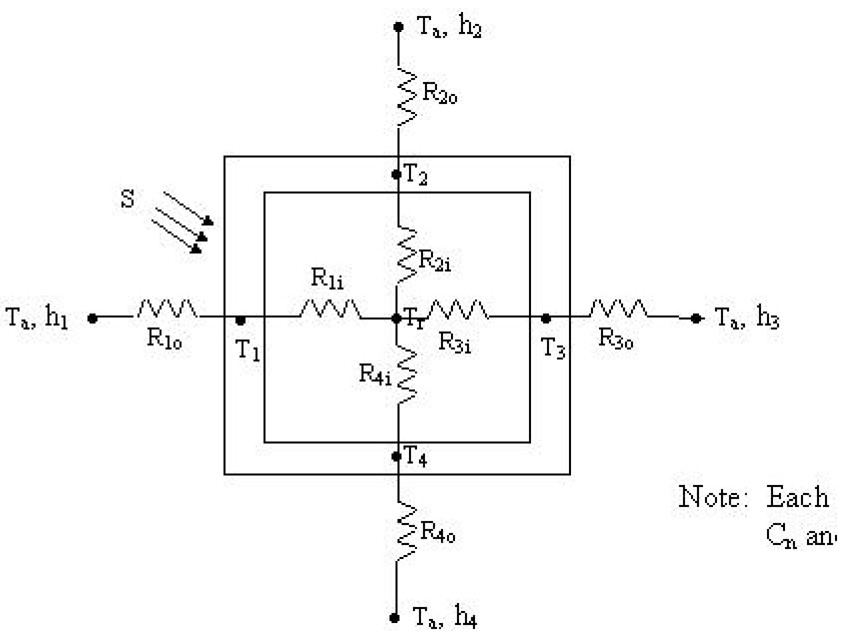
Modelling

- R-C circuit analogy
- Nonlinear Lumped parameter model
- Linear state space methods

$$\dot{x}(t) = Ax(t) + Bu(t) + Fd(t)$$

$$y(t) = Cx(t) + Du(t) + Ed(t)$$

$$k_1 \frac{dT_i}{dt} = k_2 Q_i - k_3 (T_i - T_o)$$



Symbolic Analysis

- Aerospace, automotive, robotics
- Controllability science

$$\begin{matrix} & Q_{pwh} & q_{mv} & \\ & \left(\begin{matrix} \dfrac{\beta}{\rho_a V_a c_{pa}} & \dfrac{\left(\bar{T}_o - \bar{T}_a\right)}{V_a} \\ 0 & \dfrac{\left(\bar{C}_o - \bar{C}_a\right)}{V_a} \end{matrix} \right) & & \begin{matrix} T_a \\ C_a \end{matrix} \end{matrix}$$

$$k_1 = \frac{-4U_w A_w}{\rho_w V_w c_{pw}}$$

$$k_2 = \frac{-U_c A_c - U_{in} A_{in}}{\rho_c V_c c_{pc}}$$

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Results

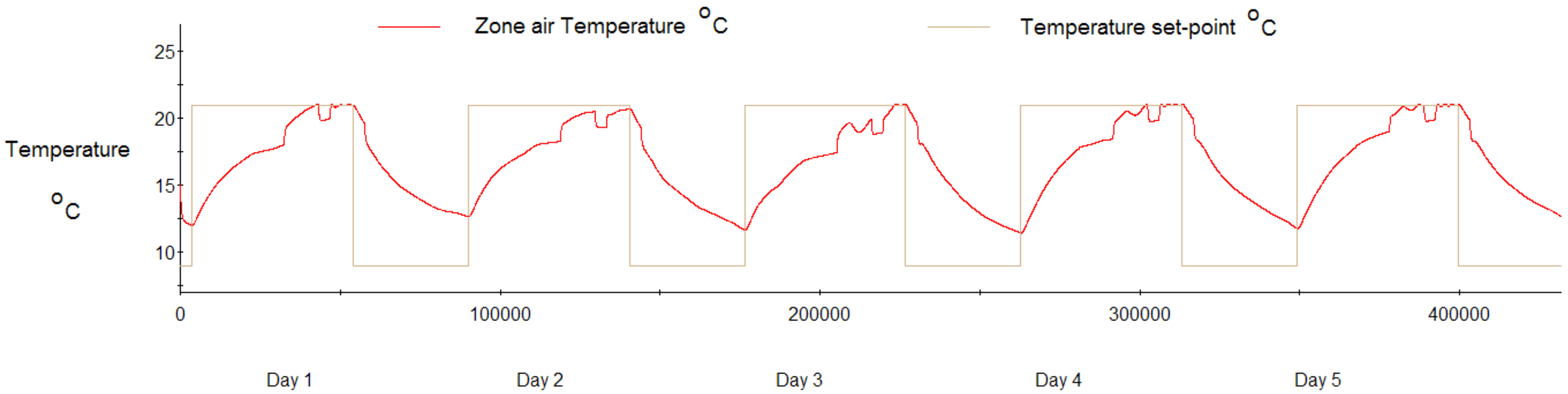
- When controlling air temperature in the building neither the thermal mass of the external Walls or internal Walls have any effect!

- When controlling thermal comfort the thermal mass has an effect the magnitude of which can be derived using one formula

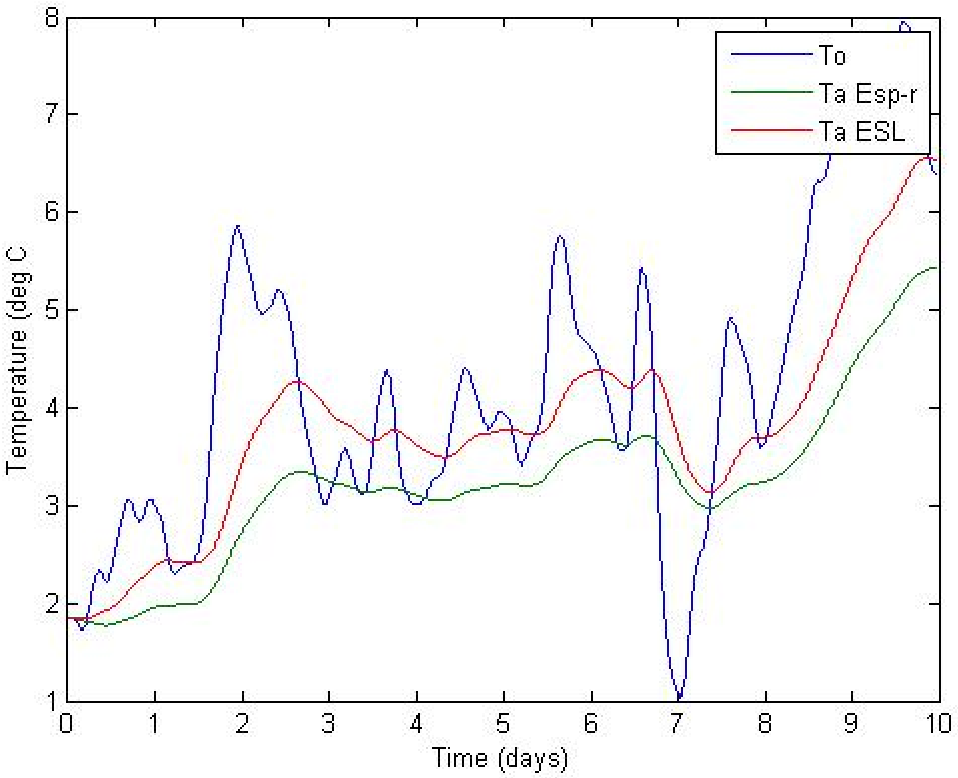
$$u_{trim}(s) = \frac{1}{\beta}\left[\begin{array}{l}\left(U_{win}A_{win} + V_a \overline{n}_i \rho_a c_{pa}\right)\left(T_a(s) - T_o(s)\right) + \left(2U_w A_w\right)\left(T_a(s) - T_w(s)\right) \\ + \left(U_m A_m\right)\left(T_a(s) - T_m(s)\right) - \left(\sigma_s A_w\right) L_{dir}(s) - \left(k_e\right) P_L(s) - Q_{oc}(s) - Q_{ap}(s)\end{array}\right]$$

Simulation

- European Simulation Language (ESL)



Models in ESP-r and ESL



Dynamic Domestic Modelling

- Domestic Modelling Procedure (SAP)
  - Quasi Steady State
  - Constant Disturbances
  - Responsivity Factor
- SAP cannot model dynamics of advanced systems without real data
  - Complex Heating e.g. heat pumps and CHP / Lighting with controls/ Renewables
  - Systems represented by one equation in SAP to provide a yearly average
- Dynamics Values
  - Allow Dynamic values to be used in a SAP environment
  - Values are calculated at small time steps

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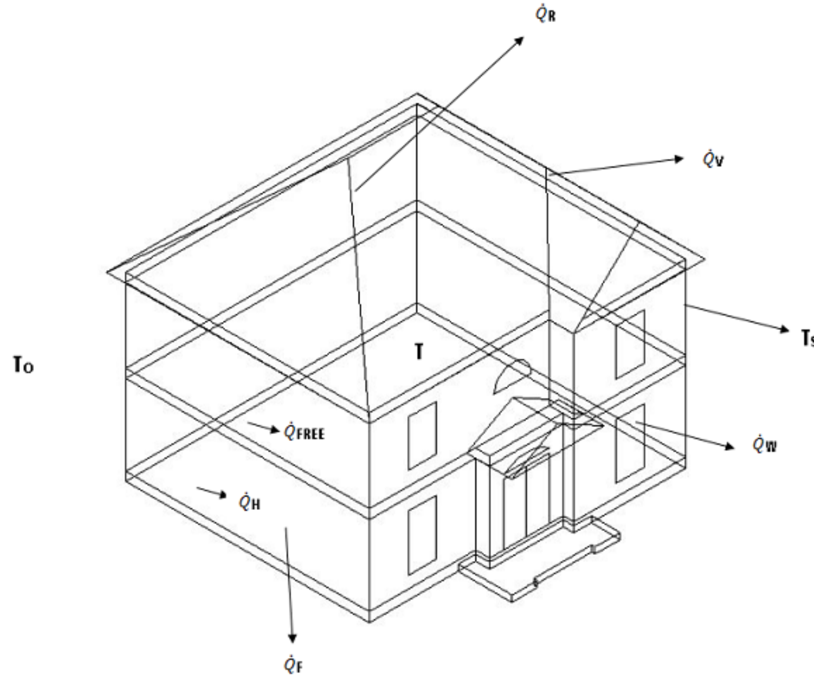
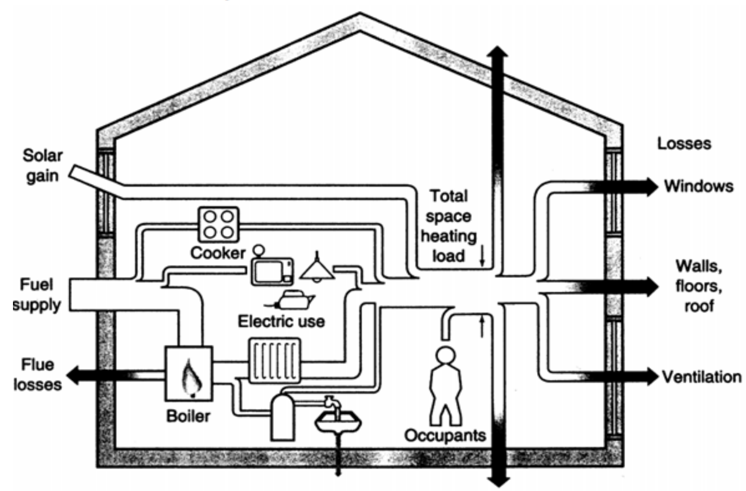
Energy Estimation

- Relationships which affect the Energy Estimation of a dwelling
- Assumptions:
  - Air is fully mixed at constant pressure
  - Windows, Roof and Floor in Steady State
    - U-Values taken from SAP
- Purpose of model is not to emulate Future Reality
  - Advanced integration tools such as ESP and IES already exist
- Fundamental Building Physics Model Created
  - Differential equations derived from first principles
    - Put into State Space Form for Controllability Analysis





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State Space Representation

- Apply Controllability Science to SAP Procedure – dynamic equations must be represented in State Space Form:

$$\dot{x}(t) = Ax(t) + Bu(t) + Dd(t)$$

State Vector: define States

State Matrix

Input Matrix

Disturbances Matrix

$$\begin{bmatrix} \dot{T}(t) \\ \dot{T}_S(t) \\ \dot{T}_{FT}(t) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & 0 \\ a_{31} & 0 & a_{33} \end{bmatrix} \begin{bmatrix} T(t) \\ T_S(t) \\ \dot{T}_{FT}(t) \end{bmatrix} + \begin{bmatrix} b_{11} \\ 0 \\ 0 \end{bmatrix} \left[\dot{Q}_H(t) \right] + \begin{bmatrix} d_{11} & d_{12} \\ 0 & d_{22} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{Q}_{FREE}(t) \\ T_o \end{bmatrix}$$

State Variables: Temperature of Dwelling Air, Structure, Internal Mass

State Matrix: A Matrix constants * State Variables

Input Matrix:

Direct Acting Heater Q_H

Disturbances Matrix:

-QFree (solar, metabolic, appliances)

-T_O (Outside Temperature)

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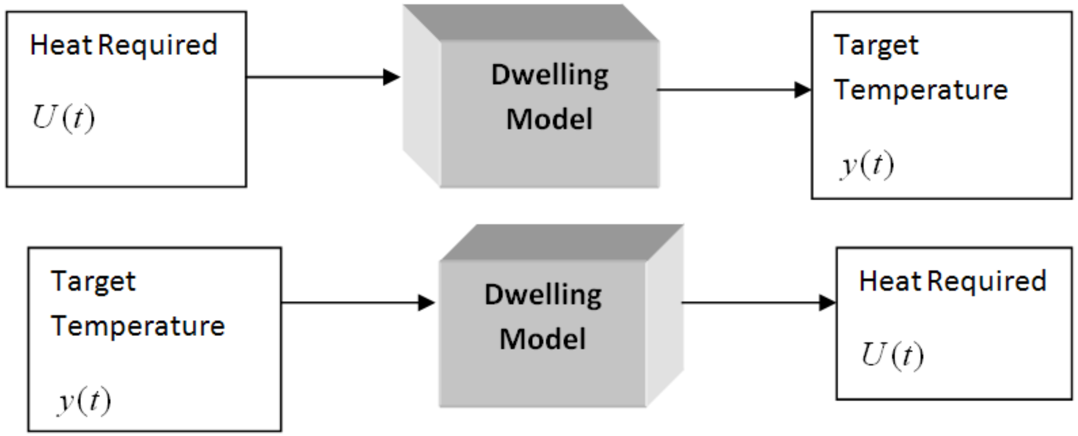
Excel Implementation

- Data placed into Excel Columns
- Model set to time resolution of 5 minutes
- Current focus on systems with a fast responsivity
  - gas boilers / direct acting electric heating
- Use of real data in model
  - Weather – Sheffield location - Meteonorm software
  - Real Free Heats generated
    - Solar Gains (Sheffield location - Meteonorm)
    - Appliances Gains (International Energy Agency / Energy Conservation in Buildings and Community Systems Program (ECBCS) Annex 42)
    - Metabolic Gains (based upon BREDEM principles)

Inverse Dynamics

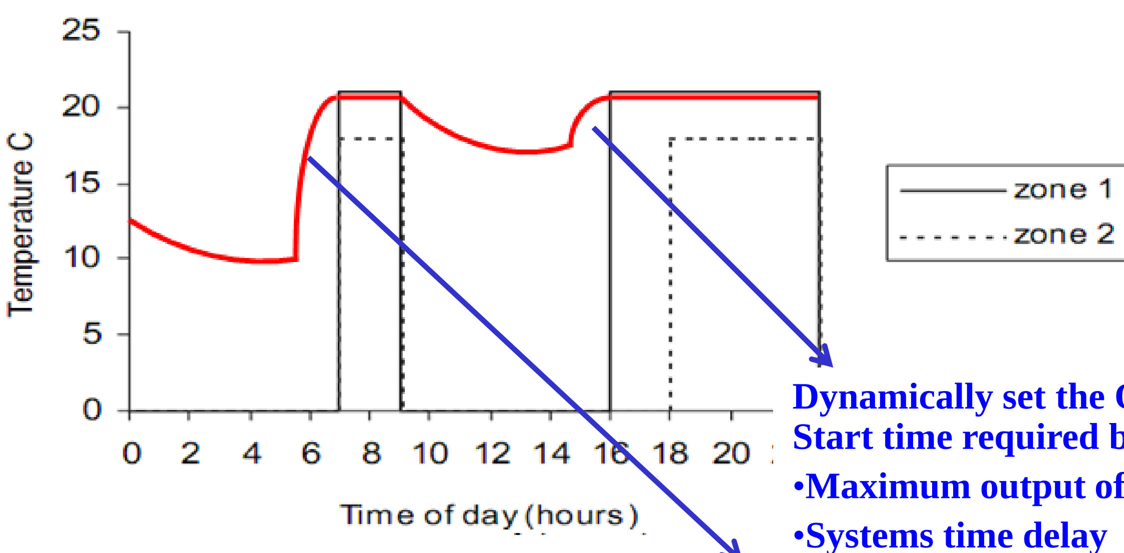
- Control Systems calculate the input required for a desired output
  - This can be achieved by inverting the plant
  - Inverse Dynamics

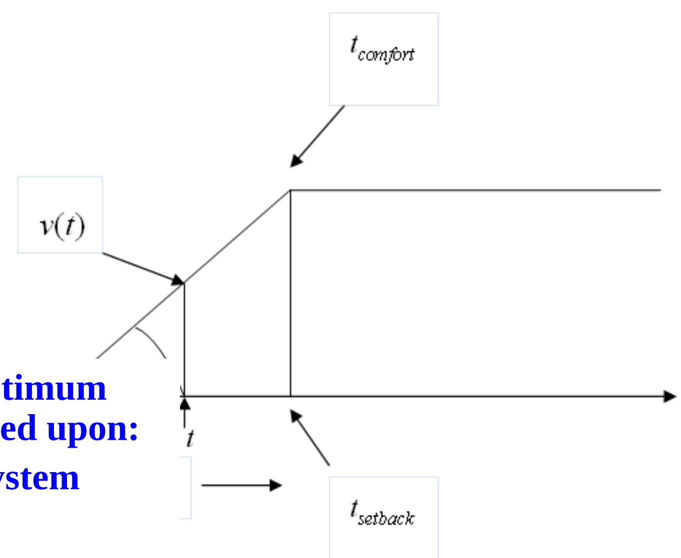
- A controller based upon Inverse Dynamics
  - Cancel the non-linear dynamics of the system
  - Decouple the controlled variables
- Use of Inverse Dynamics to calculate Dynamic SAP results at each timestep
  - Example: Room Temperature in Controller Design
  - We invert the dynamics of the system to establish what heat is required



Optimum Start

- Addition of Optimum Start to Dynamic SAP
  - Particularly required to model Slow acting systems (slow responsivity in SAP) such as underfloor heating
- Dynamically track SAP setpoint based upon power and response of heating system





Dynamically set the Optimum Start time required based upon:

•Maximum output of system

•Systems time delay

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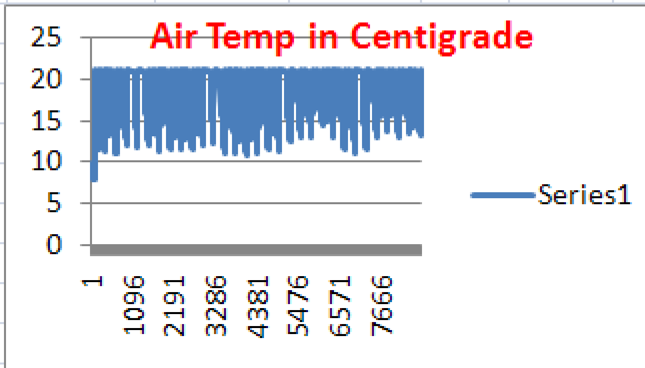
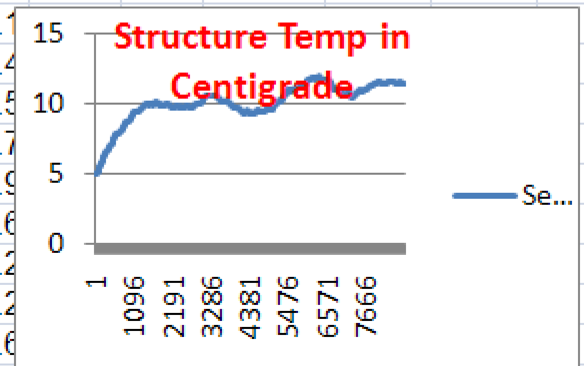
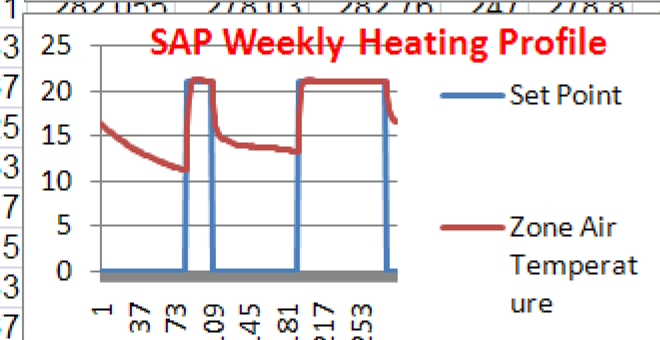
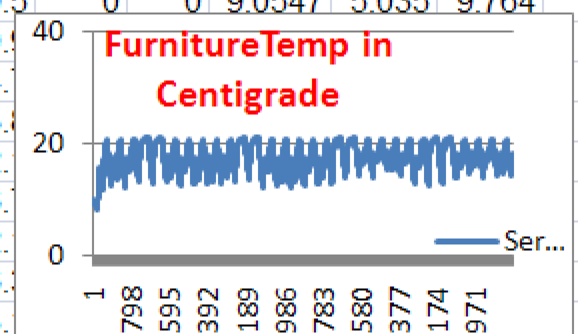
Initial conditions			Temperature Initial Conditions			Timestep	
Define Limits of Heating System (Watts)				K	Celcius		Seconds
Ul	5000		To	273	0	T	300
Ll	0		Ta	283	10		
G	0.002	minutes	Ts	278	5		
Qfree	718	Watts	Tft	283	10		

setpoint v	K	time t (h)	Ta(k) (Zone Air)	Ts (k) (Structure)	Tft(k) (Furniture)	Qfree	To - Kelvin	u(k) (heat in Watts)	u(k) (discontinuity)	Set Point - C	Ta(k) in C	StructureTemp in C	Furniture Temp in C	Time (Seconds)	Solar Gains	Appliance Gains
273	0	0	283	278	283	335	278.8	0	0	0	10	5	10	0	0	335
273	1	0.083	282.731	278	283	326	278.8	-4769.7	0	0	9.7307	5.003	10	300	0	326
273	2	0.167	282.562	278.01	282.99	311	278.8	-4735.8	0	0	9.5624	5.006	9.99	600	0	311
273	3	0.25						4703.1						900	0	300
273	4	0.333						4677.4						1200	0	302
273	5	0.417						4666.5						1500	0	291
273	6	0.5						4644.7						1800	0	287
273	7	0.583						4629.9						2100	0	281
273	8	0.667						4614.6						2400	0	275
273	9	0.75						4598.2						2700	0	266
273	10	0.833						4579.2						3000	0	259
273	11	0.917						4562.6						3300	0	256
273	12	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-4549.5	0	0	9.0547	5.035	9.764	3600	0	247
273	13	1.083						4530.9						3900	0	241
273	14	1.167						4514.1						4200	0	240
273	15	1.25						4503.8						4500	0	238
273	16	1.333						4492.1						4800	0	232
273	17	1.417						4476.1						5100	0	238
273	18	1.5						4472.1						5400	0	231
273	19	1.583						4456.1						5700	0	232
273	20	1.667						4448.1						6000	0	237



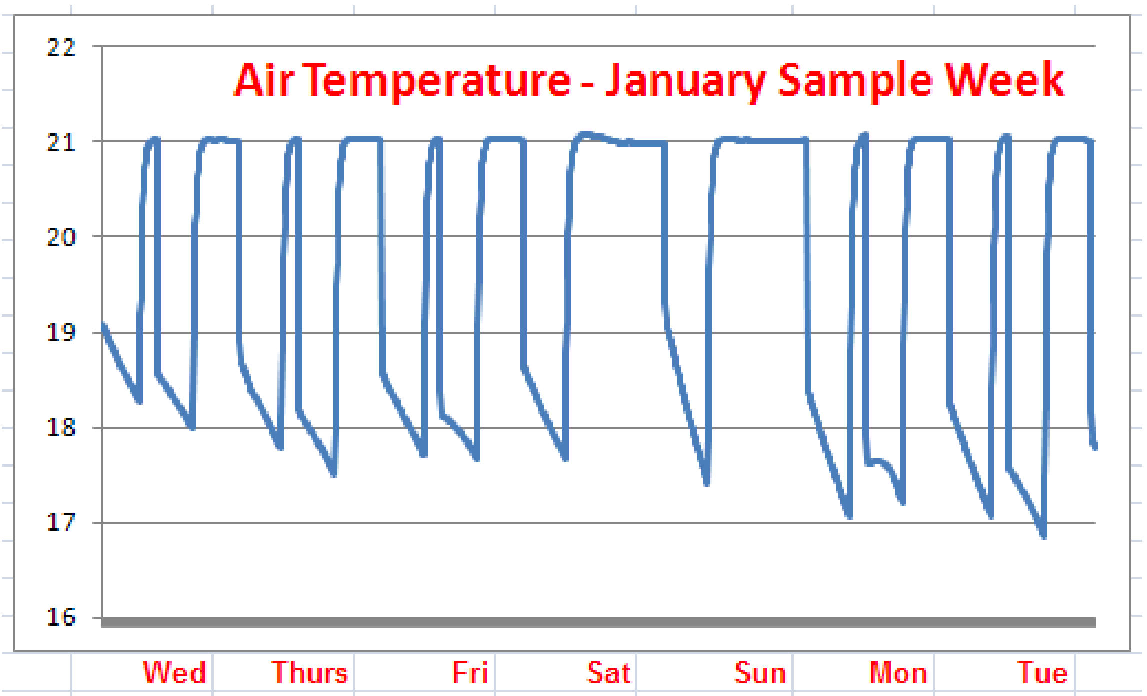






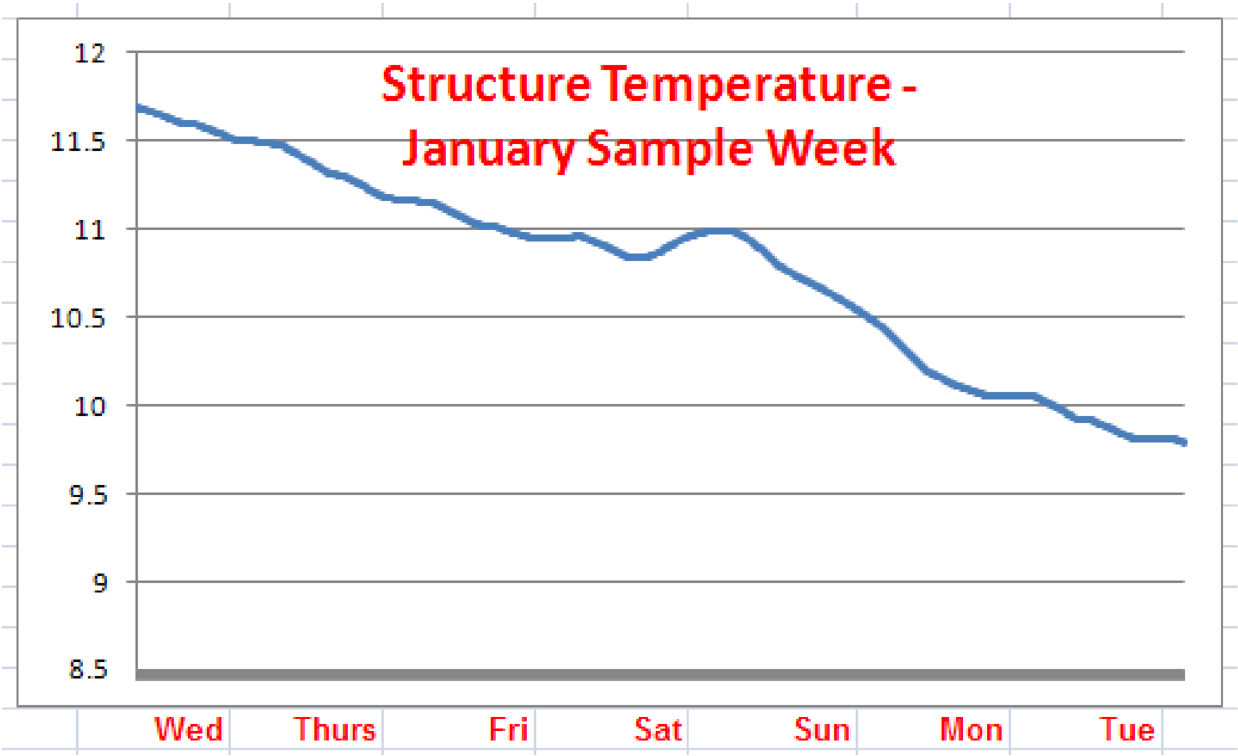
Sample Output – 1 of 3

- Air Temperature in Dwelling



Sample Output – 2 of 3

- Structure Temperature in Dwelling



Sample Output – 3 of 3

- Internal Mass Temperature in Dwelling