Uncertainty of Energy Consumption Assessment of Domestic Buildings

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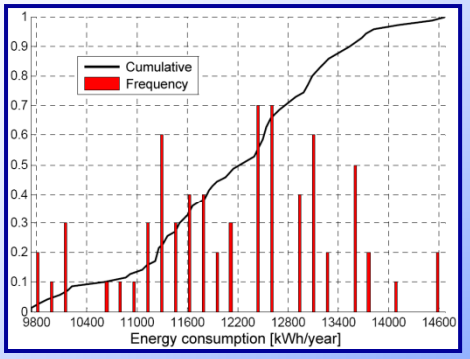

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Introduction

- Assessment of energy reduction initiatives, annual cost, life cycle cost, emission impact, etc. requires reasonably accurate energy consumption calculations
- Several investigations reveal significant uncertainties in the determination of building energy consumption (deviation may exceed 100% in extreme cases)
- Theoretical and empirical study of the uncertainty of energy consumption in domestic buildings are undertaken
- The purpose is to improve understanding and estimation of energy consumption including quantification of uncertainty
- A number of similar Danish domestic buildings are investigated to determine uncertainty and indentify important sources of variance

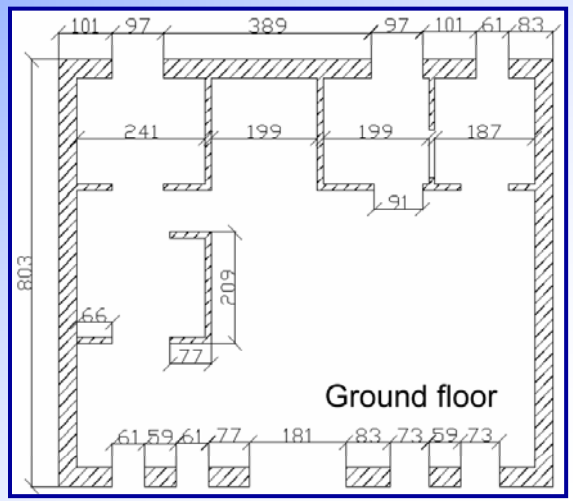
Building Description

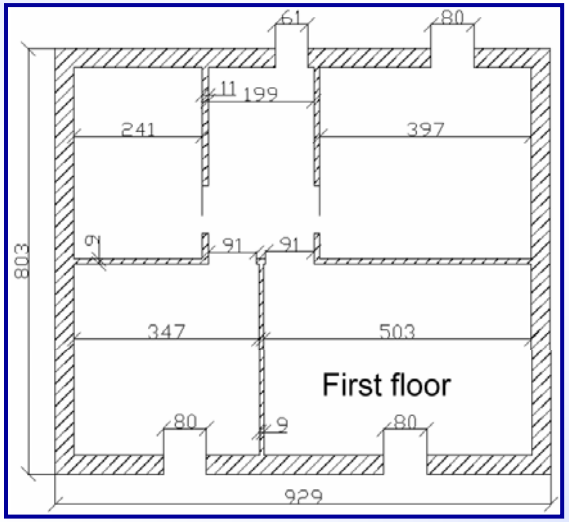
8 almost similar red-bricked semi-detached houses

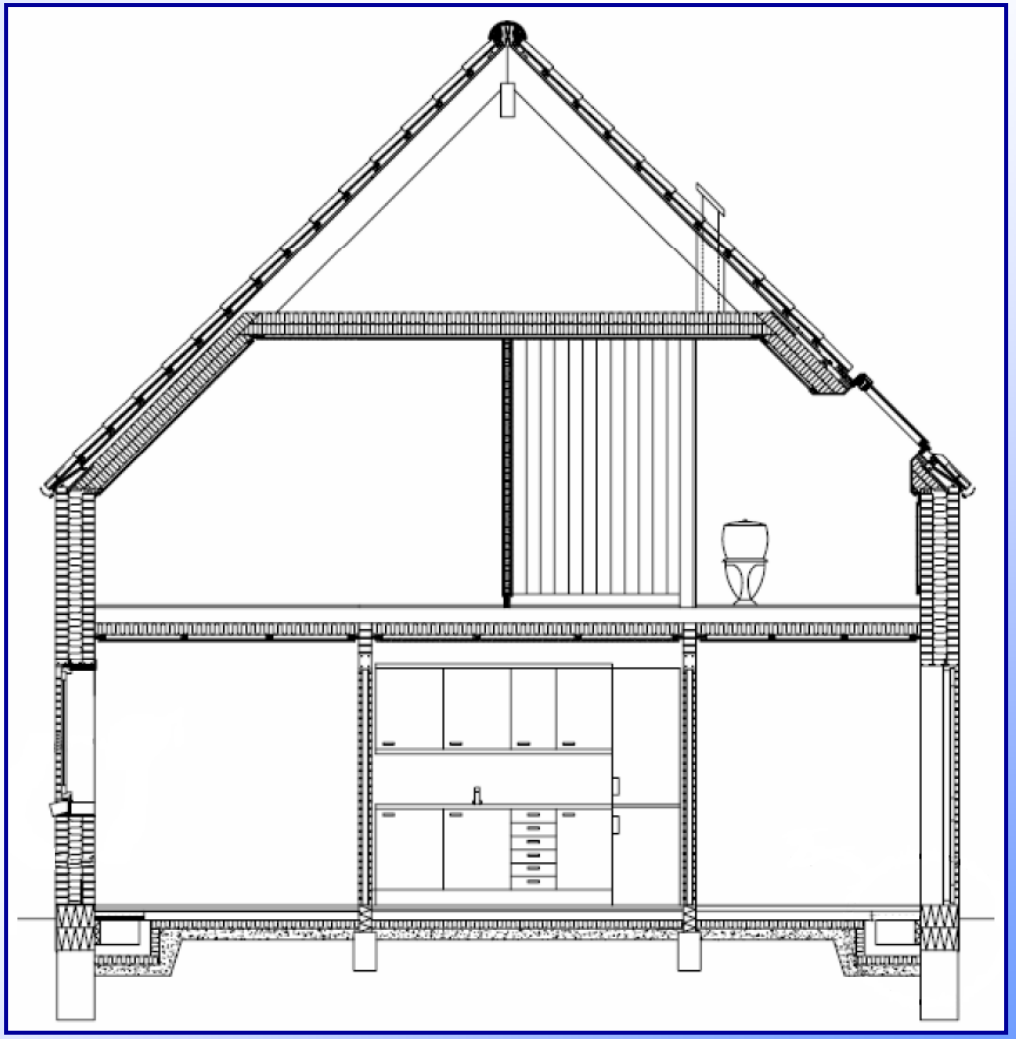
- Located in western part of Denmark
- Conditioned area 149 m^2
- Room height 2.37 m, 0.35 m cavity walls
- Naturally ventilated
- Heated by district heating

Building Description, 2

Horizontal plan and sectional view







Measurements

- Blower door (building leakage @ 50 Pa)
- Tracer gas (leakage distribution and air infiltration)
- Internal temperature (thermal comfort and preferences)
- Weather data: local external temperature, local meteo data (wind speed, wind direction, temperature, rel. humidity, atm. pressure, cloud cover, global solar rad.)
- Questionnaire (occupant number, age, occupied period, bathing habits, use of computers, TV, appliances, etc.)
- District heating, water, electricity (reading of meters)

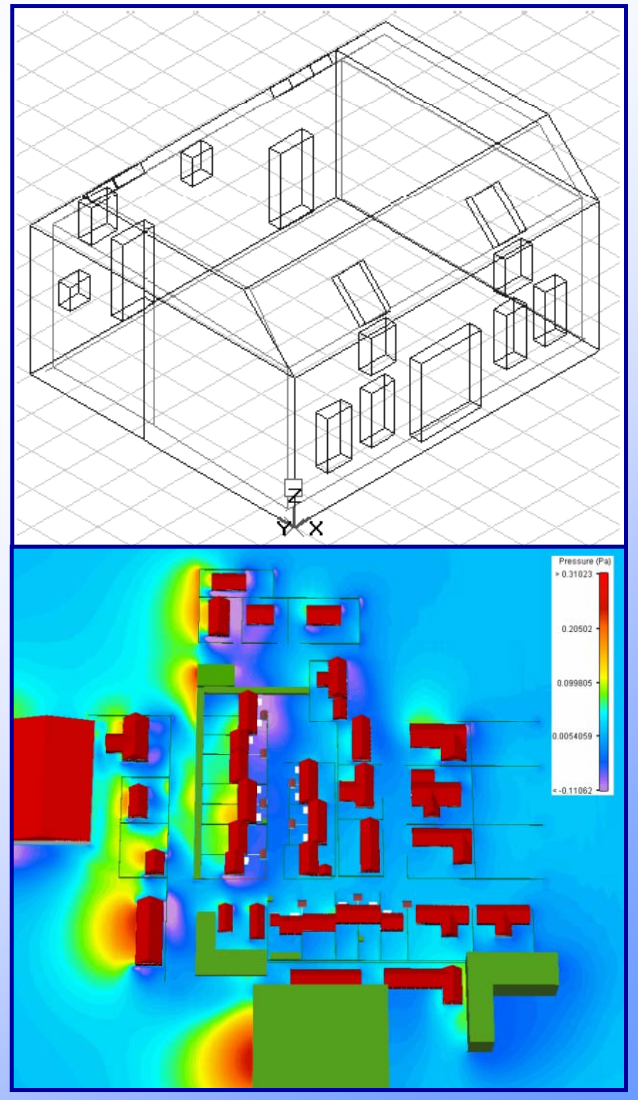
Measurement Results

8 buildings, μ is mean value and σ is standard deviation (2005 is a "typical" year)

Measurement	Unit	μ	σ
Infiltration (leakage)	l/(s·m^2) @ 50Pa	3.00	0.23
Internal air temperature set-point	°C	22.19	1.03
Internal heat load, appliances	W/m^2 (time average)	2.93	1.21
Internal heat load, occupants	W/m^2 (time average)	1.11	0.56
2005 total water consumption	m^3/year	125.3	41.2
2005 electricity consumption	kWh/(m^2·year) (kWh/year)	27.3 (4,079)	11.4 (1,697)
2005 district heating consumption	kWh/(m^2·year) (kWh/year)	73.0 (10,886)	16.6 (2,480)

Building Model

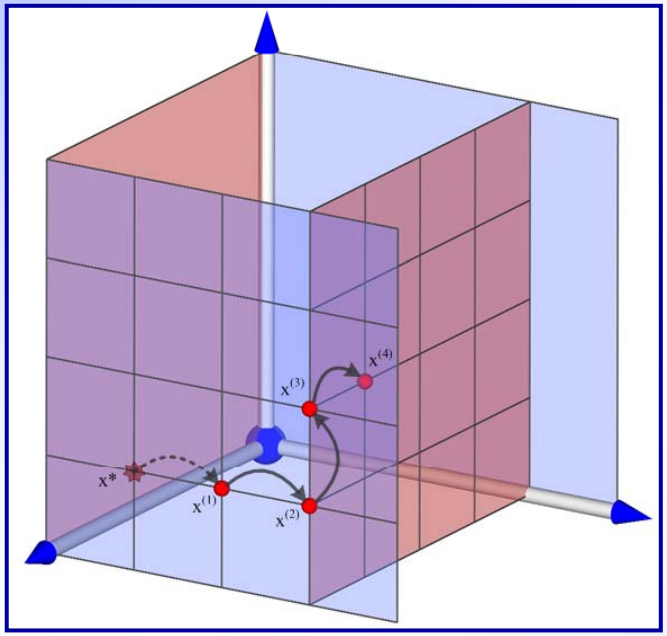
- Hygrothermal building simulation programme *BSim* applied for the simulations
- CFD (*Flovent*) and MZM (*Comis*) used to improve description of natural ventilation and air infiltration
- Danish DRY applied as weather data (compared with local meteo station data)
- 13 stochastic input parameters (distributions) for screening SA
- Reduced set applied for quantitative analyses (SA and UA)



Screening Sensitivity Analysis

Method of Elementary Effects (Morris Method)

$$EE\left(x_1,\ldots,x_k\right)=\frac{y\left(x_1,x_2,\ldots,x_{i-1},x_i+\Delta,x_{i+1},\ldots,x_k\right)-y\left(x_1,\ldots,x_k\right)}{\Delta}$$



- OAT (one factor at a time)
- Baseline changes at each step wanders in the input factors space
- Estimate the main effect of a factor by computing *r* numbers of local measures at $\mathbf{x}_1,\mathbf{x}_2,\ldots\mathbf{x}_r$ in the input space

$$\mu=\sum_{i=1}^{r}\left|EE_i\right|/r$$

$$\sigma=\sqrt{\sum_{i=1}^{r}\left(EE_i-\mu\right)^2/r}$$

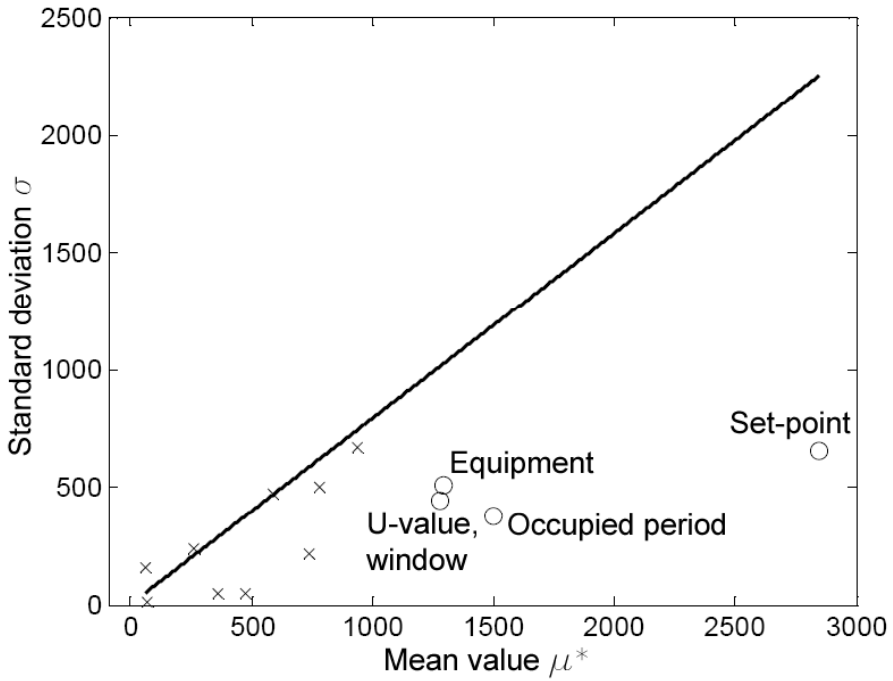
Screening SA Input Parameters

- 13 stochastic input parameters (distributions)
- Normal, Lognormal and Discrete distributions applied
- No correlation assumed

Input parameter		Distribution	
Name	Unit	Type	Interval; μ; σ
Set-point space heating	°C	N	21 - 24; 22; 0.71
Occupied period	h/day	D	10 – 18; see NOTE 1
Appliances heat load	W	N	215 – 730; 437; 100
U-value windows	W/m^2K	N	1.1 – 2.9; 2.4; 0.4
U-value doors	W/m^2K	N	2.2 – 3.3; 2.9; 0.2
Thermal conductivity (re *U*-value of walls)	%	L	0 - 40; 2.5; 0.7
Occupant heat load	Occupants	N	0.522 – 2.861; 1.594; 0.5
Natural ventilation	m^3/s	N	0.0386 – 0.0433; 0.041; 0.001
Solar shading factor	-	N	0.5 – 1.0; 0.8; 0.1
Glass *g*-value	-	N	0.59 – 0.76; 0.67; 0.04
Building orientation	°	D	21 – 291; see NOTE 2
Infiltration	$l/(s \cdot m^2)$	N	0.20 – 0.24; 0.215; 0.008
Building heat capacity	Wh/m^2K	N	120 - 144; 132; 4

Results from Screening SA

- Screening by the method of Elementary Effects
- 140 parameter combinations
- Four most important parameters marked as circles



Input parameter	Elementary Effects [kWh/year]		
Name	Rank	μ^*	σ
Set-point space heating	1	2850	656
Occupied period	2	1500	376
Appliances heat load	3	1290	510
U-value windows	4	1280	439
U-value doors	5	940	666
Thermal conductivity (re *U*-value of walls)	6	782	501
Occupant heat load	7	741	218
Natural ventilation	8	587	473
Solar shading factor	9	472	49
Glass *g*-value	10	362	47
Building orientation	11	261	236
Infiltration	12	71	9
Building heat capacity	13	58	158

Detailed SA and UA Input

- Most important parameters selected
- Normal and Exponential distributions applied
- No correlation assumed

Input parameter		Distribution	
Name	Unit	Type	Interval; μ; σ *or* d
Set-point space heating	°C	N	20 - 25; 22.27; 0.75
Infiltration / Nat. vent.			
Basic air change rate, n_0	1/h	N	1.0 - 1.2; 1.1; 0.033
Temperature exponent, t_p	-	N	0.5 – 0.6; 0.55; 0.017
Wind factor, c_v	s/(h·m)	N	0.034 – 0.064; 0.058; 0.007
Occupied period	h/day	N	12 – 18; 14.9; 0.95
Occupant heat load	W/m^2 (Occupants)	E	0.68 – 6.00; 1.10; 0.68 (1.01 – 8.95; 1.64; 1.01)
Appliances heat load	W/m^2 (kW)	E	1.62 – 6.00; 0.70; 1.62 (0.24 – 0.90; 0.10; 0.24)

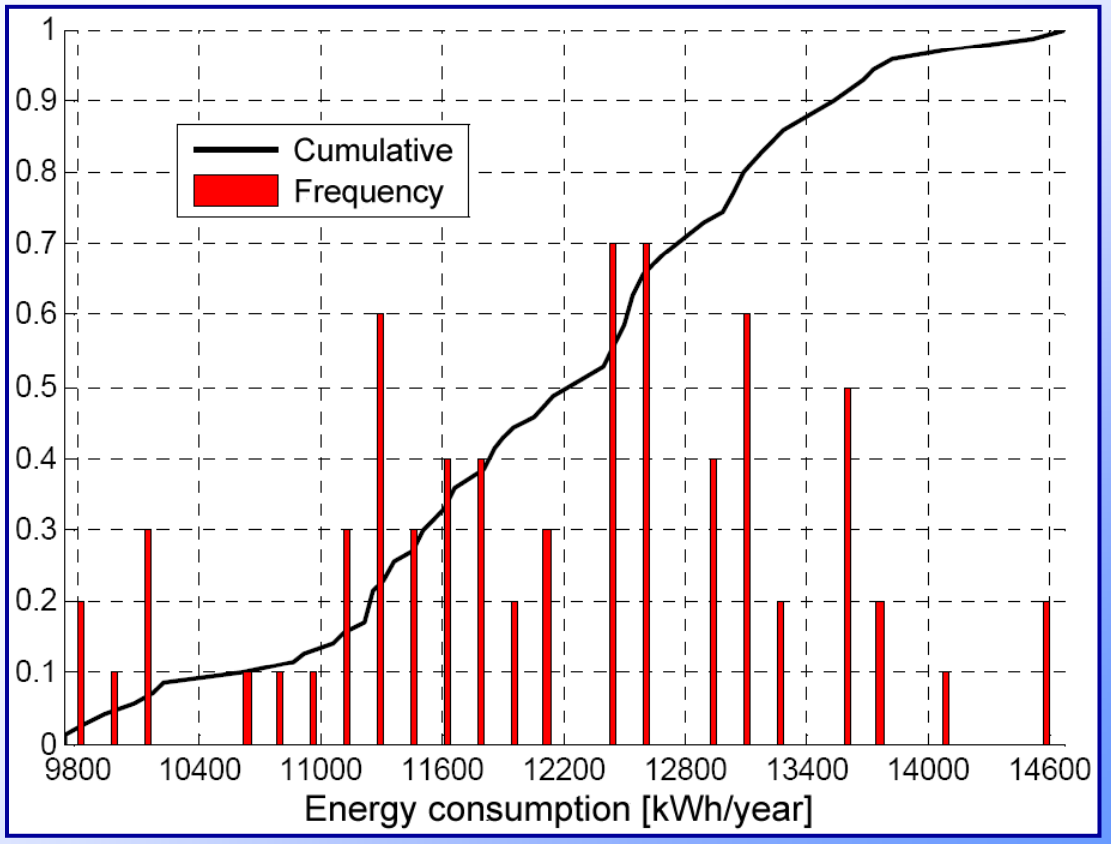
Results from Quantitative SA

- SPEA = Spearman coefficient
- PEAR = Pearson product moment correlation coefficient
- SRC = Standardised Regression Coefficient
- SRRC = Standardised Rank Regression Coefficient

Input parameter	SPEA		PEAR		SRC		SRRC	
	%	Rank	%	Rank	%	Rank	%	Rank
Set-point space heating	36.9	1	38.0	1	34.7	1	41.1	1
Occupant heat load	22.6	2	22.8	2	25.5	2	22.1	2
Appliances heat load	15.7	3	20.7	3	15.6	4	19.3	3
Occupied period	5.9	5	6.8	4	5.6	5	7.7	4
Basic air change rate, n_0	14.6	4	4.7	5	16.0	3	6.2	5
Temperature exponent, t_p	2.4	6	3.0	7	0.3	7	0.8	7
Wind factor, c_v	2.0	7	3.9	6	2.4	6	2.9	6

Results from Uncertainty Analysis

- Frequency and CDF shown in figure
- Based on 70 realisations (Monte Carlo analysis)
- Latin Hypercube sampling
- **Mean 12,008 kWh/year**
- Median 11,925 kWh/year
- Std.dev. 1,294 kWh/year
- **Coef. of variation 0.11**
- Skewness 0.025
- Kurtosis 2.269



Measurements (2005)

- Mean 10,886 kWh/year
- Coef. of variation 0.23

Conclusions

- A theoretical and empirical study of the uncertainty of energy consumption of domestic buildings are undertaken
- Calculated energy consumption of 8 almost identical domestic buildings in Denmark is compared with measured energy consumption
- Uncertainty and sensitivity are determined by stochastic modelling based on input distributions and Monte Carlo simulation
- Ranking of input parameters in terms of importance:
  - Heating set-point
  - Internal heat load (occupants and appliances)
  - Natural ventilation and air infiltration
  - Occupied Period
  - *U*-values
- Reasonable agreement between measurement and simulation, however, significant differences may occur (coef. of variation approx. 0.1 – 0.2)