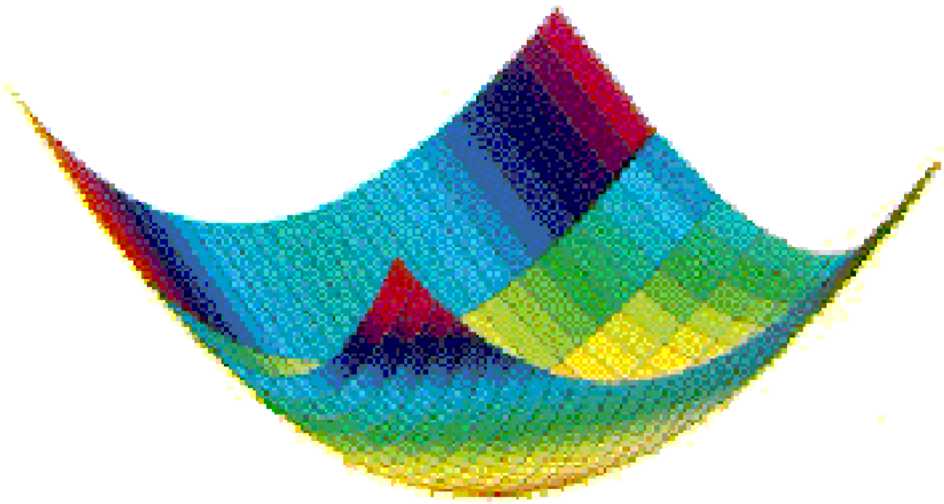
DYNASTEE



# Dynamic Testing, Analysis and Modelling

www.dynastee.info

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30 April 2010

## The DYNASTEE Network

DYNASTEE stands for: "**DYN**amic **A**nalysis, **S**imulation and **T**esting applied to the **E**nergy and **E**nvironmental performance of buildings". DYNASTEE is an informal grouping of organisations actively involved in the application of dynamic tools and methodologies relative to this field. DYNASTEE functions under the auspices of the INIVE EEIG and constitutes a sustainable informal networking mechanism, which is intended for those who are involved in research and applications related to the energy performance assessment of buildings.

The objective of DYNASTEE is to provide a multidisciplinary environment for a cohesive approach to the research work related to the energy performance assessment of buildings in relation to the Energy Performance for Buildings Directive (EPBD).

# 1. GENERAL PROJECT/NETWORK DESCRIPTION

## 1.1 WHAT CAN THE DYNASTEE NETWORK DO FOR YOU?

Over the years, the Grouping of Outdoor Test Centres (formerly PASLINK EEIG), has actively supported activities and initiated European research projects related to the energy performance assessment of buildings. A real experimental set-up for the outdoor testing of building components provided high quality dataseries for the estimation of thermal characteristic parameters. Often statisticians and mathematicians do not have the technical knowledge to correctly apply dynamic analysis techniques to physical processes, whilst engineers may not have adequate knowledge of the complex statistical and mathematical processes. The objective of DYNASTEE is therefore to provide a multidisciplinary environment, by bringing together the scientific community in the field, to add further momentum to many years of applied research, to identify feasible approaches for the practical implementation of dynamic techniques, and to instil the necessary continuity for a cohesive approach to the research work related to the energy performance assessment of buildings in relation to the EPB Directive.

The building sector in the European Union continues to account for approximately 40% of final energy consumption. Whilst the energy intensity of consumption is declining as a result of technological advancements and proactive energy policy, the standard of living in society as a whole, as well as the expectations for an improved indoor environment, continue to rise. Building envelope technologies, such as double facades, transparent insulation and integrated photovoltaics, to name just a few, remain a topic where scientific research is of considerable importance. This applies not only to the development of new, innovative, efficient and effective products of reduced environmental impact, but also of tools and methodologies for analyszing the performance of these products and the buildings into which they are integrated. Furthermore, such tools are required in order to develop simplified methods for practical applications, such as the energy performance assessment of existing and new buildings. On this merit, the recast of the Energy Performance of Buildings Directive of the European Union will become a reality, coming into force across the European Union from 2010 onwards and a second generation of CEN energy standards will be developed.

The DYNASTEE network aims to provide a forum for the study of the above mentioned themes by creating an environment of scientific collaboration and awareness, bringing together the scientific community in the field, and adding further momentum to many years of applied research, thus bringing ideas into application.

## 1.2 WHAT IS THE BACKGROUND OF THE DYNASTEE NETWORK AND ITS COMPETENCE?

**1985**

After the oil crisis in the seventies, Europe started to rethink the energy situation. Buildings were recognised as a sector where energy consumption could be reduced by improving insulation. The application of passive solar technology was also an interesting option for building designers. An international effort was supported by DG XII (now DG Research) to develop policy, technologies and tools in the building sector. One of the RTD activities launched in 1985 was the PASSYS project. Seven Member States joined the consortium, which aimed at creating an environment for outdoor testing of building components including analysis techniques for performance assessment under real climatic conditions. An additional objective was to develop modelling of building energy performance by simulation techniques. The interaction with architects and building designers lead to the development of simplified design tools. At the same time, the European Commission was preparing a Directive for Construction Products which was finally adopted in 1989 [1]. A general characteristic of the period until 1995 was the development of a common infrastructure in terms of computer technology, software and hardware.

A series of successful projects was carried out during that period, including PASSYS I and PASSYS II, COMPASS and PASCOOL. Meanwhile, three Mediterranean countries and Finland joined the consortium. A further project, named PASLINK, aimed to make the expertise gained through these research actions available to industry. In February 1994, the legal entity PASLINK EEIG was founded. The consortium also supported standardisation activities, such as those of CEN TC89, with the development of a standard for “In-situ measurement” which incorporated analysis through the application of dynamic calculation techniques.

**1995**

Global political interest in a more environmentally-conscious use of available energy resources came into the spotlight. The White Paper [2], the Green Paper [3] and the Kyoto Agreement [4] are well known to all. More and more interest in solar technologies became evident and the market for solar collectors and photovoltaics was growing fast. The grouping profiled itself as a scientific community of experts on Testing, Analysis and Modelling. After ten successful years of European collaboration, the PASLINK EEIG started a new project on the application of photovoltaic technologies in the building envelope. This project, PV-HYBRID-PAS, aimed to study the overall performance assessment of this specific integrated technology in buildings. The use of the outdoor test facilities in several Member States situated in different climates, together with the available expertise on analysis and simulation techniques, offered the ingredients for a successful project.

Several other projects were started, for example IQ-TEST, DAME-BC and the expertise of the grouping was also offered to other European projects, such as ROOFSOL, PRESCRIPT, IMPACT and PV-ROOF.

The advancements in computer software and hardware were creating an environment for improved software tools for analysis and simulation. Several system identification competitions were organised to develop the level of skill for dynamic analysis methodology.

**2005**

European policy takes into account evidence of changes in global climate and is adapting its policy to reduce energy consumption and to stimulate the use of renewable energies up to 12% by 2010. It does so by defining a number of Directives, many more than the Construction Products Directive in 1989 [1]. The development of standards and national regulations is expected to contribute to achieving the goals set in the White Paper. The Directives cover the topics of energy efficiency [5], electricity from renewable energy technologies [6], energy labelling [7], energy performance of building [8], use of biofuels [9], cogeneration, etc. Increasing interest in research in energy technologies that result in the rapid transformation into a sustainable and secure energy future for Europe, together with further advancements in information technology (internet, fast computers and portable platforms), herald many opportunities for European research and industry and implicitly for the PASLINK community. The grouping offers its expertise to the new Member States that joined the European Union in 2004 and investigates the means to evolve through support of activities which adopt a global approach to energy and environmental design in the built environment, including the DYNASTEE network (an informal network created from the DAME-BC project), thus preparing for the changes in the next ten years.

## 2. PROJECT/NETWORK ACTIVITIES

### 2.1 WHAT ARE DYNAMIC MATHEMATICAL METHODS?

Roughly 1/3 of the energy consumed in Europe is in the building sector, mainly for heating and cooling purposes. Therefore it is important to achieve a proper assessment of thermal characteristics of building components (such as windows, walls etc.) under real conditions. Innovative and often complex façade construction elements require a careful study of their energy characteristics. Dynamic ventilated walls or building integrated photovoltaic elements are a few examples.

The main parameters of interest in the research area of energy in buildings are the thermal transmittance and the solar aperture as defined below. Whilst these parameters can be derived from tests with a relatively long duration using the averaging method, commonly used in laboratory experiments, the use of dynamic test sequences and dynamic system identification techniques can reduce the test period and improve accuracy. Such powerful methods for the identification of physical parameters can enable the construction industry to optimise their products for the efficient use of solar energy and to fulfil legislative requirements, like energy labelling.

Dynamic analysis methods are techniques to analyse dynamic processes and to identify typical parameters of the physical process. Dynamic methods take into account the aspect of time whereas a static analysis method does not. By dynamic evaluation techniques (parameter identification) dynamic effects due to accumulation of heat in the equipment, test room envelope and test specimen are properly taken into account. In general, parameter identification is needed to be able to derive the steady state properties from a short test with dynamic (e.g. fluctuating outdoor) conditions.

The application of system identification techniques to the energy performance assessment of buildings and building components requires a high level of knowledge of physical and mathematical processes. This factor, combined with the quality of the data, the description of the monitoring procedure and test environment, together with the experience of the user of the analysis software itself, can produce varying results from different users when applying different models and software packages. Past international system identification competitions (1994 and 1996) demonstrated the spread in results that can be expected regarding the application of different models and techniques to the same benchmark data. The PASLINK network has attempted to consolidate and strengthen knowledge and expertise of system identification techniques within the grouping by organising lectures and workshops and also to ensure that data analysis meets minimum quality levels.

Chapter 3.2 highlights the milestones in the development of practical software tools, defining data series for training and selected practical case studies. As an example, the spread in results from analysis will be discussed obtained during the previous competitions to that obtained during the recent workshops [10] carried out by the PASLINK network, following ten years of networking activities in the field. The objective was to identify the extent to which these activities have strengthened the position of the individual teams working in the field and to identify the areas where quality assurance is met and where further improvements can be made. In order to maintain the quality in analysis and modelling work a third system identification competition has been organised.

## 2.2 APPLICATION AREAS

The test methodology and analysis methods in the early days of the PASLINK network were based around steady state evaluations. However, as the project progressed it became increasingly clear that both dynamic testing and analysis methods were required to deliver high quality performance characteristics for building components tested in real climates [11]. During the '90's the PASLINK Network moved away from the original philosophy of prescribed common equipment to one of agreed quality procedures for testing which includes the calibration of instrumentation and the test cells, and also data processing and analysis.

The latest developments that have taken place in dynamic testing and analysis driven by the research activities of the PASLINK Network are described and reviews the historical development of the test and analysis procedures currently in use.

Definitions of the physical parameters of interest derived from the energy balance equation:

UA is the heat transmission coefficient: the heat flow rate in the steady state divided by the temperature difference between the surroundings on each side of the system or component, in W/K. For the 1-D case the U-value, in W/m$^2$ K.

gA is the total solar energy transmittance or solar aperture: the heat flow rate leaving the component at the inside surface, under steady state conditions, caused by solar radiation incident at the outside surface, divided by the intensity of incident solar radiation on the component, in m$^2$. For the 1-D case the g-value [-]

Energy performance concerning buildings can be divided in three research areas:

<u>Building components</u> (such as bricks, window systems, insulation material, wall components). The experimental conditions are well-known and the experiment is optimised to investigate one dependent parameter. Often these experiments are performed in laboratories (hot-box and guarded hot-plate experiments).

<u>Test cells</u>**.** The European outdoor test facility created under the PASSYS project offers to industry the possibility to perform research on complete building wall components under real climate (including effects of phenomena like rain, wind and sunshine) and well controlled conditions. Specific tools have been developed to analyse the obtained data.

<u>Real buildings</u>**.** A complex situation appears when occupied buildings have to be analysed. The behaviour of the occupants cannot be controlled (opening windows) and additional techniques have to be used for the analysis of the data. Interaction of simulation tools based on physical properties and system identification techniques are under investigation. However when carefully applied, system identification could offer the way for the energy labelling of buildings.

- Buildings; Improving Energy Efficiency
  - In-situ measurements for renovation (CEN)
  - Optimisation of district heating
  - Energy labelling by intelligent metering

- Optimal integration of solar thermal for DHW
- Double skin facades
- Solar Control
- Cool Roofs

Over the past decade the interest in renewable energy has increased. Analysis of complex dynamic energy flow systems that contain non-linear processes needs a skill. Considering the built environment, the focus has been mainly on utilising solar energy with promising developments in the integration of photovoltaic (PV) technology in buildings. Building Integrated Photovoltaic (BIPV) systems combine other functions of the building envelope with electricity generation. Examples include the following.

- External shading devices containing PV cells.
- Roofing tiles, directly replacing traditional pitched-roof materials and also being placed on low-sloped roofs in some climates.
- Rain-screen cladding and curtain walling.
- Ventilated facades where PV is used as the external cladding element. The larger part of the incident solar radiation on the PV elements is converted into sensible heat, which results in a warming-up of the PV elements, which may reduce their electrical efficiency. Ventilating the cavity behind the PV limits the temperature rise, and the warm air may be used for ventilation pre-heat in winter, or driving natural ventilation in summer. Such systems may be termed hybrid-PV components.
- Dynamic ventilated window systems
- CEN - dynamic methods for in-situ measurement analysis

As part of the building envelope the impact of any construction element on the whole building performance must be considered and in the case of PV panels the electrical performance as well Various projects have investigated the impact of BIPV on building performance. The PV-Hybrid-Pas project [see www.dynastee.info] was concerned with thermal performance evaluation of hybrid-PV components (with both natural and forced ventilation), as well as the measurement of electrical performance under real climate conditions, using the PASLINK outdoor test facility. A number of case studies are discussed on the PASLINK web-site. A recent study [12 and 13] discusses non-linear models for BIPV heat exchange.

Apart from energy performance assessment for buildings, dynamic mathematical techniques as have been developed by the Network during several European research projects, can be applied to a wide range of applications; to mention some:

- Integration of Renewable Energies
  - Improved control of energy supply and marketing
  - Wind and Solar Power Prediction for the grid
- Medicines
  - Improving efficiency (Insulin dosing)
  - Pharmaceutical Kinetic and Dynamic Modelling [see Ref 33]

## 3. PROJECT/NETWORK RESULTS

DYNASTEE, being a network of competence in the field of outdoor testing, dynamic analysis and simulation has 25 years experience and would like to transfer its knowledge to industry, decision makers and research. Specific outdoor experimental work needs knowledge of the analysis process in order to optimise the dynamic information in the measurement data. Simulation requires results from analysis in order to be able to scale and replicate the results from analysis and testing.

### 3.1 TESTING

A brief introduction to outdoor testing. The test cells were designed and installed during the EU PASSYS and PASLINK projects. In the nineties 38 test cells at 13 sites in Europe were available for testing. Over the years the test facility has been improved to produce high quality data for dynamic analysis methods. Figure 1 gives an idea of an outdoor test facility with two test cells and climate sensors positioned around its south-facing wall. A schematic view of different energy flows is given in figure 2. The tests are carried out under real outdoor weather conditions. For obtaining dynamic information from the components a dynamic heating and cooling strategy inside the test cell is needed to ensure that the data obtained from the test contain at least the minimum of information needed to derive the required characteristics. An auxiliary resistive heater is used for that purpose and is controlled applying a pseudo randomly ordered on/off sequence. In general, the thermal and solar characteristics of the test specimens are a function of the indoor and outdoor environment conditions, such as temperature level, temperature difference, solar radiation level and position of the sun and sky conditions (clear, overcast). This implies that in case the intention of the test is to obtain results in terms of product information, the characteristics derived from the test may require conversion from actual test conditions to certain standard conditions, such as conditions specified in European standards.

*Figure 1. Homogeneous opaque insulated panel and a simple window system placed in the south wall.*

It is well known from theoretical analysis that the solar aperture is influenced by the season and the geophysical position of the building component of interest. For general applications the following steady state equation (the energy balance equation) can be used:

$$UA*(\theta_i - \theta_o) - gA*Qsolar - Qheater = 0 \quad (3.1.1)$$

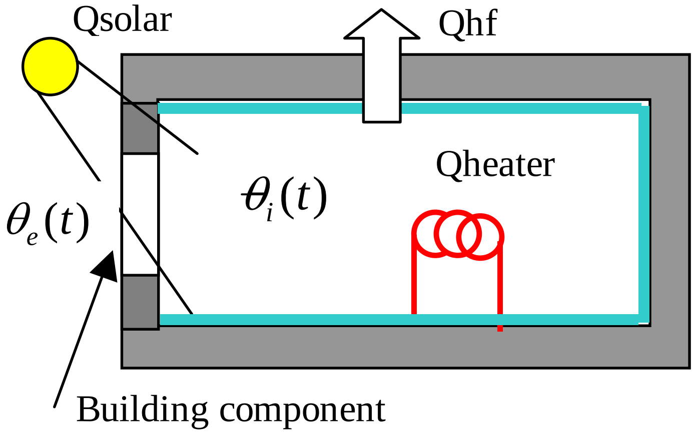



*Figure 2. Schematic view of energy flows.*

The input signals are: $\theta_i(t)$, the internal air temperature at time t, in °C and $\theta_e(t)$, the external air temperature at time t, in °C respectively, the solar radiation, Qsolar and the auxiliary heat, Qheater, applied to disturb the system. The flow of heat, Qhf through the envelope (excluding the component under test) is measured also. All flows are in W/m$^2$.

## 3.2 ANALYSIS

During the last 20 years with the development of computing hardware and software, a huge advancement has made been made in assessing the specific characterisation of the energetic behaviour of buildings and building components (see also reference [14]). Computer technology has made calculation as well as monitoring of thermal processes in buildings much easier than ever before. However the implementation of hardware and software tools and the proper design of experiments require a certain skill. During 20 years of international research dedicated to the energy characterisation of buildings and components through several EU funded projects expertise has been made available. In 1994 the PASLINK EEIG focused on outdoor testing, analysis and modelling of buildings and components. A good example was recently published on testing and analysis by the PASLINK network [15]. The development of dedicated software tools to identify thermal parameters from physical systems has gone hand in hand with the fast development of computing hardware. Software tools like CTSM [16], LORD [17] or the SIT in the MATLAB environment [18] are good examples. Also modelling software tools like TRNSYS and ESP-r show a similar progress and user friendly interface.

System identification techniques have been developed in order to assist researchers in obtaining a better and more accurate knowledge of the thermal characteristics of building components [4]. System identification is the field of modelling dynamic systems from experimental data (see also [19]). A good academic book is given in reference [20] and [21]. A dynamic system has a number of input variables, *u(t)*, it is affected by disturbances *N(t),* and it has output signals *y(t)*. The general form of a dynamic system is shown in Figure 3.

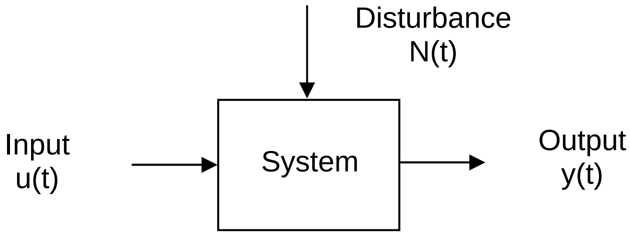



Figure 3. General form of a dynamic system

System identification is applied by the following procedure:

1. An experiment is performed by exciting the system and regular observing its input and output signals over a specific time interval.
2. These signals are recorded for subsequent “information processing”.
3. A parametric model is developed to process the recorded input and output sequences. Several models can be applied.
4. An appropriate form of the model is determined (typically a linear differential equation of a certain order).
5. A statistically based method is used to estimate the unknown parameters of the model.

Applying system identification techniques on physical systems requires at all stages knowledge of the physical system. For buildings it is important to know what the impact is of cold-bridges, corner effects, etc. The researchers goal is to estimate physical parameters by using mathematical models.

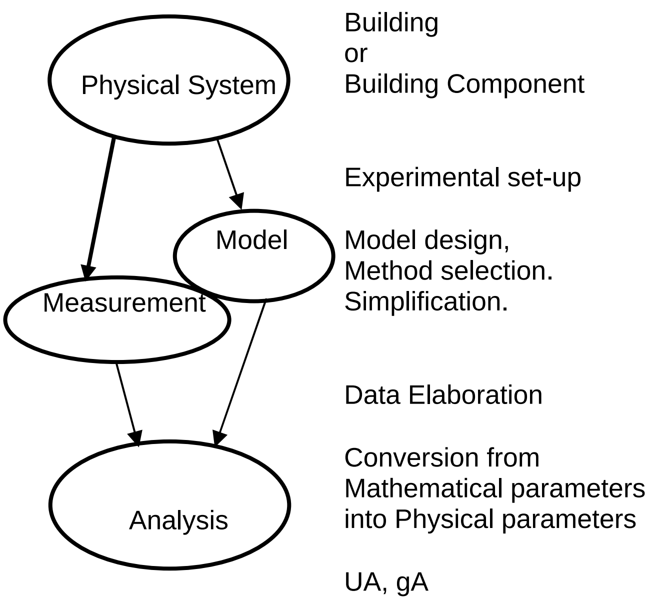



*Figure 4. Overview of process steps.*

In most cases the calculation from mathematical parameters, which are derived from the chosen model, to physical parameters, in this case the heat resistance and solar aperture, introduces another point for discussion between physicists and mathematicians. Physicists like to compare the obtained values of the estimates from different methods, however they do not always realise that the way they are obtained from mathematic procedures might be different.

On the other hand, for the determination of the thermal and solar characteristics the knowledge of the heat flow through the test room envelope is an absolute must, in order to be able to obtain the properties of the test component decoupled from the test cell. This asks for a separate calibration test. For the characterisation of different approaches it is necessary clearly to the following terms: tools, methods and models will be introduced briefly.

A *model* is a mathematical description of a physical system or process. By definition it is a simplification of the reality. Models can be categorized in different ways. A list of possible models to be used is the following:

- thermal models or lumped parameters models
- state-space models
- modal models
- linear regression models
- frequency domain models
- neural network models

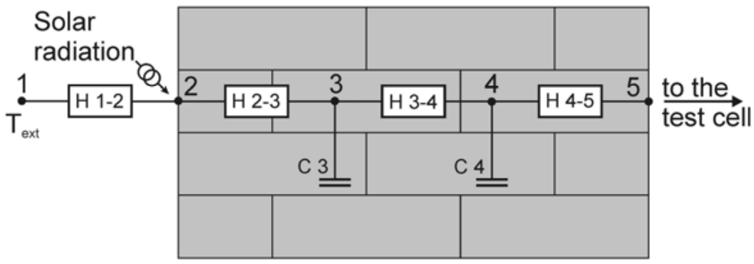



*Figure 5. Lumped model for a simple wall*

A *method*, here a system identification technique, consists of two major parts: the mathematical model (e.g. an ARMAX model) and the routine to estimate the parameters by a specific algorithm (e.g. least squares method). Minimisation is used in the context of minimising the difference between measured and corresponding data obtained from the model. Optimisation is used in the context of optimising the mathematical parameters of the model to fit the data obtained from the model with the measured data.

A *tool* is a sophisticated software program which allows the user to use a method in a user friendly way. It is a ready-to-use product. Often these types of tools come with pre-processing routines and statistical information about the identification process and accuracy of the estimates. The selection and creation of models is one of the items which is simplified in a graphical way. Toolboxes are popular among researchers. It offers the freedom of the creation of own methods using reliable algorithms and routines. The system identification toolbox [22] in MATLAB is a good example of such an environment.

The following six points can be distinguished in the general approach of solving the problem of energy performance assessment using identification techniques.

1. design the experiment. In a first phase the experiment must be designed taking into account the objective, all available physical knowledge and all possible errors must be reduced to a minimum.

2. perform the experiment. The duration of the experiment must be long enough to fulfill all objectives. Special attention needs to have the interval for data acquisition. Collect data

3. pre-processing. Check for irregularities by having a global look at the data. This can be achieved in different ways. One way is to plot some of the important input signals. Another way is to apply the average method and to examine statistical information of the data.

4. analysis by estimation. Choose and apply a model and method that you are familiar with. Determine model structure. There are several ways to classify models, methods or tools.

    - available software; general purpose software like MATLAB, MathCad, programming languages and mathematical libraries.; some examples of special purpose software are given below.

    - categories in prediction or output error method, deterministic or stochastic.

    - the minimization criteria. Least Squares Method (LS) and the Maximum Likelihood (ML).

5. post-processing of the results. The most important is the validation of the applied model. Criteria that can be used for that purpose can be the following (in [23], Norlen, 1993):

| | |
|---|---|
| 1. Fit to the data | Residuals are 'small' and 'white noise' |
| 2. Reliability | Same results with different data |
| 3. Internal validity | Cross-validation; The model agrees with other data than those used for estimation |
| 4. External validity | Results are in general not in conflict with previous experience |
| 5. Dynamic stability | From a steady state, the response from a temporary change in an input variable fades out |
| 6. Identifiability | Model's parameters are uniquely determined by the data |
| 7. Simplicity | The number of parameters is small |

Special attention needs to be applied to the conversion from mathematical parameters into the required physical ones. This is often a cause for problems, misunderstanding and errors.

6. feedback should be made in every phase of the process. Is the model accepted? It is advisable to apply more than one method to get a better understanding of the whole problem. Common sense should always be used and all available physical knowledge should be applied whenever possible.

Based on the experience from the analysis of test cell data a closer look at the properties will be given. In general two types of criteria for parameter identification can be distinguished:

the Prediction Error Method (PEM) and the Output Error Method (OEM)

The OEM is a special case of the PEM when takes the following formula in consideration:

$$Q(t) = G(q)u(t) + H(q)e(t) \quad \text{when} \quad H(q) = 1 \qquad (3.2.1)$$

1. The Prediction Error Method

PEM (e.g. CTSM, linear models) based on statistical models finds parameters by minimising the error between a k-step (usually k=1) ahead prediction and the measured output. Some characteristics are:

- more sensitive to high frequency parameters
- too optimistic on low frequency (steady state) parameters
- disturbed if residuals are auto correlated

2. The Output Error Method (OEM)

Simulation or Output Error Method (e.g. LORD) based on deterministic models finds parameters by minimising the error between simulation and measurement over a whole test period. Some characteristics are:

- more sensitive to low frequency parameters
- too optimistic confidence intervals if residuals (here simulation errors) are auto correlated
- but due to inertia these are "always" auto correlated
- the application of a correction factor in the minimization algorithm.

one can ask if different types of parameters need different correction for auto correlation?

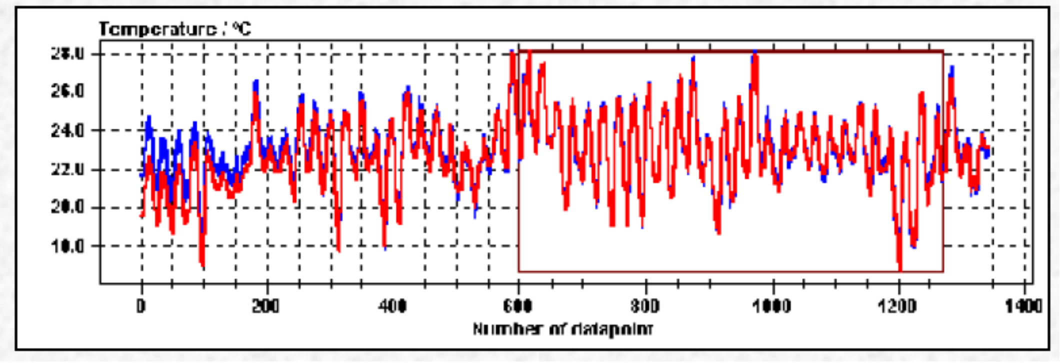



*Fig 6. Measured and simulated output from a mathematical model*

If the Prediction Error Method is used then we have reliable methods for model validation and for finding the optimal model - this is not the case for OEM. The PEM approach offers methods for identifying functional relations – this is not the case for OEM. The PEM approach used the data efficiently - this is not the case for OEM. (it is known that the PEM or MLE approach is an efficient estimator - see also [21]).

Within the frame of pre-normative research the PASLINK grouping developed a performance test aiming to offer for the CEN standard on "in-situ measurements of thermal resistances" a series of reliable dynamic analysis tools. This activity has gained renewed interest from CEN by a new WG for this topic.

### 3.2.1 IN-SITU MEASUREMENTS FOR RENOVATION

It has been estimated that in the UK around 70% of the houses in 2050 exist now. Whilst the ageing housing stock has the advantage that it already embodies carbon, it presents a major challenge to meet carbon emissions targets and improve energy efficiency. The refurbishment of traditional buildings is of particular interest to heritage agencies in order to respond to this challenge and maintain our architectural heritage. *In situ* U-value measurements have an important role to play in the assessment of the actual thermal performance of traditional building envelopes both before and after refurbishment.

Glasgow Caledonian University has been carrying out such measurements for Historic Scotland [24] and English Heritage since the winter of 2007/08 with the objective of contributing to guidance for energy performance assessments and implementing energy efficiency measures in traditional buildings. The test method uses data loggers equipped with Hukseflux HFP01 [25] heat flux and temperature sensors. The heat flux sensors are 80mm in diameter and 5mm thick. The sensors are mounted by firstly applying a layer of double sided adhesive tape to the back of the sensor. Secondly, low tack masking tape is applied to the wall. Finally, the heat flux sensor is applied firmly to the masked area. This arrangement is generally satisfactory for two or more weeks monitoring on painted or plastered surfaces only. Wallpapered surfaces are not generally used in case of damage. Sensor locations are chosen to avoid possible thermal bridges near to windows, corners, etc., with the sensor ideally located about half-way between window and corner, and floor and ceiling. A thermal imaging survey is recommended. Generally two heat flux sensors are used on each wall.

Stainless steel-sheathed thermistors are used internally and externally to measure air temperature. Internal sensors are mounted in a simple shield to minimise the influence of solar radiation, heat sources, etc. External temperature sensors are placed in a radiation shield mounted either on the exterior wall surface or attached to a drainpipe, etc. if there is concern about penetrating the structure. Thermocouples are used to measure surface temperatures.

Monitoring should be carried out over the heating season to maximise the temperature difference between inside and outside. The normal heating schedule provided by the occupants is generally satisfactory.

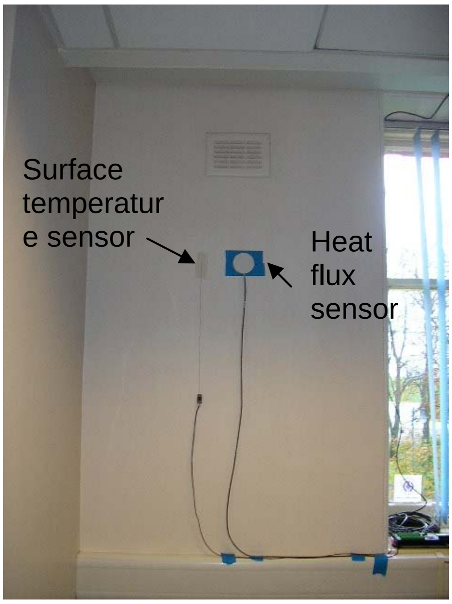



*Figure 7:* Typical heat flux sensor and temperature measurement locations

*Figure 8:* Mounting of shielded external temperature sensor strapped to drainpipe using cable ties.

Given that the monitoring conditions are non-steady state, it is considered necessary to monitor for a minimum of two weeks to allow for thermal inertia, in order to collect sufficient data to estimate *in situ* U-values by a simple averaging procedure. Figure 9, shows the results from longer term monitoring of a wall in a 18$^{th}$ Century building constructed of brick with a timber panel internal lining. The Figure 9 shows the U-value and its uncertainty estimate (the RMS measurement errors and confidence interval) with increasing monitoring period using the simple averaging method and the dynamic analysis software tool LORD [2]. For two weeks' data the uncertainty is 13% for the averaging procedure, whilst LORD gives an improved uncertainty of 7%.

Using the dynamic analysis tool enables the effect of thermal inertia to be fully considered and the monitoring period optimised.

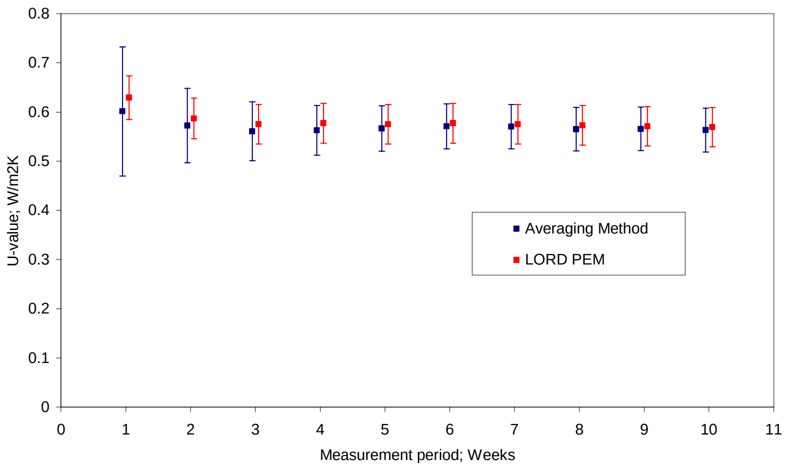



*Figure 9:* The effect of increasing the monitoring period and the uncertainties in the U-value estimates for a simple averaging procedure and using LORD (PEM).

### 3.2.2 DYNAMIC MODELLING AND ENERGY METERING.

Soon energy meters will allow for simultaneous and frequent readings of power, heat and water consumption also in family houses, and the readings will in most cases be transferred by the IP protocol to a central facility for energy managements.

Energy meters give possibilities for obtaining time series of actual energy consumption in households with readings say every 10 minutes. At the same time meteorological services will facilitate possibilities for obtaining local time series of relevant and local meteorological parameters.

To clarify the difference between smart and intelligent meters the following brief definitions can be applied:

Smart meters are, compared to traditional electricity, water or gas meters, taking readings in more and regular detail and communicate them electronically through some network to the utility (and end-user) for monitoring and billing purposes (often referred as automated meter reading).

Intelligent meters can in addition, analyse these observations, identify characteristics and make decisions aiming to improve further the optimisation of energy efficiency. The utility as well as the end-user can communicate with the intelligent meter also (two-way communication).

Readings from smart meters might be analysed on a central server and so become a part of an intelligent metering environment, for example for district heating management or an energy service company (ESCO).

In the near future these time series will provide the background for using the developed methods for dynamical modelling for:

1) Automatic energy labelling of buildings.

2) Improved control of the energy supply to buildings, eg. by use of MET forecasts.

3) Using buildings to facilitate the integration of large fractions of renewable energy.

4) Providing advises on the best ways of improving the energy performance of a building.

In this chapter the status of energy metering in EU is outlined followed by a discussion on methods for the use of dynamic modelling for calculating energy labelling of buildings. The other subjects, ie. subjects 2) to 4) above, are only briefly discussed here; some important references will however be given.

#### *3.2.2.1 Plans on rolling out energy meters in EU*

Smart and intelligent meters are one of the big energy saving hopes by reducing the energy used in family houses, lowering your energy bill, and carbon emissions. These energy meters are the next generation of electricity, heat or gas meters. They are different from the old-style metering devices as they are able to transmit data to eg. the energy supplier, say every 10 minutes or even more frequently. Intelligent meters can in addition analyse the observed readings.

It is expected that by 2020 almost every UK home will have a smart meter, and similar plans are observed in many other European countries. More specifically the foundations for rolling out smart meters in Europe were laid down in a 2006 EU directive on energy end-use efficiency and energy services. The directive required member states to ensure that consumers of energy and water are provided with individual meters and accurate billing, including time-of-use information.

The gas and electricity directives of the third energy package, adopted in 2009, require member states to prepare a timetable for the introduction of intelligent metering systems.

According to EurActiv.com EU legislation on buildings has also sought to pave the way for the introduction of smart meters. In April 2009, the European Parliament voted to add a provision to the Energy Performance of Buildings Directive that would have required the installation of smart meters by default in all new buildings as well as when renovating older ones.

#### *3.2.2.2 Energy Labelling.*

Today the energy performance of a building is more or less subjectively judged by an expert in building physics. It is however well known that these judgements are rather not precise and of a subjective nature. This is partly due to the fact that detailed information about the construction of the building is either non-precise or lacking.

Dynamic modelling can be used to process time series from smart meters and time series of relevant meteorological data to provide a non-subjective and automatically generated values characterising the energy performance of the building. Once the software is Integrated in a smart meter, the device becomes an intelligent energy meter.

In Denmark the Electricity Savings Thrust initiated research on the use of dynamic methods and smart meters for energy savings. In Ref [34] data from smart meters from 56 households in Denmark has been used to derive rather simple models for the energy transfer, which provides estimation of the coefficients characterising the response of the building to changes in air temperature (UA-value), solar radiation (gA-value), and wind (wA-value). The effect of wind is characterised both in terms of wind speed and wind direction, and the effect of wind can be represented as an increase in the UA-value given a high-wind situation.

The methods do not require measurements of the indoor air temperature, as the methods proposed in Ref [34] also delivers estimates of the indoor air temperature as an integrated part of the procedure. For the 56 households quite reasonable values (from 17.7 to 25.7 °C) were observed.

The heating of the 56 households is provided by district heating, and in the report the estimation has been performed both based on the total energy consumption (district heating and electricity), as well as on the district heating consumption alone. Overall, the estimated UA-values only change marginally (up to 10 W/°C) depending on which variable was used for modelling. However, it is recommended to use the total energy consumption for calculating the energy characteristics of the buildings.

Regarding the dynamic response it is concluded that on the time scale considered the dynamic effect of temperature and solar radiation are well described by a single time constant.

*Figure 10.* Experimental FlexHouse at RISØ in Denmark

The lumped parameter models and methods for estimating the thermal performance of buildings as developed during the DYNASTEE related projects are described in a number of articles. In figure 11 a representation of the model that has been identified using the software tools developed by the Dynastee grouping.

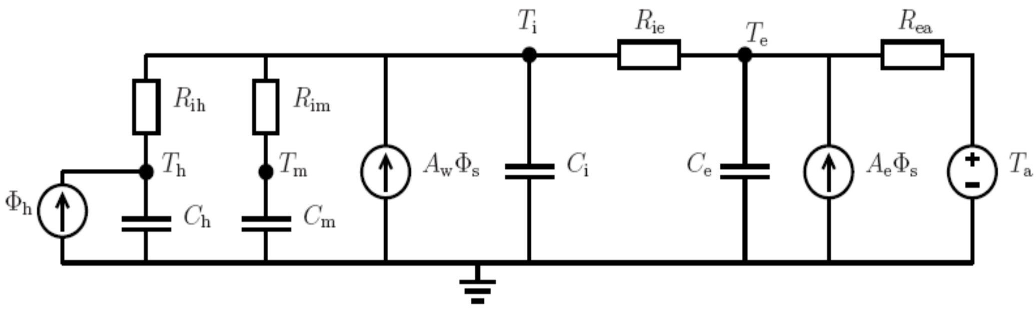



*Figure 11.* Model used for identification.

In Ref [35] the main principles are described for a single room building. Models for the energy performance of a green house is considered in Ref [36]. Models for multi-room buildings are the focus in Ref [37]. The used of MATLAB for estimating the main thermal characteristics is described in Ref [38]. A non-linear model is needed for instance for modelling buildings with PV integration on the facade as described in Ref [39].

#### *3.2.2.3 Improved Control of the energy supply.*

Adequately calibrated dynamic models are also needed for the next generation of control of the energy supply. This includes optimal use of night set back systems, time varying temperature zones, air temperature and solar radiation compensations, etc.

In future versions of control systems meteorological forecasts may be used as an input to provide forecasts of the heat load of building and optimal control of the heat supply. This includes a next generation of forecast based temperature compensation controllers as well as optimal planning of the local energy production.

As an example it is demonstrated that dynamic models can lead to significant savings in district heating systems. In Ref [40 and 41] dynamic models developed under PASSYS are suggested for predictive control of the heat supply using some controllers described in Ref [42]. Similar controllers are suggested for green houses in Ref [43]. In Ref [44] these controllers are considered for more complex systems.

The potential for energy saving using the controllers based on dynamic models is large; in [Ref 45] it is demonstrated that the heat loss in district heating systems can be reduce with 10 to 20 %. by using dynamic models for predictive control of the temperature level.

#### *3.2.2.4 Integration of large fractions of renewable energy*

It is expected that buildings in the future will play an active role in the integration of renewable energy in the energy system, and in order to operate such a system in an optimal way it is essential to have access to dynamical models for the heat dynamics of the building as well as reasonable forecasts of the heat and electricity load for the household. In some new research projects in Denmark, where today 23 % of the electricity is from wind, the use of dynamic models for buildings for integration of up to 50 % of renewable energy will be studied. This is the goal set for 2020 by the Danish Government.

In some areas it is expected that a large share of the households will integrate some sort of solar or wind power related to their heating system. An optimal operation of such a system requires on-line forecasts of the expected solar or wind power production, and dynamical models for on-line prediction of the solar power production is described in [Ref 46]. Similar models for on-line forecasts of the wind power productions using dynamic models are described in [Ref 47 and 48].

#### *3.2.2.5 Advises for energy savings*

The developed dynamical methods will enable new methods for providing guidelines for improving the building with the purpose of obtaining energy savings. The tool will indicate the most beneficial subject of improvement, as eg. further insulation in the walls, tighten the building, change the windows, or insulate the roof.

## 3.3 MODELLING

### The Role of Simulation

Researchers in the DYNASTEE network and its precursors have been involved with measurement and analysis of building components and buildings. As described elsewhere in this document, system identification techniques have been employed to extract key energy performance characteristics that can be used to quantify the thermal performance of the energy system.

In parallel with the system identification analysis techniques, model calibration and scaling procedures have been developed that make use of the experimental data to formulate simulation models of the building components and then apply them to full-scale application. Over the last 30 years, dynamic simulation programs have improved in functionality and are becoming more routinely used in design and energy performance compliance checking of buildings. There have been numerous international validation projects (organised through the International Energy Agency (IEA), in particular) to check the predictions from leading simulation programs. Although validation is a never-ending task, the current situation is that, in the hands of a skilled user, the major simulation programs that are in common use today can be used with some confidence in predicting the energy and environmental performance of buildings.

However, new building components (e.g. advanced glazing, building-integrated renewables, phase change materials, new insulation products, ventilated constructions, to name a few) are constantly being developed, most of which have significant interactive effects on building performance. As an example, a double facade construction with integral blinds, when configured for pre-heating of ventilation air, will have significant direct impacts on the heating and cooling loads, on the lighting levels (and therefore electricity consumption of artificial lighting and indirectly on heating and cooling loads) and on indoor air quality and facade acoustic performance. To study the energy and environmental performance of such a facade, perhaps with different building orientations and with different airflow configurations, requires simulation modelling. However, it is first necessary to have confidence in the ability of the simulation program to model such performance – this is where the use of measured building component data in a controlled but realistic outdoor environment has a role.

A procedure has been developed, and applied within several major European projects, that consists of calibrating a simulation model with high quality data from the outdoor tests and then applying scaling and replication to one or more buildings and locations to determine performance in practice of building components. The procedure has three elements:

> *Calibration*. This involves creating a simulation model of the test component and the test environment, undertaking simulations using the measured climatic data, and then comparing predicted performance with measured performance (heating and cooling energy consumption, temperatures etc.). If successful, it gives confidence that the simulation program can correctly model the component characteristics when that component is subject to dynamically varying outdoor conditions. In many cases, it is difficult or too time-consuming to measure all the required model parameters – a good example is the flow of air in double facades which is very difficult to measure accurately. In such cases sensitivity studies can be undertaken to determine the impact of the input uncertainties and to determine the most appropriate values to use. The advantage of using outdoor test cells is that the experiments are well-controlled, so the number of uncertain parameters is significantly less than for whole buildings, particularly when they are occupied.
>
> *Scaling*. This step requires the modelling of selected full-scale buildings for deployment of the building component under test. Simulations are undertaken of a base case of the building without the component, and then with the component included. Comparisons are made over a range of appropriate performance metrics such as energy consumption, thermal comfort and visual comfort. The technique allows a more realistic estimate of how the component will perform when it is fully

integrated into a building, taking account of, for example, the utilisation of passive solar heating. In essence, it uses calibrated simulation models to extrapolate the test component measured performance, obtained from outdoor test cell experiments, to the full scale.

*Replication*. This (optional) step involves repeating the simulations with different climate datasets and, perhaps, different local operational regimes to determine performance in different locations.

This use of simulation models to investigate the full-scale building-integrated performance has been applied to a number of new building components. Several examples are summarised in the papers [26] and [27], such as advanced glazing components, a sunspace, ventilated roof and hybrid photovoltaic modules. Other studies which have involved detailed comparisons of simulation models and measured data from controlled experiments on test cells have been undertaken as part of validation research projects – examples include those from the recent IEA International Energy Agency Task 34/43 on program validation, with work on shading/blind systems and double facades [28], [29].

For the future, the advent of ubiquitous monitoring of building performance with smart meters offers a chance to apply calibration and optimisation techniques to the simulation models that have been used in the design and compliance checking of those buildings. This could allow the reconciliation of the often large mismatch between performance in design and performance in practice, and to identify required remedial action to improve performance.

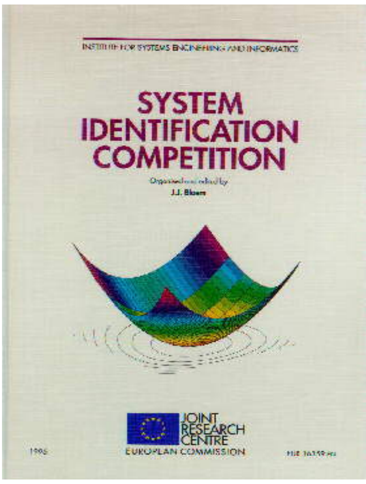
## 3.4 TRAINING

A series of case studies for estimation techniques for the energy performance characterisation of buildings and building components have been developed during several EU supported research projects. These case studies are freely available.

### 3.4.1 System Identification Competition

The objective of the system identification competitions is to further develop knowledge of system identification applied to thermal performance assessment in the built environment.

After the success of the first competition [30] in 1994 and the second one [31] in 1996, the organisation has prepared a third challenging one in 2007, involving data from in situ measurements and real experimental set-ups. The previous competitions show that a number of methods and techniques exist and how inventive researchers can be to solve the physical problem of thermal behaviour. The most important conclusion has been that one needs a certain level of skill using system identification techniques, to perform well. The PASLINK network has organised over the last couple of years several workshops and courses to bring the knowledge to the people and to further improve the tools [32]. The implementation now of the Energy Performance of Building Directive [8] requires adequate calculation and modelling tools and this is the main reason that a third competition has been organised.



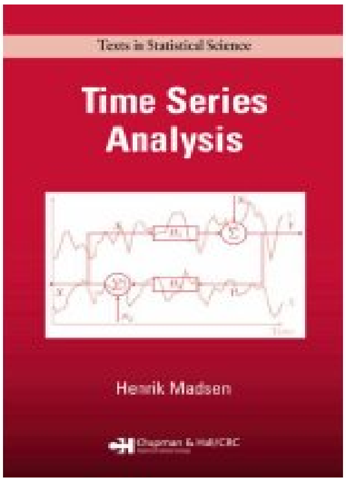



*Figure 11. Two examples of available books; Ref [30 and 21]*

The application of system identification techniques to the energy performance assessment of buildings and building components requires a high level of knowledge of physical and mathematical processes. Similar problems arise in most observational disciplines, including physics, biology, and economics. As an outcome of the DAME-BC project (funded by DG-RESEARCH) the DYNASTEE network has brought knowledge from different disciplines together to work on this subject.

This new challenge has been organised to help clarify the conflicting claims among many researchers who use and analyse building energy data and to foster contact among these persons and their institutions. The intent is not to declare winners, but rather to set up a format in which rigorous evaluations of techniques can be made. In all cases, however, the goal is to collect and analyse quantitative results in order to understand similarities and differences among the approaches. Moreover participation to this competition will offer material for training and self study.

Research on energy savings in buildings can be divided in to three major areas:

1) building components,

2) test cells and unoccupied buildings in real climate and

3) occupied buildings.

Three competitions were planned along this line, of which the present competition concerned with real data from buildings components will be the third and last one. The present competition is concerned with four different cases for estimation and prediction including real data from a retrofitted wall, an occupied house, an urban area and a solar chimney. Participants are free to submit results from any number of cases. Since all cases deal with experimental data, detailed description is accompanying the data however basic knowledge about the practical energy flows is required.

The data and description for all four cases are available from on www.dynastee.info under the data analysis menu item. The submitted results will be evaluated at regular interval, and presented at appropriate conferences. Because there are natural measures of performance; a rank-ordering will be given and published on the internet. The best contributions will be selected for publication in the SIC III book provided.

### 3.4.2 BRIEF INTRODUCTION TO THE SIC III CASES

The *first* case is concerned with the monitoring of a wall in a house constructed in the 1990's to assess its thermal performance before and after the installation of cavity-fill insulation. The wall as-built is poorly insulated compared to current standards, with a lightweight concrete block and a cavity providing the insulation. Filling the cavity with insulating material should improve thermal performance, resulting in lower energy consumption and better comfort for the occupants. As a real case study it would be interesting to assess the thermal resistance improvement and the moment of filling the cavity.


The full description and data for analysis can be downloaded from www.dynastee.info

The *second* case concerns an occupied residential house and is a modern (constructed in 1994) two storey single family house with one common wall and the whole envelop insulated (including the roof space). The walls are well insulated and all windows are double glazed. It has been monitored during two heating seasons. In addition the ventilation losses are monitored using PFT techniques.

The *third* case considers the modelling of the heat consumption in a large district heating systems, called VEKS (Vest-Egnens KraftvarmeSelskab). This system actually covers about half of the Copenhagen area. VEKS is a transmission company (established in 1984) supplying surplus heat generated from combined heat and power (CHP) plants to 19 local district heating companies at Western part of Copenhagen. The purpose of this case study is to investigate time series of measured heat production in the VEKS district heating system, and to establish models for predicting the heat consumption one to several hours ahead.

The system considered for the *fourth* case study is a solar chimney constructed and monitored at the LECE (Laboratorio de ensayos Energéticos para Components de la Edificación), from CIEMAT in Tabernas (Almería, Spain). Natural ventilation plays an important role as passive energy saving strategy, regarding cooling of buildings in this climate. Solar chimneys are some of the most useful systems that make use of this strategy. The tests have been carried out in real size and dynamic outdoors weather conditions.

# 4. THE FUTURE FOR DYNASTEE

**2010**

Looking towards the future, ten years from today, one may expect that a number of Directives will be put in place. Renewable energies, including passive solar, electrical and thermal technologies, will be visible in the built environment more than 10-20 times than we see today. Being a complex and more dynamic technology, the application of dynamic analysis and simulation techniques is evident. Dedicated energy design and evaluation software tools are needed. An integral energy performance assessment is required and industry will develop innovative building products. An in-situ measurement for the thermal performance of buildings under investigation for renovation becomes a common approach. The “near-to-zero-energy-consuming-building” can be developed and requires dynamic tools for design and operation.

The expertise available in the present DYNASTEE Network can be deployed in particular in the field of dynamic testing, analysis and simulation methods. This is a challenge which the grouping will take by fitting it into the political requirements for building research.

**2015**

Dynamic mathematical technology is recognised as crucial in optimisation of energy efficiency. Integration of renewable energy technologies in our society is rapidly taking place giving another perspective of the use of available energy resources. The recast of the EPBD, ESD and CPD Directives have taken place and work is ongoing on the update of a 2$^{nd}$ generation of energy standards for calculation methods, certification etc. New buildings consume less energy for space heating while electricity consumption for systems and appliances is increasing.

**2020**

Ten years from now and a future perspective; in the EU society electric vehicles have become an accepted means of transport in urban areas as well as for long distance. The buildings that are for living and working have become an integral part for distribution and control of energy final consumption. Intelligent metering devices communicate with consumers and utilities and control domestic appliances as well as electric cars.

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# 6. PARTNERS/MEMBERS

## 6.1 DYNASTEE

DYNASTEE

DYNamic Analysis, Simulation and Testing applied to the Energy and Environmental performance of buildings

http://www.dynastee.info