The Environmental Measurement of Residential Buildings

A Technical Guide

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Acronyms

BCA	Building Code of Australia
HER	House Energy Rating
HVAC	Heating ventilation and air-conditioning
NCC	National Construction Code
NatHERS	Nationwide House Energy Rating Scheme

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1 Purpose

This guide focuses on the methods used to obtain data sets suitable for empirically validating house energy rating (HER) software. This includes: modules for envelope, heating, ventilation and air-conditioning (HVAC) and whole of software validation.

This document is intended for researchers and organisations interested in the measurement of building thermal performance.

Although this document focuses on the measurement of residential or house type buildings, the principles are also applicable to the measurement of commercial buildings.

2 The Thermal Performance Model

The Nationwide House Energy Rating Scheme (NatHERS) was established in 1993 as a standardised system to assess the thermal performance of Australian housing. NatHERS was an initiative of the Ministerial Council on Energy to develop potential energy saving measures in new Australian homes (Thwaites 1995; Drogemuller, Delsante et al. 1999; Delsante 2005). The HER software requires building specific, (including a range of default), user-modifiable and non-standard modifications (NatHERS 2000; NatHERS 2007). The scheme was developed by representatives from federal and state government energy agencies in conjunction with CSIRO. The NatHERS tools and software involve standard parameters for assessing the thermal performance of housing, such as:

- annual energy loads associated with star bands (from 1 to 10) which correspond to the estimated amount of energy required to condition a house ;
- climate specific, thermostat settings for the activation of heating and cooling plant to maintain presumed levels of thermal comfort;
- infiltration rates for houses;
- internal heat-loads for rooms within a house, based on zone type;
- ventilation practices based on internal room temperature, external air temperature and wind speed; and
- drape usage patterns to reduce heat loss or heat gain, dependent on room temperature and external temperature and solar radiation

This list is just part of a more comprehensive list, comprising a range of preset conditions which may be significantly different from those that exist in a normal building. The times at which a building is occupied will vary from occupant to occupant, as will the amount, type and efficiency of heating and cooling plant operation and general heat producing appliances. The purpose of the standardised parameters established by NatHERS is to allow comparative analysis of house envelopes and the energy required to maintain thermal comfort in a given climate, based on a theoretical model. Detailed simulation programs were developed to efficiently and effectively cover the wide range of house types in Australia.

2.1 Detailed Simulation Programs

The detailed simulation programs developed in Australia for use in the assessment of housing have been called House Energy Rating (HER) software. These programs have three principle components, namely:

- an envelope thermal simulation model;
- a heating and cooling energy model; and
- a Star Rating report interface.

Each component contains default input values which can vary significantly from building to building. Each component requires inputs.

An envelope simulation model would include (modifiable and/or default) input values for:

- material conductivity, thermal capacity and emittance. These materials may be grouped together for the simulation of a composite element of the house’s internal or external envelope;
- libraries for windows, where each window type includes conductivity, emittance and infiltration values for the window and window frame;
- default internal heat gains for each room or zone which includes values for appliance loads and human occupation;
- default infiltration rates for each room or zone;

- default ventilation styles for each room or zone;

- default curtain operation for each room or zone; and

- modifiable external shading parameters for each room or zone.

The envelope simulation output is a set of simulated room or zone temperatures for each hour of each day, for a complete calendar year. The software heating and cooling modules use this room temperature information to calculate energy use.

The heating and cooling modules may be simple or complex models. In both cases the model requires inputs for the minimum and maximum temperatures within a room or zone for each twenty-four hour period. Most programs assume the same daily room usage pattern for all days within a year. The usage pattern defines two key components, namely:

- the times the room is to be occupied and hence conditioned; and

- the minimum and maximum temperatures to which the room is to be conditioned. This may vary, depending on usage type (i.e., a bedroom requires a different level of thermal comfort when occupied during day-time usage, as opposed to usage when the occupants are sleeping);

The simplified heating and cooling models then apply default energy efficiency parameters to a heating or cooling appliance and calculate the energy required to maintain the required temperatures.

The less simplified heating or cooling models require input on the appliance information. This may be a manual input of appliance variables, or it may require the selection of the appliance from a default heating/cooling appliance library. The program then takes into account the efficiency of the appliances when calculating room energy use.

The calculated energy is then used within the Star Rating interface to allocate the appropriate star rating, based on the amount of energy required to maintain the minimum or maximum comfort temperatures.

Before an empirical validation activity is commenced, researchers must determine which input parameters can be assigned default values and which should be modified.

3 Defining Empirical Validation

There are three principal types of HER software validation, namely: mathematical, software comparison and empirical validation (Allen, Bloomfield et al. 1985; Bowman and Lomas 1985; Bloomfield 1988; del Mar Izquierdo, Lefebvre et al. 1995; Bloomfield 1999; Guyon, Moinard et al. 1999; Delsante 2005; Strachan, Kokogiannakis et al. 2005; ASHRAE 2009). These methods require different forms of data sets and have significantly different resource requirements, namely:

- The comparison of the HER software output values to mathematically calculated values is the simplest and least time consuming method, however this method has many limitations. The HER software is the resultant assemblage of more than forty years of building science research, which has incorporated the development and inclusion of many mathematical models. In the process of developing the software, many simplifications were made, to allow for a suitable range of variables that a program user could modify (Clarke 2001; Soebarto and Williamson 2001; Travesi, Knabe et al. 2001). The mathematical comparison may bear little resemblance to the real thermal condition within a building. Due to these limitations this method is often viewed as unsuitable for HER software improvement and/or calibration (Delsante 2005).

- Comparing program outputs to those of other accepted programs is an internationally recognised method of validating a building simulation program (Judkoff and Neymark 2006; Agami Reddy, Maor et al. 2007; ASHRAE 2009; Beausoleil-Morrison, Griffith et al. 2009). CSIRO software developers have previously compared modules of the CHENATH simulation engine to other building simulation programs (Delsante 2005). This method was adopted by the NatHERS protocols, where other residential HER software are required to have similar resultant output values to that of the AccuRate software (NatHERS 2007). Internationally the BESTEST and the ASHRAE Standard 140 were developed for this purpose and this method has been in use since the 1970s (Judkoff and Neymark 1995; Judkoff and Neymark 1999; ASHRAE 2001; ASHRAE 2004; Neymark, Judkoff et al. 2008). Many building simulation validation activities have used this method (Neymark and Judkoff 1997; Haddad and Beausoleil-Morrison 2001; Hayez, Dalibart et al. 2001; Henninger, Witte et al. 2003; Roujol, Fleury et al. 2003; Tsai and Milne 2003; Haberl 2004; Henninger and Witte 2004; Strachan, Kokogiannakis et al. 2006). Internationally, from the early 1970s to the present, differences have been observed between building simulation program outputs and measured building temperatures. As there is no certainty that the software in question can predict the room temperature or energy required to maintain present temperatures, comparing the result on one software to that of another software, (which may also be producing an incorrect zone temperature), is not viewed as best practice for software validation. This method is considerably better than the mathematical comparison but not as comprehensive as empirical validation.

- The empirical validation method requires the most resources and will take the longest time to produce results. However this method offers advantages that are critical in the control and quantification of the various research elements (Strachan and Vandaele 2008). If the test buildings are designed and constructed under close supervision, variations between the buildings can be kept to a minimum (Strachan and Vandaele 2008). Empirical validation requires the appropriate measurement of the test building and the detailed simulation of the building using the HER software being validated. Whereas a normal building simulation requires standard inputs, the simulation for this type of validation normally would require modifications to both front and back end inputs.. This method is generally accepted as the most suitable form of software validation, as it can promote algorithm improvement and calibration.

The methods vary in their resource requirements including: time and physical, human and financial resources. Each method is appropriate for certain levels of validation and has respective advantages and disadvantages, as shown in Table

1. The most complex type is empirical validation and embarking on this type of validation can take several years, depending on the purpose and resources available.

Table 1: Types of Validation

Method	Advantages	Disadvantages
Analytical/Mathematical	Limitation of input uncertainty, Pure mathematical modelling, Limited expense of the desktop form of research.	Limitation of calculations that would be economically undertaken The presumption that the current mathematical models were correct Does the data bear resemblance to real buildings
Software Comparison	Level of complexity was researcher and software dependent Certainty of input variables Various aspects of the software could be analysed separately Limited expense of the desktop form of research.	The presumption that the current mathematical models within the software is correct Does the data bear resemblance to real buildings?
Empirical	The comparison of software outputs to measurements from real buildings Complexity is defined by the test buildings Modelling certainties if the building is known	Experimental uncertainties in the form of equipment calibration and tolerances Modelling uncertainties if the building is unknown Detailed measurement is expensive and time-consuming Types of validation are dependent on fabric variables that can be changed in the test building

(Dewsbury 2011)

Most programs are the assemblage of several years of thermal building science research. Many mathematical models have been developed and revised in accordance with the results of empirical validation and/or software comparison. As computers have become more capable at completing complex calculations in relatively short periods of time, the complexity of the HER programs has increased. This pattern of program development has allowed for extensive calibration and fine-tuning of the mathematical models within some programs. However, empirical validation is the only method which can bridge models and measured data, hence providing a level of confidence in the capability and capacity of HER programs. A credible empirical validation process is a critical component of the legal basis for policies on building fabric thermal efficiency.

3.1 Key Components of Empirical Validation

A house energy rating software calculates hourly room temperature, which inputs into the software's energy calculation engine (Figure 1). The software then assigns an energy or star rating, depending on the amount of energy and the particular climate zone. The purpose of gathering empirical data is to establish the accuracy of the house energy rating software and determine its' sensitivity to key factors of climate and certain construction practices. It must be noted here, that any validation exercise is only as precise as the inputs provided to the research. Empirical validation is reliant on the appropriateness of the HER software inputs and the quality of measured data from the test building. Differences between measured and simulated temperatures may result from errors in simulation inputs, the program itself, or in the measuring equipment.

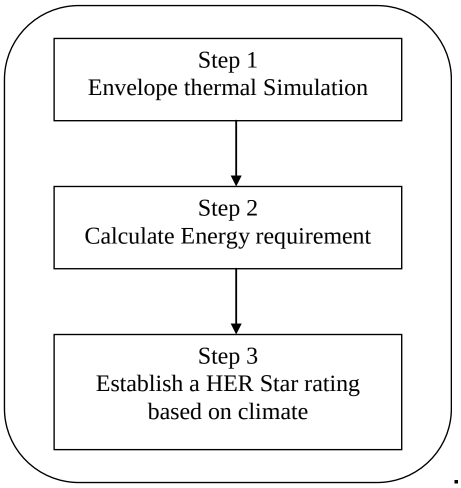

Figure 1 – Schematic of building simulation software process to establish a HER Star Rating

(Dewsbury 2011)

The first step is to identify which parameters are to be validated depending on the purpose of empirical validation. As mentioned earlier, most HER programs comprise three components, namely:

- an envelope model;
- a heating and cooling model; and
- the Star Rating interface.

The empirical validation process entails the comparison of building simulation software output data with measured data sets. There are three principal types of empirical software validation that may occur: complete software comparison; envelope comparison and HVAC comparison. These methods require different forms of data sets and have significantly different resource requirements, as follows:

- Complete software comparison: The whole software comparison is the most complex method and requires a lengthy process where both the envelope and heating outputs are compared as separate elements, prior to being integrated for a whole of software capability comparison. Each comparison is a separate research task and as much as this is acknowledged as an ideal long-term research goal, its complexity and time needed to undertake the tasks often makes this approach undesirable.

- Envelope component comparison: An envelope output comparison is a lengthy process, as it requires the detailed simulation of a suitable building and the comparison of the software output data with a measured temperature data set associated with the building. However, it is argued that this method is the most sensible starting point for software validation. This method allows for the envelope model to be improved and/or calibrated before any of the energy calculations associated with the HVAC model are analysed (Clarke, Strachan et al. 1994; Delsante 2006; Agami Reddy, Maor et al. 2007; Donn 2007; Strachan 2008).

- Heating and cooling energy component comparison: The comparison of the energy outputs relies on the heating and cooling requirements obtained by the means of envelope simulation. As many HER softwares use a simplistic heating and cooling calculation model, there are acknowledged weaknesses with this part of the software. In 2011 the NatHERS protocol did not require the specification of heating or cooling equipment and there is no formal system in place within Australia, where a database or library of heating options is available (Delsante 1996).

However, it is envisaged that this function will be improved significantly prior to 2020 and only then can this component be validated. As this area is still in the research stage, it is not a suitable first stage in an empirical validation process. However, once an envelope validation has been completed, a heating or cooling comparison can be undertaken.

In most cases the only error that may occur within the Star Rating interface would be a scripting error between quantity of calculated energy and the corresponding star rating. As such this is not viewed as an area of great importance in validation research. However, a systematic checking of this function should occur at regular intervals.

4 Empirical Validation Requirements & Methodology

Much has been published on the principles and practices of empirical validation (Lomas 1991; Lomas 1991; Agami Reddy, Maor et al. 2007; Dewsbury, Soriano et al. 2009; Raftery, Keane et al. 2009; Dewsbury 2011). In all of these studies, there were general principles that were followed and these are represented in Figure 2. This figure shows four distinct types of simulation, each varying in the type of climate and building fabric data input. The site climate observations are used for two of the simulation types. Once the data is obtained from the HER simulation and the building thermal measurements, the two data sets are compared. The type of validation is dependent on the type of HER simulation. To validate the capability of a thermal performance model to predict realistic energy requirements, the As-built Fabric / Measured Climate is the most appropriate scenario (Dewsbury 2011). All other methods would produce simulation data which would be unsuitable for comparison with the thermal measurements from the building zones.

Recent research at the University of Tasmania established a simple methodology as shown in Figure 3 (Dewsbury 2011). In this research, one-room test buildings called ‘test cells’ were used. The research process was divided into four distinct stages of activities and functions (Lomas 1994). Experienced building thermal performance researchers can often have the tendency to rationalise the data or the results based on personal experience, rather than allowing the data to tell its own story. The separation of the data through a staged approach to the research can correct this tendency. However, if resources permit, having each task performed by different researchers would be a best practice. Figure 3 illustrates the four elements of the empirical validation, namely:

- a suitable building;
- measurements of the building and its external climate to obtain empirical data;

- a detailed HER software simulation, which provided suitable outputs for comparison; and

- analytical methods for analysing and comparing the empirical and simulated data sets.

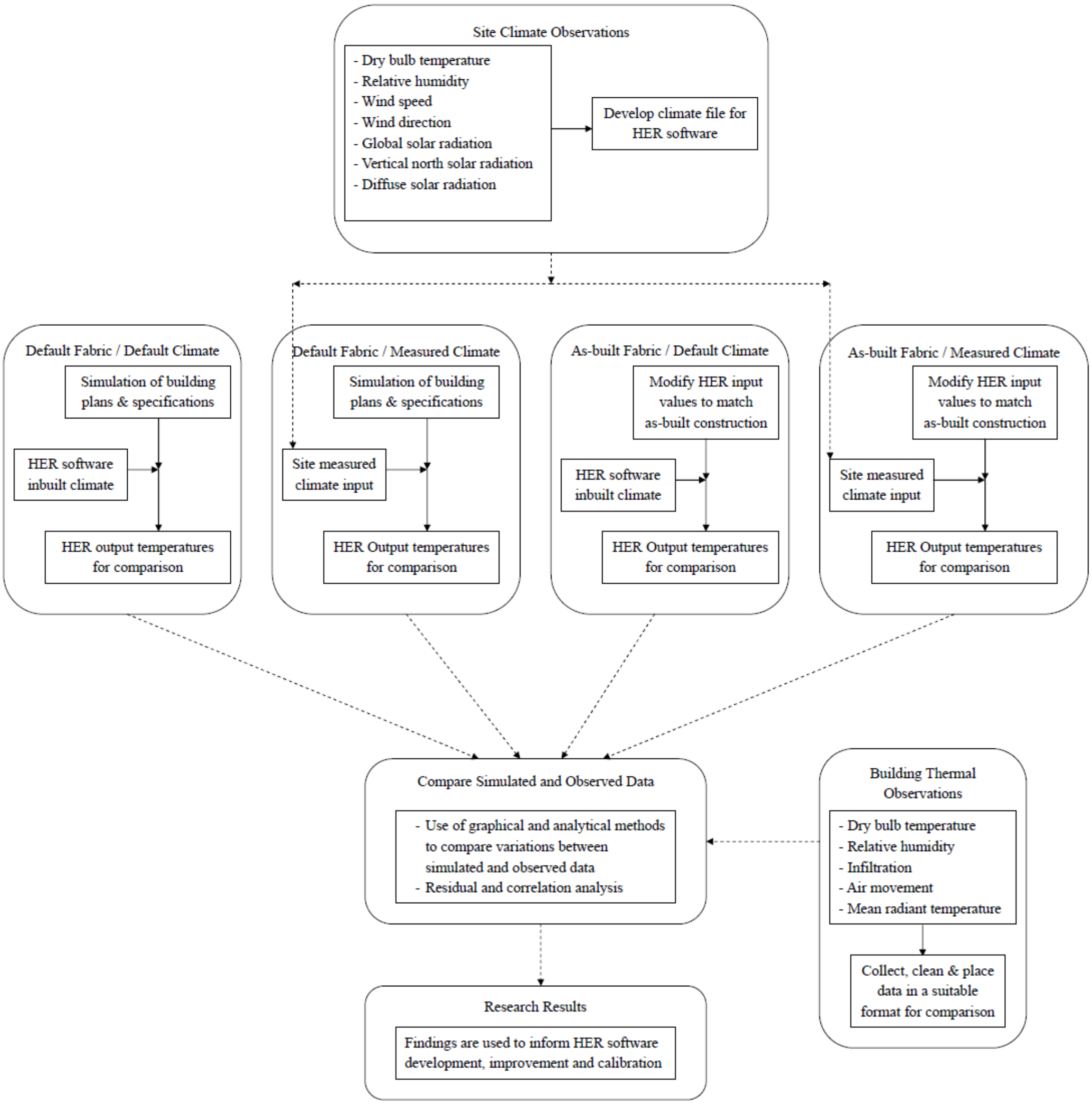

Figure 2 – A Validation Methodology

(Dewsbury 2011)

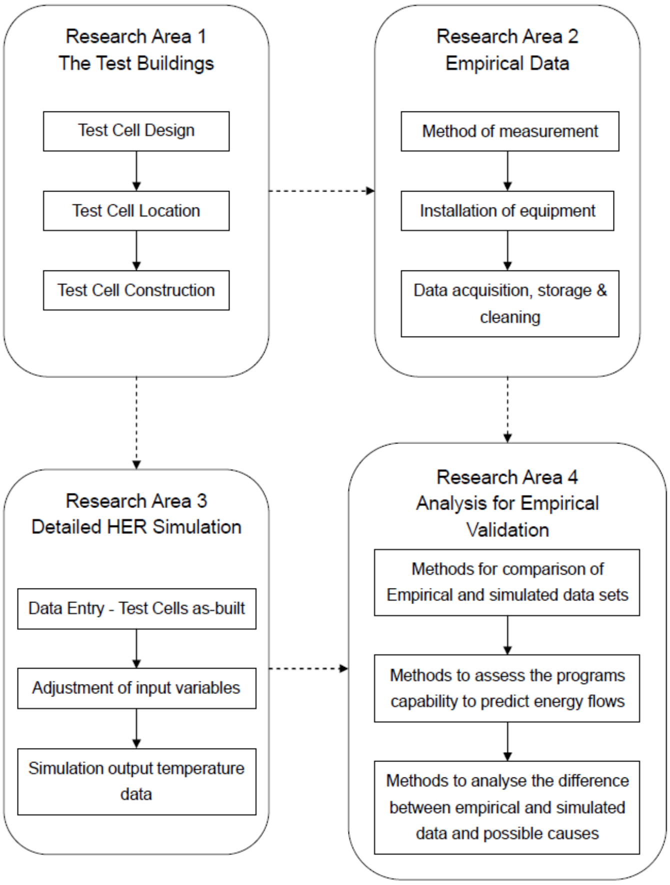

Figure 3 – Launceston Test Cell Methodology

(Dewsbury 2011)

The empirical validation of building simulation software requires carefully designed methods of continuously measuring both climate and thermal performance data at suitable intervals (Bowman and Lomas 1985; Lomas, Eppel et al. 1994; Agami Reddy, Maor et al. 2007).

The list of key considerations for projects attempting to validate a detailed simulation program empirically has grown over the years. Many of these documents refer back to Lomas, who specified key data requirements for a validation process (Bowman and Lomas 1985; Lomas 1991; Lomas 1991; Lomas, Eppel et al. 1994; Delsante 2005).

Generally the required empirical data is broken into two categories. The first is the minimum elements to be measured. The second is a list of building and operational parameters which should be adhered to. These include the following prerequisites:

- the building must not include active solar space heating or cooling system;
- weather data must be collected on site;
- all measured data for site weather and building thermal performance must be collected at hourly or ideally, smaller intervals;
- measured site weather data should include air temperature, wind speed, direct and diffuse solar radiation;
- the building must be unoccupied;
- the building must not contain any features of a solar passive nature that can not be modelled;
- If the building is multi-zoned, each zone should have its own heating and cooling plant;
- zone and inter-zone infiltration should be measured; and
- the building should contain no features that the detailed building simulation software is unable to model.

The rationale for these prerequisites is discussed below and in Sections 4.2 and 4.3.

The building data requires measurement of all building zones, that is: roof, room/s, and subfloor, if any. The minimum thermal performance data set (Loutzenhiser, Manz et al. 2007) should allow comparison and analysis against the various simulation methods discussed above. The building empirical data can also be compared with data from other co-located test buildings. The requirements of the empirical climate data are discussed later in Section 5 (Bowman and Lomas 1985; Lomas 1991).

4.1 The Test Building

The adequacy of information on the building construction can have a significant impact on the simulation of building thermal performance. In the case of purpose-built test buildings, these variables can be kept to a minimum. This is a critical area of empirical validation, so much so that researchers, in the past, have requested the dismantling of the building to ensure that what was simulated matches the actual construction details.

The measurement of building thermal performance parameters is physically affected by a number of non–constant environmental inputs (Figure 4). Furthermore, the design and construction of the test building require careful consideration, so as to minimise, if not totally avoid, unmeasurable effects, (like unknown fabric variations) and ensures accurate measurement of relevant environmental values, such as air temperature (Lomas, Eppel et al. 1994; Dewsbury, Nolan et al. 2007).

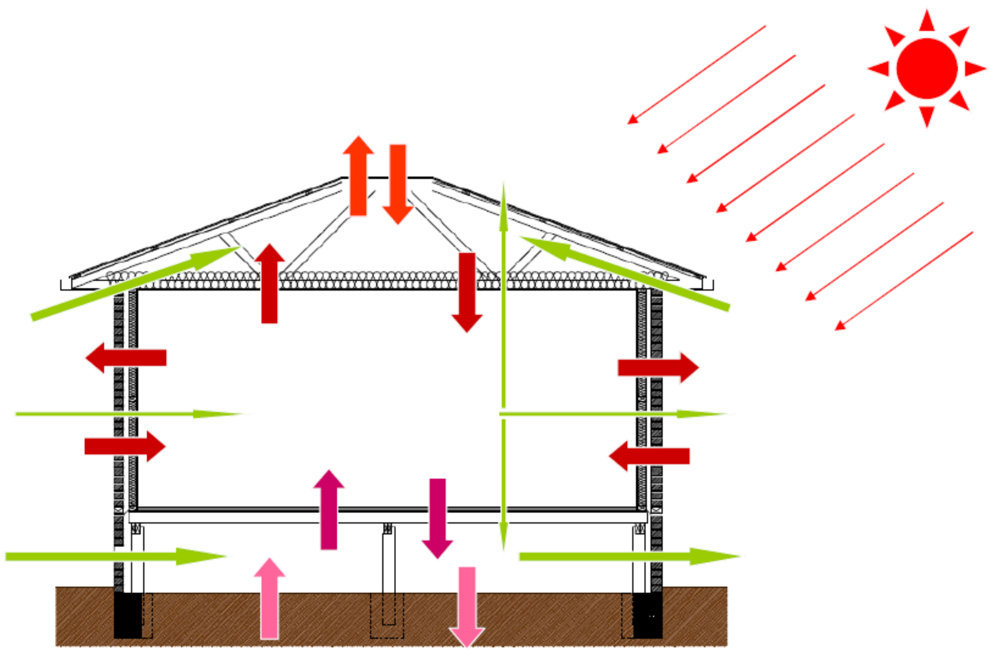

Figure 4 – A Building is affected by many differing non–constant environmental inputs

(Dewsbury 2011)

There are several aspects of the test building that must be considered, namely:

- no or minimal overshadowing;
- access to electricity to supply power for the measuring and other operational equipment;
- access to a telephone/data network to enable the automated collection of data without hindering the test building's thermal performance; and
- the use of a three-dimensional computer-aided drafting software to model the site and surrounding features of the test building, to be informed of any unaccounted for shading.

4.1.1 Test Building Considerations

Critically apparent from all past building thermal performance research is the need, if at all possible, for the research team to observe and provide best practice construction advice during the construction of a test building. Doing so prevents errors in inputs due to inaccurate construction information during later research stages. Several details require careful attention during construction, namely:

Wall Cavity Construction

Air infiltration within a wall cavity has a significant impact on the thermal performance and default thermal resistance values of wall assemblages. It cannot be presumed that a still air space will be created by simply sealing the wall cavity at its base, as shown in Figure 5. Resent research by Baker (2008) showed that the infiltration rates in sealed wall cavities is significantly greater than currently used rates.

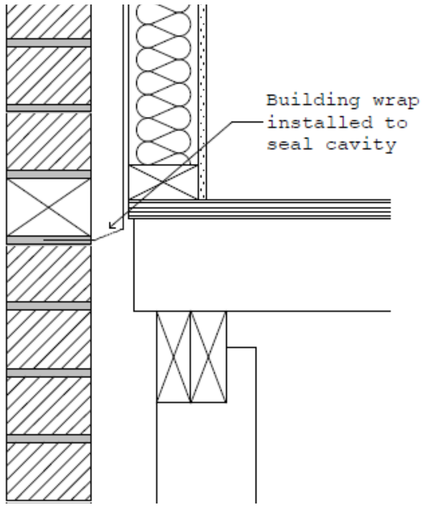

Figure 5 - Enclosed platform-floored test cell subfloor and wall cavity infiltration control

(Dewsbury 2011)

Wall Infiltration

Internationally there is a great awareness that building infiltration affects building thermal performance (Coldicutt, Coldicutt et al. 1978; Quirouette 1986; Biggs, Bennie et al. 1987; Biggs and Bennie 1988; Swinton, Brown et al. 1990; Rudd, Chandra et al. 1993; Willrath 1997; Guyon, Girault et al. 1999; US DOE 2000; OEENR 2004; Sherman 2006; Anis, Quirouette et al. 2007; Nolan and Dewsbury 2007). All test buildings should include a carefully applied building wrap, which should preferably be taped at all joints, as shown in Figures 6 and 7 (Dewsbury 2011).

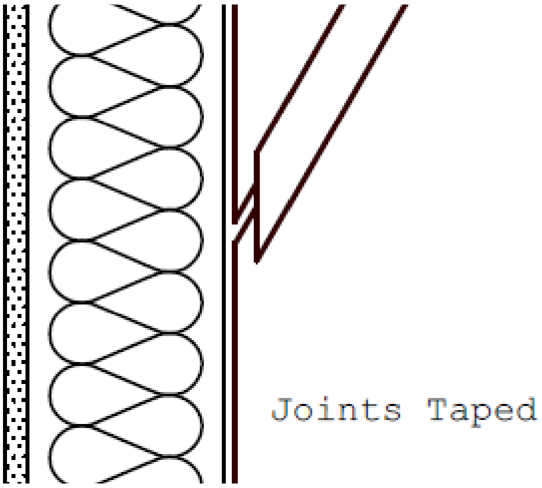

Figure 6 - Building wrap with joints taped together

Figure 7- Building wrap with all holes and joints taped

Roof Space Infiltration and Reflective Insulation

Similarly, the roof sarking of the test building must be carefully constructed. The installation of the sarking must be checked such that its five principal purposes are achieved, namely:

- to reflect heat back towards the roofing material;
- to reflect heat back into the roof space;
- to provide an insulation air space between the sarking and the roofing material;
- to provide a location for moisture to condense and be drained from the roof space; and
- to reduce roof space infiltration rates.

Similar in purpose to the wall wrap, the roof sarking acts as an element of infiltration control (Coldicutt, Coldicutt et al. 1978; Hendron, Farrar-Nagy et al. 2003; OEENR 2004; Lstiburek 2006) and taped joints will assist in reducing variability in air pressure. In previous research, where a tracer gas was used to calculate the roof space infiltration rate, it was observed that the more unsealed the roof space, the more variant the infiltration rate, making the estimation of infiltration rate difficult.

Additionally, for the reflective foil sarking to effectively reflect heat, it requires an air space (Hassall 1977; AFIA 2004). The building simulation software has a default thermal resistance value for reflective foil sarking, and this varies from R0.0 for a contact joint between the sarking and sheet metal roofing, to a possible R0.942 for a highly reflective sarking material with a nominal 40mm vented air gap (AccuRate 2007). If the standard draped method is used for sarking installation, the reflective foil sarking must be draped between battens to maintain a reflective air space and to reduce bridging. This practice inhibits vapour condensation on the outside surface of the material (Chadderton 2000), as illustrated in Figure 8. Researchers and industry representatives have frequently observed that the sarking is pulled tight during installation (Figure 9). However, this method negates most of the insulation functions of the reflective foil sarking and has been measured to promote an increase of moisture and condensation in the roof space (Anis, Quirouette et al. 2007).

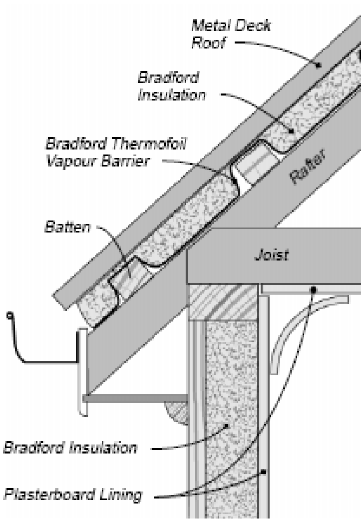

Figure 8- Draped roof sarking

(CSR 2003)

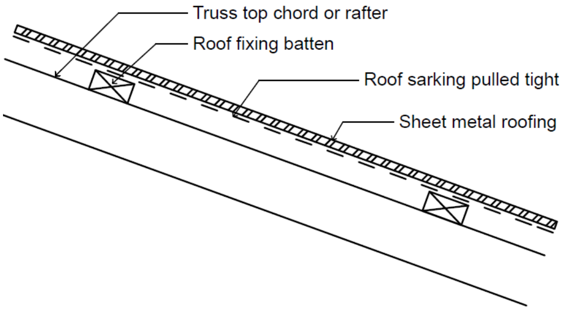

Figure 9- Common practice of pulling roof sarking taut during installation

(Dewsbury 2011)

It has been observed that sarking installed under the roofing battens, as in Figure 10, ensures that the relatively still air cavity is maintained.

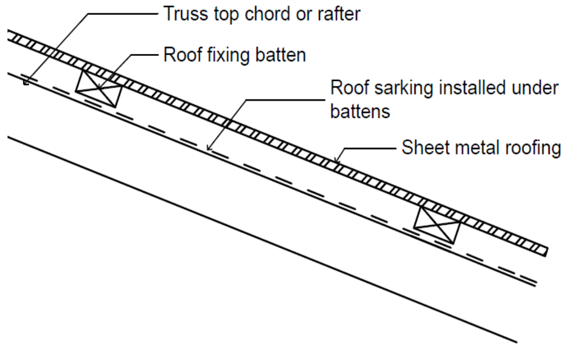

Figure 10 - Sarking installed over rafters, under battens

(Dewsbury 2011)

Infiltration Losses: Wall, Floor and Ceiling Penetrations

All penetrations, whether planned or unplanned, in the wall, floor and ceiling are potential causes of unwanted and sometimes immeasurable infiltration. In a single room building this is less of an issue, where a single infiltration measurement can provide a value to be used in the building simulation software. But, in a multi-zoned building, where each room is simulated as a separate zone and air penetrations will differ, significant differences between measured and simulated temperatures can occur.

If the test building is to be constructed or is under construction, gaps and openings that can potentially affect infiltration rates should be sealed between key elements, namely:

- between door jamb and wall frame;
- between door and door jamb;
- between window frame and wall frame;
- at all locations where plumbing pipes penetrate the fabric;
- at all locations where electrical services penetrate the fabric;

- at all locations where data services penetrate the fabric;
- all ceiling mounted down-light penetrations;
- access hatches between a room and the roof space;
- wall frame bottom-plate and floor junction; and
- ceiling and wall junction, as in Figures 10 and 11.

This is not an exhaustive list and building researchers must make themselves aware of any potential infiltration problems that may exist and explore methods to remedy or measure their impact.

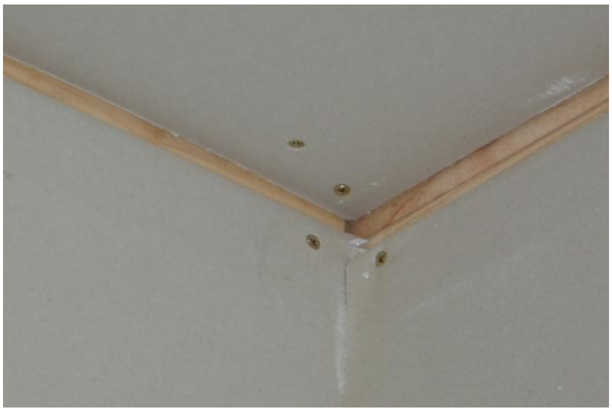

Figure 11 - Gap in ceiling corner between wall and ceiling plasterboard

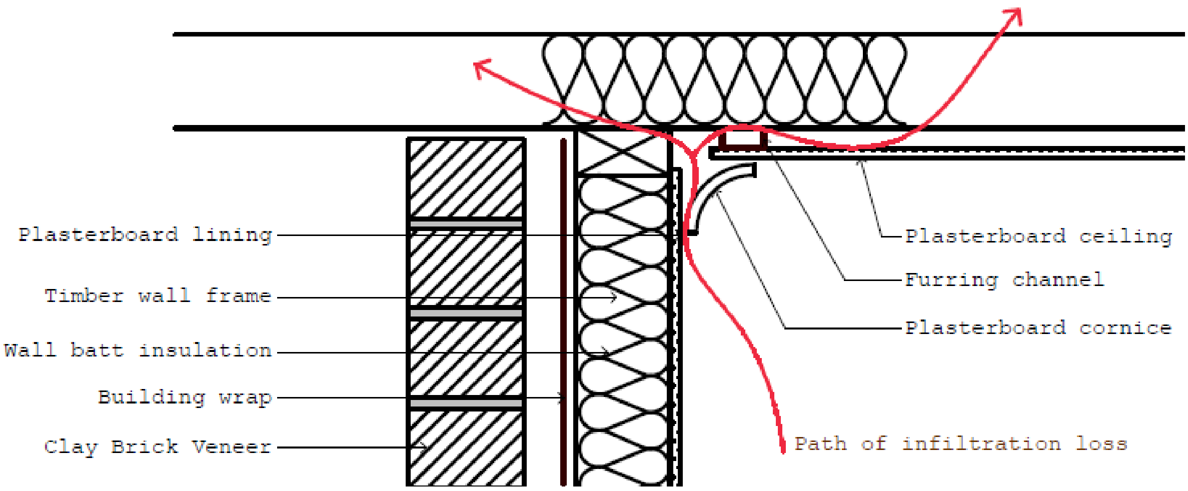

Figure 12 - Diagram showing potential unrestricted infiltration losses.

The Installation of Insulation

Recent research in Australia has called into question the current practices of many insulation installers. These concerns relate to subfloor, wall and ceiling insulation. Depending on the systems and methods used, two cases are worth considering, i.e., in situations where the insulation will be enclosed by a lining or cladding system, an inspection must occur prior to enclosure. Any area missing insulation must be rectified. In situations where the insulation is not enclosed, a visual inspection must occur prior to building measurements commencing. Subsequently, the preferred action is to either ensure the building is fully insulated or to measure the amount of missing insulation and account for this variation when the building is simulated. This method should be avoided as it can result in building simulation errors.

Framing Factor

The framing factor applies to floors, walls, ceilings and windows. The framing factor is a numerical value given to the proportion of the area occupied by a framing element to the entire plane of a wall or a window.

As the amount of framing in a floor, wall or ceiling increases, the amount of insulation decreases, which will have a significant effect on their respective conductivity values (Bell and Overend 2001; Fricker 2003; Trethowen 2004; Kosny, Yarbrough et al. 2006; Kosny, Yarbrough et al. 2006; Syed and Kosny 2006; Kosny, Yarbrough et al. 2007; Dewsbury, Wallis et al. 2009; Lstuburek 2010). The amount of framing in floors, walls and ceilings must be measured so that a revised conductivity value for the plane in question can be calculated using an appropriate method. Depending on the magnitude of difference between the framing element and the insulation, either the parallel path, isotherm planes or zone method should be used. This is discussed further in Section 6.

5 Generating the Empirical Data

The collection of high quality empirical data requires particular environmental measuring, data acquisition and data storage equipment. The type and quantity of equipment depends on the purpose of the validation. Prior to planning the equipment set up, a review of the software to be empirically validated must be completed, possibly in consultation with the software developers, as information critical to the validation may not always be readily available.

All building simulation software require some basic inputs. During the simulation process, the software calculates a temperature for pre-set time periods of each day, for a full calendar year, for each zone. If the time period set is for one hour, the software calculates the hourly temperature for the zone. Most building simulation programs calculate the zone temperature to tenths of a degree Celsius (e.g. 23.2^{o}C), as shown in Figure 13. To perform this task the software requires various inputs, with climate as the most significant input data set. The environmental parameters that should be measured within the building and at the site are discussed below.

```
               2009-10-19 Test Cell 2 unbridged & bridged_Cell 2 - Bridged.tem
-41.4 CLIMAT23.txt
 Total number of zones =   3

 Month Day Hour Outdoor       Test cell      Roof Space       Sub Floor
     1   1    0    17.2            17.4            16.9            17.9
     1   1    1    16.9            17.4            17.0            17.8
     1   1    2    16.4            17.4            16.8            17.7
     1   1    3    15.7            16.8            16.4            17.5
     1   1    4    15.4            16.7            16.0            17.4
     1   1    5    15.1            16.4            15.6            17.2
     1   1    6    15.4            16.2            15.5            17.1
     1   1    7    17.2            16.8            15.9            17.2
```

Figure 13 – Sample of AccuRate output temperature file

5.1 *Platforms for Environmental Measurement*

There are a range of commercially available analogue, digital and building management systems (BMS) which can record building and site thermal performance. Historically, many researchers had used analogue data acquisition systems due to their robustness. However, improvements are continuously being made to digital and BMS equipment to address power outage issues that have led to considerable loss of data, to improve the range of devices that may be used, and to ensure software integrity. With data integrity as the utmost consideration in empirical validation, it is the responsibility of each research team to select the type of data acquisition platform best suited to their research,

5.2 Site / Climate Measurements

The minimum site-measured weather or climate data collected must include the nine key climate file inputs, namely:

- dry bulb (air) temperature(tenths of degree Celsius);
- moisture content (tenths gram per kilogram);
- atmospheric (air) pressure (tenths of kilopascal)*;
- wind speed (tenths of metres per second);
- wind direction;
- cloud cover in Octaves**;
- global solar radiation (Wh/m^2);
- diffuse solar radiation (Wh/m^2) ***;
- normal direct solar radiation (Wh/m^2) ***.

* If the relative height above sea level is known for the research site, mathematical methods may be used if there is a suitable weather station nearby which records Mean Sea Level or normal atmospheric pressure.

** Australian HER software only uses the cloud cover data for night-time roof surface sol-air calculations. Collecting cloud cover data at night is difficult. The Bureau of Meteorology is in the process of developing methods to provide night-time cloud cover from satellite imagery. Past projects have simulated the building with differing cloud cover values to assess any significant impact on building simulation. Once this test had established a minimal impact of cloud cover on night-time zone simulations, the value of 4 for cloud cover was adopted. This will depend on the amount of thermal insulation in the roof space.

*** Due to the complicated nature of measuring diffuse and normal direct solar radiation, many projects measure global solar radiation on site. The research team may then use appropriately reviewed mathematical methods to calculate diffuse and normal direct solar radiation values.

5.3 Building Measurement

A number of comprehensive empirical validation research activities have been completed internationally since the 1970s (Bowman and Lomas 1985). As computer capacity and building simulation programs have evolved and building thermal performance regulations are increasingly becoming more stringent, the validation regimes for each software have intensified. Key international and Australian projects include:

- International Energy Agency projects (Lomas 1994; Lomas, Eppel et al. 1994; Lomas, Martin et al. 1994; Torcellini, Pless et al. 2005; Loutzenhiser, Manz et al. 2007; Judkoff 2008),

- PASSYSS & PASLINK projects (CSTB 1990; Leal and Maldonado 2008; Strachan 2008; Strachan and Vandaele 2008)

- Other National projects (Girault 1994; Guyon, Moinard et al. 1999; Moinard and Guyon 1999)

- Other Australian Projects (Clark, Sugo et al. 2003; Sugo, Page et al. 2004; Sugo, Page et al. 2005; Dewsbury, Fay et al. 2007; Dewsbury, Soriano et al. 2009; Dewsbury 2011) +GEARD 2011

Many of these research projects have involved the detailed measurement of several elements of the building fabric. However Geard's project (2011XX) involved a much simpler building measurement profile. The definition of the Zone

Temperature as used in the software has dictated the specific measurements in the building.

There have been varying opinions on the output temperature that a HER software provides. The output temperature has been described as one of the following: an environmental temperature; a mean radiant temperature and as a combination of air and surface temperatures. Davies (1990) described the temperature as undefinable. This problem appears to arise from the method used to calculate the heat flows through a building fabric. The equations consider heat flow through materials and the subsequent surface film conductance before room air temperature is affected (Muncey 1979; Clarke 2001). This is an aspect that has been queried in other research (Wong 1990; Lomas, Eppel et al. 1994; Barnaby, Spitler et al. 2005; Davies, Martin et al. 2005; Loutzenhiser, Manz et al. 2006). In any room with a wall, floor and ceiling there is a significant impact from the surface film conductance.

For the first stages of an empirical validation, the building must be operated in a free running mode (as discussed in Section XX). This means that the doors and windows in all rooms within the building are closed, with no ventilation, and it is assumed that the only change to a zone's air is caused by infiltration. It has been observed in several projects research that temperature gradients are established in rooms with relatively still air (Muncey 1979; Ahmad and Szokolay 1993; Beausoleil-Morrison and Strachan 1999; Dewsbury, Fay et al. 2008; Dewsbury 2011). The simulation software presumes that the air within a room is well-mixed (Muncey and Holden 1967; Lomas, Eppel et al. 1994; Clarke 2001; Strachan, Kokogiannakis et al. 2006), hence stratification is eliminated. Recognising this anomaly, zones were measured in stages as described in Table 2.

In deciding the specific location of measurements, it is important to consider that aside from the minimum requirement, it may be wise to install a range of other sensors that can be used to corroborate the minimum data set, and to enable further assessment of the results. Figure 14 and Figure 15 show typical vertical and horizontal measurement profiles.

When the temperature within a room zone is measured at various heights, for example at 600mm, 1200mm and 1800mm, the zone temperature is taken to be the average of the three zones.

Table 2: Minimum and Additional Elements to be Measured within a Zone

Zone	Minimum Requirement	Preferred Requirement	Additional Information
Roof space	Mid-zone dry bulb air temperature Mid-zone relative humidity Infiltration measurement	Top of zone dry bulb air temperature Bottom of zone dry bulb air temperature Mid-zone Globe temperature	Surface temperature for each material Vertical and horizontal air movement Air movement in still or moving air spaces
Rooms	Mid-zone dry bulb air temperature Mid-zone relative humidity (i.e., 1200mm in a room with a ceiling height of 2400mm) Infiltration measurement Mid-zone Globe temperature	Dry bulb air temperature measured at equal height divisions with the zone (i.e., 600mm, 1200mm & 1800mm in a room with a ceiling height of 2400mm)	Surface temperature of walls, flooring and ceiling Surface temperatures of building fabric in section (as in Figure 14 and Figure 15) Air movement in still or moving air spaces
Sub-floor	Mid-zone dry bulb air temperature Mid-zone relative humidity Infiltration measurement	Concrete slab-on-ground floored construction	
		Under concrete slab dry bulb air temperature	Below ground dry bulb air temperature (i.e., -1000mm) Interior and exterior slab edge surface temperatures
		Platform floored construction	
		Under platform floor dry bulb air temperature Ground surface dry bulb air temperature Mid-zone Globe temperature	Below ground dry bulb air temperature (i.e., -1000mm) Air movement in still or moving air spaces

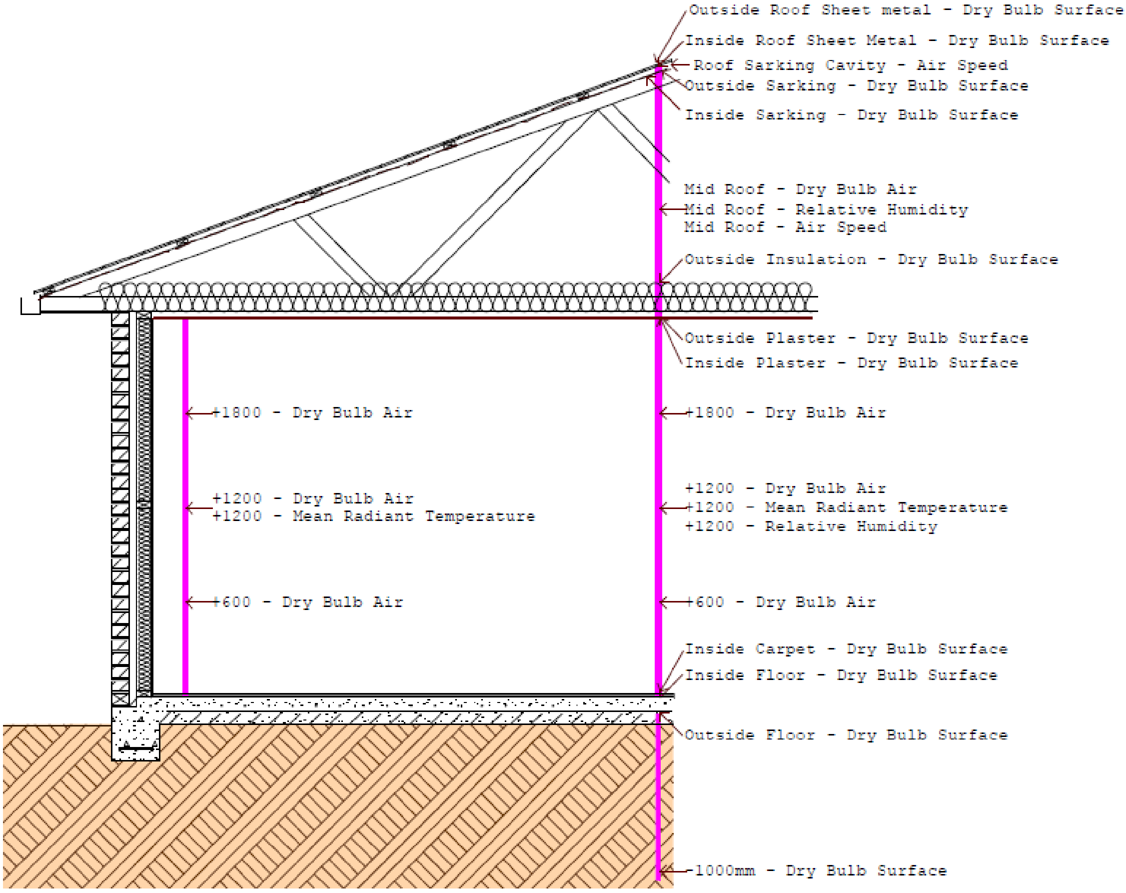

Figure 14 – Sample vertical measurement profile for a concrete slab-on-ground floored building

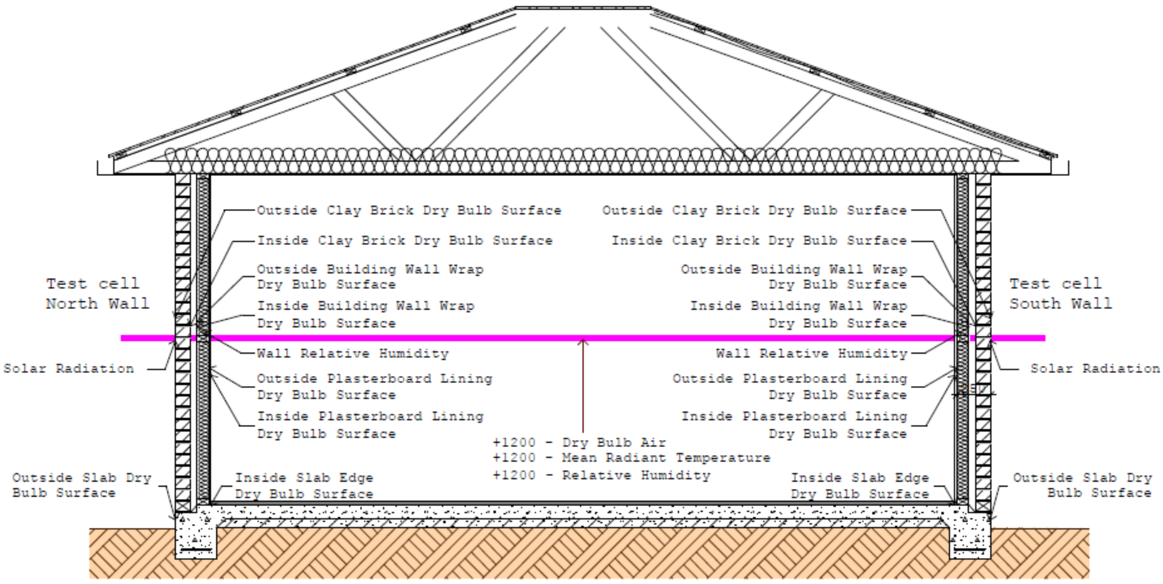

Figure 15 – Sample horizontal measurement profile for a concrete slab-on-ground floored building

The choice of sensor type for each measurement depends on the purpose and scope of validation and this can be dictated by: the availability of space, configuration, and environmental exposure of the building or specific building component, the level of accuracy required, and whether it is a short-term or long-term period measurement regime. The minimum level of measurement for each sensor type must be truly representative of the environmental parameter (as in Table 3). Similarly, the accuracy of the probe must be such that measurements are able to account for significant trends..

Table 3: Minimum Level of Measurement for Common Probe Types

Dry Bulb (Air Temp)	Tenths of a Degree C
Moisture Content	Tenths g per kg
Atmospheric (Air) Pressure	Tenths of kPa
Wind Speed	Tenths of metres per second
Wind Direction	0-16 (0=CALM,1=NNE, …, 16=N)
Cloud Cover	0-8 (0= no cloud,8= full cloud)
Global Solar Radiation on a horizontal plane	Wh/m2
Diffuse Solar Radiation on a horizontal plane	Wh/m2

In some conditions, sensors will require appropriate shielding to reduce any effect that can cause errors. For a temperature probe, this may be a reflective tube to shield against convective currents and to reduce radiant errors (Guyon and Rahni 1997; ASHRAE 2005; Sugo 2005-2009; Loutzenhiser, Manz et al. 2006; ASHRAE 2009).

Infiltration

The measurement of actual infiltration is preferred over the use of the default input values within the HER software (Bowman and Lomas 1985; Lomas 1991; Lomas 1994; Torcellini, Pless et al. 2005; Dewsbury, Nolan et al. 2007). Infiltration must be individually measured in all distinct zones. Common methods for measuring infiltration are the tracer gas and the blower door tests.

Infra-Red Camera Imagery

An additional method that may be used to further explore the thermal properties of the built fabric can be infrared imagery. This method has been shown suitable in assessing the thermal performance of the built fabric (Pearson 2002; Torcellini, Pless et al. 2005). This is not a form of measurement for validation purposes but may be used to inform and clarify the effects of construction practices on built fabric thermal performance (Fricker 2003; Dewsbury 2009; Dewsbury, Soriano et al. 2009; Dewsbury 2011).

Calibration of Environmental Measuring Equipment

Calibration of measuring equipment is a critical factor in empirical validation (Bowman and Lomas 1985). The calibration of the environmental measuring equipment must be precise and in accordance with international standards before and during installation, especially in prolonged measurement periods (more than 2 months). Ideally, calibration must be performed by an accredited external entity with certified calibration equipment. It has been found that calibration errors are not just confined to the device in question but can be caused by: cabling, data logger errors and power supply (Dewsbury 2011). The calibration must meet the requirements of the National Association of Testing Authorities.

5.4 Operational Control of the Test Building

The operational control of the test building must include a detailed log of activities. Details such as the time, duration and frequency of activities that can potentially affect the environment conditions in the place of measurement have to be recorded and regularly reviewed. Examples of these activities are:

- a researcher entering the building;
- a lamp was turned on;
- a window/door was opened; and
- a heater or air-conditioner was turned on/off.

For the purpose of monitoring building thermal performance, a building can be operated in one of four possible operation conditions, namely:

- unoccupied unconditioned;
- unoccupied continuously conditioned;
- unoccupied variably conditioned; and
- occupied conditioned

It should be noted, however, that for empirical validation purposes, the subject building must firstly be unoccupied and unconditioned (Lomas 1991). After this initial empirical validation has occurred, and the simulated and measured temperatures have agreement, the building performance can also be validated in other operational modes.

Whenever a test building is operated in a conditioned mode or has other internal loads mimicked, great care must be taken in the measurement of energy. This is an area where significant errors can occur and the energy measurement must include key factors, namely:

- measurement of the voltage into the building;
- continuous measurement of energy use by the appliance, which is then averaged to ten minute data; and
- a detailed assessment of all appliances prior to measurements, specifically the energy in, heat energy produced and any other energy consuming activities that the device performs (i.e., a fan heater also has a heating element).

Unoccupied Unconditioned

This method is often called 'free-running' or 'free-floating' and refers to building operation where:

- No thermostatically controlled methods are used to condition the spaces within the building through either cooling or heating

- No ventilation methods are triggered via doors windows or other means

- No internal electrical loads (i.e., stove, refrigerator, television) are added to any space within the building.

This method allows for the building to respond naturally to the external environment. This method is the most appropriate for empirically validating HER software as it allows the research to focus on the thermal simulation engine and not on the energy calculations (Bowman and Lomas 1985; Strachan, Kokogiannakis et al. 2006). Considering the string of calculation processes in the HER software, its thermal simulation engine must firstly be validated (Lomas 1991). Only when there is confidence in the thermal simulation engine's capacity to calculate zone temperatures, can further investigation progress to examining the energy required to condition space through either heating or cooling.

Unoccupied Continuously Conditioned

This method refers to building operation where:

- thermostat controlled methods are used to condition, (via heating or cooling), the spaces within the building to an unchanging pre-set temperature for an extended period;

- no ventilation methods are invoked via doors windows or other means; and

- no internal electrical loads (i.e., stove, refrigerator, television) are added to any space within the building.

This method allows the building's thermal performance to be further explored. This may include thermal capacitance and built fabric heat flows and infiltration. This can also be the first stage of validation of the heating or cooling model within the HER software. Subsequently, discussions must occur with the HER software developers, to ensure that the software can simulate the desired parameters of building operation.

Unoccupied Variably Conditioned

This method refers to building operation where:

- thermostat controlled methods are used to variably condition, (via heating or cooling), the spaces within the building for an extended period;
- ventilation methods may be invoked via doors windows or other means; and
- internal electrical loads may be simulated (i.e., stove, refrigerator, television) within respective spaces in the building.

In this method, the building is operated in conditions similar to the accepted values within the house energy rating protocol (ABCB 2006). The rooms are conditioned to mimic an occupied building. This can be for the purpose: of analysing thermal capacitance, built fabric heat flows, infiltration issues and natural ventilation models. This is suitable for validating the ventilation, and heating or cooling models within the HER software.

Occupied Conditioned

This method should not be used for empirical validation. It refers to building operation where:

- the temperature within the building is randomly controlled by live-in occupants;
- ventilation methods vary based on occupant operation of doors and windows; and
- uncontrolled electrical loads exist in all internal rooms.

This method is suitable for data collection on specific user energy and thermal comfort expectations. This data may be used to inform the HER software and NatHERS variations to pre-set requirements, but should not be used for empirical validation purposes. This method is discussed further in Appendix 1.

5.5 Data Cleaning

The process of data cleaning transforms site measured data into a suitable format; i.e., for the purpose of adopting site measured climate data as the climate file during simulation; or for comparison with simulated zone temperatures. Collecting temperature measurements at ten-minute intervals (especially in prolonged periods of observation, say several weeks or months), will result in a huge volume of data that can ideally be handled using spreadsheets or other computer programs. These should be capable of systematic checking and subsequent conversion to average hourly values. The steps that should be undertaken in the data cleaning process are shown in Table 4 (Dewsbury 2011). Throughout the process, a new version of the data is created with the completion of each step. This enables the various versions of the data to be kept for future reference. Based on this method, Version 1 of the data is the original raw data and Version 10 is the final data set for empirical validation purposes.

Table 4: Data Cleaning Method

Stage	Title	Description
1	10 Minute data range check	Each measuring device is allocated an expected range of measurement between ten-minute intervals.
2	10 Minute data null value check	All data is analysed to ascertain periods with corrupted or missing data. All values for these periods are converted to a null value.
3	10 Minute data step value check	Each measuring device is allocated with a step value, which is an estimate of the expected change in value between each ten-minute measurement.
4	Modification of data based on log book entries	The logbooks of the test building is analysed and notes are added to the data. If there was an activity within a test building, which would affect the free-running nature of the data, the data is modified to a null value.
5	10 minute data graphical analysis	A final checking process for the ten-minute data is the use of graphing software, which converts the data into graphical form. This analysis allows for the researchers to notice any phase shift or other anomalies in the pattern of the data.
5	Averaging 10 minute data into an average hourly	The data from the 40 minute, 50 minute, 0 minute, 10 minute, 20 minute and 30 minute readings are averaged to

	value	establish a new average hourly value. The only exception to this method is the wind direction, which will use a mix of mode, mean and wind speed to establish an average hourly wind direction value.
6	Average hourly data range check	Each measuring device is allocated with an expected range of measurement. All data for each device is checked to ensure it was within the expected range.
7	Average hourly data step value check	Each measuring device is allocated with a step value, which is an estimate of the expected change in measurement between each average hourly data value. All data for each device is checked to ensure that the data did not have steps in value greater than those defined.
8	Average hourly graphical analysis	A final checking process for the average hourly data is the use of graphing software that converts the data into graphical form. This analysis allows for the researchers to notice any phase shift or other anomalies in the pattern of the data.
9	Test building log book cross check	A final crosscheck of the logbook entries is undertaken, to ensure that no data that would be affected by activity within the test building has occurred.
10	Final Cleaned Data Set/s	

Throughout this process the key building thermal performance researcher should preferably not perform data checking. This is to avoid unwarranted data modification, as a result of personal biases, based on previous building science experience. However, he can assess all errors raised during the data cleaning process, and in co-operation with other researchers, make informed amendments to the data if necessary.

6 Generating the Simulation data

The empirical validation process requires the production of data sets that are suitable for comparison of simulated and measured temperatures. The HER software library contains default values to make standard house energy ratings simple and quick to undertake. To produce an output temperature data set that is close to reality, a number of default parameters can be replaced with actual measurements (Guyon 1997; Dewsbury 2011). This requires a thorough understanding of the data input parameters required by the HER software and the effect that they have on the thermal simulation process. This may require consultation with the software developer, and performing numerous envelope simulations to ascertain any effect from changing an input variable. Before progressing to this stage, it is important that properties of the test building elements are defined as follows:

- determine 'as built' values for roof, ceiling, wall and floor assemblages to modify fabric thermal properties;
- determine 'as built' values for shading elements that would affect fabric thermal performance;
- measure appliance-generated heat loads that occurred within the test building;
- measure infiltration values for each zone of the test building; and
- modify thermostat settings within the software to recognise the free running or other operational method within each zone of the test building.

Only when each of these values is established, can there be confidence that the output simulation temperature data from the HER software may correctly reflect the building being modelled (Allen, Bloomfield et al. 1985; Lomas 1991; Lomas, Eppel et al. 1994; Stazi, Di Perna et al. 2007; Raftery, Keane et al. 2009). It is also important to note that when validation involves monitoring periods of less than one year, it is necessary to acquire synchronised site-measured climate data, for use in the creating a site-measured climate file for input in the HER simulation.

This list of minimum input requirements for the HER simulation can be summarised in a validation matrix as shown in Figure 16.

		Built Fabric	
		HER Default Built Fabric	As-Built Fabric
Climate	Default Climate File	Default fabric / Default climate (A standard house energy rating)	As-built fabric / Default climate (Mixed Inputs)
	Site Observed Climate File	Default fabric / Measured climate (Mixed Inputs)	As-built fabric / Measured climate (Empirical Validation Simulation)

Figure 16 – AccuRate Detailed Simulation Matrix (Dewsbury 2011)

Each HER simulation type requires different levels of data inputs for the simulation. The only method internationally recognised as suitable for empirical validation is the "As-Built / Measured Climate" version (Lomas 1991; Delsante 2005; Torcellini, Pless et al. 2005; Dewsbury 2009; Dewsbury 2011).

6.1 Site-measured Weather File

The climate files within HER programs have been developed from several years of BOM measured data (Delsante and Mason 1990). In many cases the BOM data has missing portions; hence mathematical methods have been utilised to fill in the gaps (Boland 1995; Delsante 1996; Boland 2002; Stokes 2007). For HER software validation, however, much of this data is unsuitable (Lomas 1994), as variations of up to 7.0^{o}C have been measured between hourly values in the HER software climate file and site-measured dry bulb air temperature data (Dewsbury 2011). It has been observed that there are significant differences between the default climate file and site measured conditions for: relative humidity, wind speed, wind direction, solar radiation and diffuse solar radiation (Dewsbury 2011). Each of these weather inputs has a varying impact on the thermal simulation of a building.

The HER software has in its library, several sets of site climate files corresponding to the various climate-specific geographical locations in Australia. The software assigns the climate file based on a postcode entry. As mentioned in Section 5.2, a site weather station is required to measure site-specific climate variables. The HER software weather file provides a matrix of climate data, which the software uses to simulate heat flows through the building's envelope and for natural ventilation calculations. The typical meteorological year or TMY file type which is used by Australian HER software (AccuRate 2007) consists of 27 inputs, as shown in Figure 17.

Columns 1 and 2 contain a two letter code for the site (eg AD for Adelaide)
Columns 3 and 4 contain the last two digits of the year number eg 67 for 1967
Columns 5 and 6 contain the month number (zero-filled) eg 01 for January
Columns 7 and 8 contain the day number (zero-filled) eg 01 for first of the month
Columns 9 and 10 contain the hour number 0-23 (0=midnight, 1=1am etc)
Columns 11 to 14 contain the Dry Bulb (Air) temperature in tenths of degrees C
Columns 15 to 17 contain the Moisture Content in tenths of g per kg
Columns 18 to 21 contain the Atmospheric (Air) Pressure in tenths of kPa
Columns 22 to 24 contain the Wind Speed in tenths of metres per second
Columns 25 to 26 contain the Wind Direction 0-16 (0=CALM,1=NNE, …, 16=N)
Columns 27 contains the Cloud Cover 0-8 (0= no cloud, …, 8= full cloud)
Column 28 contains the Flag for Dry Bulb Temp. (0=Actual, 1=Estimated)
Column 29 contains the Flag for Moisture Content (0=Actual, 1=Estimated)
Column 30 contains the Flag for Atmospheric Pressure (0=Actual, 1=Estimated)
Column 31 contains the Flag for Wind Speed (0=Actual, 1=Estimated)
Column 32 contains the Flag for Cloud Cover (0=Actual, 1=Estimated)
Column 33 contains the Flag for Wind Direction (0=Actual, 1=Estimated)
Columns 34 to 37 contain Global Solar Radiation on a horizontal plane (Wh/m^2)
Columns 38 to 40 contain Diffuse Solar Radiation on a horizontal plane (Wh/m^2)
Columns 41 to 44 contain the Normal Direct Solar Radiation (Wh/m^2)
Columns 45 to 46 contain Solar Altitude in degrees (0 to 90)
Columns 47 to 49 contain the Solar Azimuth in degrees (0 to 359, 0=N, 90=E, …)
Column 50 contains the Flag for Global Solar Radiation. (0=Actual, 1=Estimated)
Column 51 contains the Flag for Diffuse Solar Radiation (0=Actual, 1=Estimated)
Column 52 contains Flag for Normal Direct Solar Radiation (0=Actual, 1=Estim.)
Columns 53 and 54 contain the first two digits of the year number eg 19 for 1967
Columns 55 to 60 are blank

Figure 17 – TMY1 weather file format

(ACDB 2006)

For the HER software simulation, only 14 of the 27 inputs are relevant. They are:

- month number;
- day number;

- hour number;
- dry bulb (air) temperature (tenths of degree Celsius);
- moisture content (tenths gram per kilogram);
- atmospheric (air) pressure (tenths of kilopascal);
- wind speed (tenths of metres per second);
- wind direction (0 to 16);
- cloud cover (0 to 8);
- global solar radiation (Wh/m^2);
- diffuse solar radiation (Wh/m^2);
- normal direct solar radiation (Wh/m^2);
- solar altitude (0 to 90 degrees); and
- solar Azimuth (degrees).

Depending on the approach taken some elements of the existing TMY file can be retained and the site- measured data can be used to complete pertinent categories. The new site-measured climate file can be produced quite quickly, using appropriate software.

As mentioned in Section 5.2, mathematical methods can be used to establish diffuse and normal direct beam solar radiation values. There is a long history of mathematical methods used to calculate these values (Scanes 1974; Peterson and Dirmhirn 1981; Spencer 1981; Bird and Riordan 1986; Moriarty 1991; Subhakar and Thyagarajan 1994; Halthore, Schwartz et al. 1996; Halthore and Schwartz 2001; Myers 2003; Ulgen and Hepbasli 2004; Ridley and Boland 2005; Boland, Ridley et al. 2007; Ridley and Boland 2008). Care must be taken and consultation should occur with CSIRO and other specialists in the field, to ensure that the methods used are suitable and current. However, if there are adequate resources to measure diffuse and/or normal direct beam solar radiation, this data could be used by researchers to further improve the mathematical models.

The new weather file can be created only after the measured climate data is cleaned, as discussed in section 5.5. To ensure that formatting and scripting are correct, the new climate file should be carefully compared to the original site-measured data and an existing TMY1 type file. The final file is then given a name suitable for reading by the HER software.

6.2 Detailed Envelope Simulation

The HER software uses simplified input parameters, default values and assumptions which are used in a standard house energy rating simulation (Delsante 1996; Soebarto and Williamson 2001). Modifying these input parameters and default values using measured values could have a significant impact on the simulation (Allen, Bloomfield et al. 1985; Bannister 2009). In modifying these values, the following are required:

- detailed information of the materials and construction of the test building;
- a thorough knowledge on the application of this detailed information in the HER simulation; and
- a correctly formatted climate file that comprises the site-measured data, synchronised with the building environmental measurements.

Conducting a detailed envelope simulation process should ideally be a collaborative undertaking with the software developers. Previous work has resulted in errors when this approach is not taken. On the other hand, a collaborative approach ensures that modifications to the input variables are appropriate. In assessing the appropriateness of the modified value, it should not be expected that a single simulation is sufficient. It takes numerous simulations and constant sensitivity analysis to make gradual and informed improvements to the simulation input variables.

NatHERS prescribes the requirements of HER software in Australia. The HER software outputs are a mix of text and data files, which cannot be modified by the user. For researchers attempting to empirically validate the HER software, inputs can be made in both the standard front-end user interface and the back-end non-standard area of the software.

The standard front-end inputs involve the following:

- the postcode, which defines the climate file the software will use for the simulation;
- the definition of roof, ceiling, wall, floor, door and window construction elements;
- the definition of the zone types for all volumes within the built fabric;
- the definition of external shading features;
- the detailed definition of built elements and their relationships; and
- a general orientation of the building for infiltration calculations.

The non-standard front-end and back-end inputs are:

- the modification of fabric assemblages to account for framing factors (walls and windows);
- the modification of sensible internal heat gains to account for the mode of test building operation and the measured heat inputs for each zone;
- the modification of latent internal heat gains to account for the mode of test building operation and the measured heat inputs for each zone;

- the modification of heating thermostat controls to account for the mode of test building operation;
- the modification of cooling thermostat controls to account for the mode of test building operation;
- the modification of zone infiltration values from default to measured values; and
- the development and use of a site-measured climate file.

When the appropriate standard and non-standard input values are suitably modified for each zone within the test building, the HER simulation can be undertaken. The energy use by zone provides a final checking mechanism to ensure that the simulation inputs are appropriately configured according to the operational mode for the test building. The resultant HER software output zone temperature and energy-use files can then be used for comparison to site and test building measured data.

6.2.1 HER Software Front-end Standard Inputs

For empirical validation and to enable on-going calibration of HER software it is necessary to eliminate programming or input variable simplifications and speculation, which affect the underlying physics of the building thermal simulation (Sullivan and Winkelmann 1998; Clarke 2001; Donn 2001; Agami Reddy 2006; Ahmad and Culp 2006; Bannister 2009). Previous research has documented extensive scattering of resultant data when input errors relating to fabric variations occurred (Diamond, Cappiello et al. 1985; Guyon 1997). This requires a detailed analysis of the built fabric, which enables informed data entry modifications.

Prior to the data entry, a critical analysis of the built fabric and nearby elements is to be completed. The required inputs for this stage of the empirical validation process comprise standard and non-standard (or improved) inputs, entered via the normal HER software front-end user interface.

Postcode

The postcode enables the software to assign the appropriate site-measured climate file.

Exposure and Ground Reflectance

The site exposure and ground reflectance values are allocated based on the definitions within the software and advice provided by the software developers. The definition, which is provided by the AccuRate software is:

> *"Exposed: Flat open country with few or no trees or buildings*
> *Open: Normal countryside with some trees and scattered buildings*
> *Suburban: Low-rise built-up areas in the suburbs of towns and cities*
> *Protected: High-density inner city or CBD, with tall buildings nearby"*
> *(AccuRate 2007)*

Likewise, the AccuRate software defines ground reflectance as: "*The proportion of solar radiation that is reflected by the ground immediately adjacent to the building*"
(AccuRate 2007)." This value should be measured and discussed with software developers before an input value is chosen.

Construction Information

The construction information on all internal and external built elements of the test building should be precisely defined. The built fabric elements include: external and internal walls, doors, windows, floors, ceilings and roofs. Thermal and related properties of various building fabric elements are found in the inbuilt materials library of a HER software. When the input selection is made, the software creates an assemblage that corresponds to the as-built fabric matrix. The internal library also includes external surface colours and solar absorptance values. These values should be selected in consultation with the software developers. Table 5, details variations in the construction data that must be considered. The framing factor, which is discussed in more detail later, applies to many of these inputs. At this stage in the data entry process, the selection of the materials and their assemblage allows for the future non-standard modification to input values.

Table 5: Construction Data Input Requirements

Iteration	As Built Fabric
External Walls	Modified values based on analysis of test building as-built walls. Including the accounting of framing factor (See Section 6.2.2).
Windows	Refer to HER Software Back-end non-standard inputs
Doors	Modified values based on analysis of test building as-built values
Floor	Modified values based on analysis of test building as-built floors. Including the accounting of framing factor (See Section 6.2.2).
Ceiling	Modified values based on analysis of test building as-built ceilings. Including the accounting of framing factor (See Section 6.2.2).
Internal Wall	Modified values based on analysis of test building as-built walls. Including the accounting of framing factor (See Section 6.2.2).
Roof	Modified values based on analysis of test building as-built roof/roofs.
Skylight & Roof Window	Modified values based on analysis of test building as-built windows. Including the accounting of framing factor (See Section 6.2.36.2.2).

Zone Information

The zone information includes the zone's: title, function, volume, floor height, ceiling height, zone specific ventilation profiles, and heating and cooling parameters. The requirement for each of these input variables is detailed in Table 6.

Table 6: Zone Information Input Requirements

Iteration	Requirement
Title	As per test building documentation
Function	This can have anything entered at this stage. It is sensible to add the same value for each zone. This field allocated the sensible and latent heat loads, and the heating and cooling parameters. All of these values are to be modified manually in the non-standard back-end data entry stage.
Volume	From an as-built measurement of each zone
Floor Height	From an as-built measurement of each zone
Ceiling Height	From an as-built measurement of each zone
Specific ventilation profiles	The data entry in these fields should be ignored at this stage. The measured infiltration rates for each zone will be input during the non-standard back-end data entry stage.
Heating & Cooling Parameters	As discussed above in Zone function

Shading Features

All shading features of the building's external walls must be defined. This entails the use of graphics software to model the building in three-dimensions, relative to its surrounding landscape, enabling sun study simulations that provide details of structures and objects that may shade the test building. The input of each shading feature is linked to all relevant external walls and roofs. Commonly building shading features are: eaves, gutters and pergolas. For empirical validation, the effect of nearby buildings, fences and trees are important and must be factored into the simulation.

As with other inputs, these should be completed in close consultation with the software developers, as each HER software has different input methods for shading features.

Built Elements

The detailed input of the building properties is the most complex stage of the data entry process. In this stage, the relationship of elements and spaces is created across three dimensions for the thermal simulation. The enclosure of each zone is defined by selecting the appropriate construction information. The perimeter elements (i.e., ground, floor, wall, ceiling or roof) as well as the width, height and area of each plane are defined. For external walls, the azimuth is used for solar and wind calculations. Once each zone perimeter is defined, other elements within each plane such as doors and windows are added. Depending on the software being validated, it may also include applying shading features to walls.

Ventilation

Some HER software models include a "ventilation" tab. This tab allows for the refinement of building orientation, including the choice of a general rectilinear building form. These inputs are critical to solar radiation, infiltration and natural ventilation calculations. Special care must be taken if this method is being used to set building orientation. For empirical validation, it is preferred that the azimuth of each external wall is included in the built elements data entry.

6.2.2 HER Software Front-end Non-standard Inputs

Framing Factor

Modifications to construction information can be made at the front end of most HER software. The framing factor, (which affects the conductivity values of a range of built elements) can be accounted for as a non-standard modification to the construction information. Before any non-standard inputs are included in the data entry process, a new version of the project should be saved, in order to distinguish the impact of any non-standard inputs in the simulation; tis also allows easy access to a clean base file should any errors in non-standard inputs occur.

The framing factor can have a significant effect on the thermal performance of housing (Cox-Smith 2001; Kosny and Childs 2002; Fricker 2003; Kosny, Yarbrough et al. 2006; Kosny, Yarbrough et al. 2006; Kosny, Yarbrough et al. 2007; Lstuburek 2010). For the software to be validated empirically, the correct resistance values for the various fabric elements of the entire test building require careful consideration (Lomas 1991). To establish correct as-built conductivity values for the floor, walls, and ceilings, the individual conductivity values for materials within the HER software and the method by which the software creates assemblages for thermal simulation must be examined. Many HER software do not consider the framing factor, or if they do, they often have a default value significantly lower than common construction practice (Bell and Overend 2001; Barnaby, Spitler et al. 2005; Syed and Kosny 2006; Dewsbury, Wallis et al. 2009; Belusko, Bruno et al. 2010). Figures 18 and 19 illustrate the timber framing within an external wall of a building. The framing factor in these figures consists of: bottom plates, studs, noggins, lintels, jamb studs and top plates. An analysis of the framing factor for each wall and window must be completed. A sample of the calculation for a wall is shown in Table 7.

Figure 18 – Wall framing of house during construction (2009)

Figure 19 – Multiple stud post method framing of house during construction (2009)

Table 7: Sample Calculation of Wall-framing Area

Wall Structure							
Member	Qty	Depth	Length	Width	Area m^2		Wall Area m^2
Nth Wall Studs	11	0.090	2.325	0.035	0.895	0.035	
Nth Wall 2100	8	0.090	2.030	0.035	0.568	0.025	
Nth Wall TP	2	0.090	5.480	0.035	0.384	0.006	
Nth Wall BP	1	0.090	5.480	0.045	0.247	0.004	
Nth Wall Noggins	1	0.090	4.905	0.035	0.172	0.003	
Nth Wall Window Head	1	0.090	2.000	0.035	0.070	0.003	
Nth Wall Lintel	1	0.063	2.000	0.200	0.400	0.013	2.735

There are three principal methods for calculating the revised conductivity when considering the framing factor (Standards New Zealand 2006; ASHRAE 2009; Dewsbury, Wallis et al. 2009), namely:

- the parallel path method;
- the isotherm planes method; and
- the zone method.

The parallel paths method is used when the differing materials of the built plane have similar conductivity values. This method may be suitable for houses without wall, floor or ceiling insulation.

The isotherm planes method is used when the differing materials of the built plane in question have conductivity values with a level of magnitude difference. In this method, the built plane is broken into its constituent parts and the fractional values are only applied to the elements that are different. Since 2005, most subfloors, walls and ceiling have been insulated, so it is generally accepted that this method should be used when the framing is made from timber. However, when steel framing is used, the choice of the isotherm planes or zone method requires careful consideration, and a review of relevant current literature is required.

The zone method is used for built wall planes where the magnitude of difference in conductivity values is high. An example is a large steel structural member within a highly insulated wall, where the steel member spans from the inside skin to the outside skin of the fabric (Figure 20). If the isotherm planes method is used in this type of situation, the revised average resistance value can be too low.

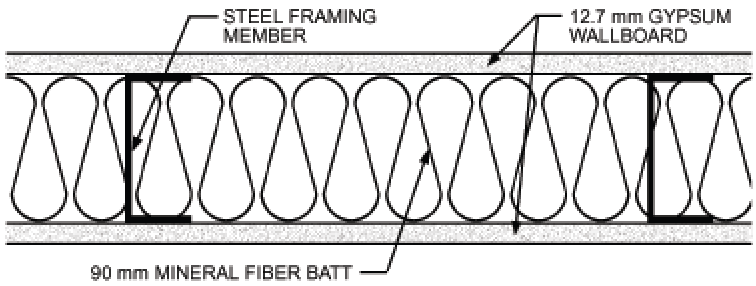

Figure 20 - Wall type suitable for Zone Method

(ASHRAE 2009)

Formulae for each method can be obtained from ASHRAE. The New Zealand Standard 4214 (2006) describes the isotherm planes method. An example of the isotherm planes method is shown in Equation 1.

Equation 1 – Isotherm Planes Method – From sample wall

<table>
<tr><td>1</td><td colspan="3">Select differing assemblages on parallel planes of the building, where the elements will have varying resistance values and number them.</td><td>R1: Insulated wall</td><td>R2: Framed Wall</td></tr>
<tr><td>2</td><td colspan="3">For each differing assemblage establish the percentage fraction of total planar area that this assemblage encompasses.</td><td>76%</td><td>24%</td></tr>
<tr><td>3</td><td colspan="3">Calculate the differing resistance value for each assemblage</td><td>R2.5 Wall Insulation – R2.5</td><td>90mm Timber – R0.90</td></tr>
<tr><td>4</td><td colspan="3">Calculate the revised resistance value for the assemblage
$1/R_b = f_1/R_1 + f_2/R_2 + f_3/R_3 + \ldots$</td><td colspan="2">$1/R_b = 0.76/2.5 + 0.24/0.90$,
$1/R_b = 0.304 + 0.216$
$1/R_b = 0.52$</td></tr>
<tr><td>5</td><td colspan="3">Then $R_b = 1/(1/R_b)$</td><td colspan="2">$R_b = 1/(0.52)$
$R_b = 1.92$</td></tr>
<tr><td rowspan="2">6</td><td colspan="2">Then $R_T = R_{si} + R_1 + R_2 + \ldots. + R_n + R_{se}$</td><td colspan="3" rowspan="2">OS Surface 0.03
12 Ply 0.09
Non Ref. Cavity 0.18
Bridged plane 1.92
10 Plasterboard 0.06
IS Surface 0.12
R_T 2.40</td></tr>
<tr><td>Where:</td><td>R_T : is the total resistance
R_{si} : is the internal surface resistance
$R_1 + R_2 + .. + R_n$: are the thermal resistances of each layer, including the bridged layers
R_{se} : is the external surface resistance</td></tr>
</table>

Once the revised average resistance value is obtained for each floor, wall and ceiling amendments can be made to material property values for floor, wall and ceiling assemblages. This may be completed by modifying the thickness of a material (e.g. a timber floor) or by changing the resistance value of wall or ceiling insulation, as shown in Equation 2.

Equation 2 – Establishing Insulation Thickness to Suit Revised Resistance Value of Wall

Insulation Resistance value (83mm)	R2.5
Desired Resistance value based on framing factor	R1.795
To obtain revised particle-board thickness Rockwool insulation (k=0.033)	R = Thickness / k R x k = Thickness R1.795 x 0.033 = 59mm

Once the revised thickness of the materials is established, they are modified for each floor, wall and ceiling within the assemblage construction input section.

6.2.3 HER Software Back-end Non-standard Inputs

To simulate the test building in a suitable manner for empirical validation, a range of non-standard inputs are required (Lomas 1991; Lomas 1991; Agami Reddy, Maor et al. 2007; Bannister 2009). The modifications required include: window framing factor, heating and cooling parameters, energy loads and infiltration values. These modifications are made by amending values via the software output 'scratch' file, prior to undertaking the simulation.

The software generates a 'scratch' file when the front-end user interface data entry is completed and the 'check' button is selected. When the inputs match defined parameters for the house energy rating, the software produces a 'scratch' file, which is used by the simulation engine to calculate house energy use, for heating and cooling. The non-standard back-end modifications require direct data entry within the HER software 'scratch' file. It is advisable that the unedited 'scratch' file is saved, to create a template for ongoing research, to allow for the ease of correction of mistakes and to allow for analysis of the effect of different input changes. In this context, each test building should have a default and as-built scratch file. This method is a logical approach to what can otherwise be a very complex exercise.

Window Framing Factor

As with floors, walls and ceilings, the framing factor for windows requires certain modifications to be made. When the HER software writes the scratch file, each window is allocated conductivity values for window frame and glazing. It also allocates a default area for each, as a percentage of the total window area. Figures 21 and 22 illustrate two houses showing the significant differences in the ratio between window frame and glazing.

Figure 21 – Sample house 1 showing significant differences in window framing factors

Figure 22 – Sample house 2 showing significant differences in window framing factors

Detailed measurements of all framing of glazed windows and doors must be taken. The exact percentage of frame and glazed areas for each window can be calculated manually. This information will then be used to modify the values in the scratch file.

Modified Thermostat and Internal Heat Gains

As the HER software has been specifically developed to meet the NatHERS protocol for house energy ratings, there are zone dependant default times for room occupancy. The room occupancy includes heating/cooling settings and internal heat gains. As the test building may be operated in different operational modes, care is required to ensure that all relevant inputs for each parameter are modified for each zone of the test building. A matrix listing the required modifications is shown in Table 8. As with other inputs, these amendments to the scratch file should be completed in consultation with the software developers.

Table 8: Modification Matrix for Heating/Cooling and Internal Heat Gains

Parameter	Mode of Operation: Free Running	Continuously Conditioned	Variably Conditioned
Heating thermostat settings	Requires modifying all values to zero	Requires modifying all heater thermostat values to pre-set fixed temperature	Requires modifying all heater thermostat values to pre-set variable temperatures
Cooling thermostat settings	Requires modifying all values to zero	Requires modifying all cooling thermostat values to pre-set fixed temperature	Requires modifying all cooling thermostat values to pre-set variable temperatures
Sensible heat loads	Requires modifying all values to zone measured internal heat loads (i.e., data logging equipment)	Requires modifying all values to zone measured internal heat loads (e.g. data logging equipment)	Requires modifying all values to zone measured internal heat loads (e.g. data logging equipment, refrigerator, stove, etc.)
Latent heat loads	Requires modifying all values to zero	Requires modifying all values dependent on cooling method	Requires modifying all values dependent on cooling method

After these amendments are made to the scratch file, simulations should be completed and the output temperature and energy files should be analysed, to ensure that the desired method of test building operation has been entered correctly for all zones.

Infiltration Parameters

The AccuRate software includes zone-dependant default values for infiltration. Many studies have found considerable differences between the default values and the measured infiltration of standard and research buildings (Stein and Meier 2000; Stazi, Di Perna et al. 2007). In current Australian HER software (2011), infiltration is determined using Equation 3. The A and B inputs require calculation.

The infiltration rates of all test building zones must be measured using a suitable method. There are two principal methods for measuring infiltration, namely tracer gas analysis and blower door tests. Both of these methods provide appropriate resultant data to calculate actual infiltration rates for each zone. The default values are to be changed to the measured and calculated values for the A and B inputs for each zone of the test building.

Equation 3 - Infiltration Formula Used by the AccuRate HER Software

Infiltration in Air Changes per Hour (ACH)
Inf. = A + B*v

Where:
A = Infiltration Constant (ACH)
B = Increased effect based on wind speed (ACH)
V = wind speed in m/s multiplied by a terrain factor

(Delsante 2006)

Care must be taken when consulting software developers, as some programs include additional default infiltration values based on external wall assemblages. These values will require negation prior to the building simulation.

6.2.4 The HER Software Simulations

Once the measured climate file and the amended scratch file for the test building are completed, all inputs should be further thoroughly reviewed in consultation with the software developers, to ensure all values are true representations of the as-built test building. Thermal simulations using the HER software can then commence.

If multiple simulations are run for the purpose of analysing the impact of different input parameters, the output files from each simulation run should be saved using distinct and easily recognisable file names, so that confusion and overwriting errors are minimised. The output files from each simulation may include: an energy report, a summary report and a zone temperature report.

The energy report provides the calculated energy required to maintain a particular temperature bandwidth, within conditioned zones of the simulated building, as shown in Figure 23. The report lists the projected energy for each hour of an annual thermal simulation cycle. The data in this report will depend on the operational mode of the test building.

If the test building was operated in free-running mode, for envelope empirical validation purposes, this report should have a zero energy result. If any energy values are shown in this report, some inputs within the scratch file are not correct and will require amendment. Whereas, if the test building was simulated in a continuous or variably conditioned mode, the times of energy use, for each zone and each day, should correspond with the test building operational parameters.

```
                                                  energy.txt
Total number of conditioned zones =   1

Month Day Hour      ----      Test cell---
                    Heat    CoolS    CoolL
    1   1    0       0.0      0.0      0.0
    1   1    1       0.0      0.0      0.0
    1   1    2       0.0      0.0      0.0
    1   1    3       0.0      0.0      0.0
    1   1    4       0.0      0.0      0.0
```

Figure 23 – Energy.txt AccuRate Output file

Similar to the energy report, the energy summary report collates the energy projections for the conditioned zones of the modelled test cell (Figure 24). This report provides a daily and monthly summary of the calculated heating and cooling energy requirements of the conditioned zones of the simulated building. Normally, the software utilises this data to determine a House Energy Star Rating. However, this report may not be of any use to the empirical validation, except as a final checking mechanism to ensure that all thermostat and heat load input values used were correct.

```
                              output.txt

              *************************************************
              *                  AccuRate Engine              *
              *                                               *
              *            Version 2.13 October 2006          *
              *                                               *
              *     Developed with funding support from the   *
              * Commonwealth, State and Territory Governments,*
              *  through the Energy Management Task Force of  *
              *  the Australian and New Zealand Minerals and  *
              *                  Energy Council               *
              *************************************************

 Jobname:
 Weather data filename: C:\Program Files\AccuRate aust\WEATHER\CLIMAT23.txt

 Window glass data filename: C:\Program Files\AccuRate aust\LIB\ALL_WINDOWS.BWC

 Date:   19/10/09

Ground floor area =    30.00 m2

         JAN 2003     DAY   1

 DAY HEATING ENERGY (MJ):       Test cell       0.0

 PEAK HEATING DEMAND (kW):       Test cell       0.0

 DAY SENSIBLE COOLING ENERGY (MJ):       Test cell       0.0
   DAY LATENT COOLING ENERGY (MJ):       Test cell       0.0

 PEAK SENSIBLE COOLING DEMAND (kW):       Test cell      0.0
   PEAK LATENT COOLING DEMAND (kW):       Test cell      0.0

         JAN 2003     DAY   2

 DAY HEATING ENERGY (MJ):       Test cell       0.0

 PEAK HEATING DEMAND (kW):       Test cell       0.0

 DAY SENSIBLE COOLING ENERGY (MJ):       Test cell       0.0
   DAY LATENT COOLING ENERGY (MJ):       Test cell       0.0

 PEAK SENSIBLE COOLING DEMAND (kW):       Test cell      0.0
   PEAK LATENT COOLING DEMAND (kW):       Test cell      0.0
```

Figure 24 – Output.txt AccuRate Output file

The AccuRate software calculates the simulated temperature of each building zone. Once the hourly temperatures are known, the energy required to condition the space can be calculated. For an empirical validation project, this is the most important file, as all other output reports from the AccuRate software are derived from this report. Figure 25 shows the temperature report for the Launceston test cells, showing the calculated hourly temperature in each zone. The data in this report is compared to measured data as part of the empirical validation process.

```
            2009-10-19 Test Cell 2 unbridged & bridged_Cell 2 - Bridged.tem
-41.4 CLIMAT23.txt
 Total number of zones =   3

 Month Day Hour Outdoor       Test cell       Roof Space       Sub Floor
     1   1    0    17.2            17.4             16.9            17.9
     1   1    1    16.9            17.4             17.0            17.8
     1   1    2    16.4            17.4             16.8            17.7
     1   1    3    15.7            16.8             16.4            17.5
     1   1    4    15.4            16.7             16.0            17.4
     1   1    5    15.1            16.4             15.6            17.2
     1   1    6    15.4            16.2             15.5            17.1
     1   1    7    17.2            16.8             15.9            17.2
     1   1    8    20.8            19.1             17.4            17.7
     1   1    9    19.3            19.0             18.7            17.9
     1   1   10    19.4            19.1             19.0            18.1
     1   1   11    20.0            19.5             19.4            18.3
     1   1   12    22.5            21.2             20.3            18.8
     1   1   13    25.1            22.8             22.0            19.4
```

Figure 25 – AccuRate temperature.tem Report

Normally the HER software produces a House Energy Star Rating report for regulatory purposes. This report is not of significance for the envelope and/or HVAC empirical validation process.

7 Comparing Simulated and Measured (or Empirical) Data

The environmental measurement and the detailed thermal simulation of the test building will produce two data sets: a simulation data set and a measured or empirical data set. Table 10 shows the type, specific environmental parameters and format of these data sets.

Table 9: Description of the Empirical Validation Data

Data Type	Parameter	Format
Measured Data	- Temperatures from test building - Site Climate data converted into TMY text format	Numerical format, stored in database. Suitable for comma separated values output.
Simulated Data	- Temperatures predicted by the HER software - Energy requirements predicted by the HER software	Text file. Suitable for exporting into an appropriate database software tool. Text file. Suitable for exporting into an appropriate database software tool.

Following are the specific objectives of analysing the data gathered, and a discussion of the various methods of analysis that may be used.

The primary objectives for analysing the data are:

- to compare the measured and simulated time series data; and
- to identify which of the built and environmental inputs contributed significantly to the observed differences (if any) between the measured and simulated data sets.

The first objective can be achieved by visually examining time series graphs. As the research may collect a considerable amount of data, viewing superimposed time series graphs may be the most suitable method to determine differences in absolute values at any one time, as well as trends and patterns over certain periods.

The second objective of the analysis aims to determine if the climate or heat transfer algorithms within the software require improvement (Agami Reddy 2006). Statistical analysis is a useful tool for this purpose.

7.1 Graphical Analysis

This type of analysis makes use of superimposed time series graphs and allows for quick visual comparisons of the measured and simulated data sets as shown in Figure 26 (Judkoff, Wortman et al. 1983; Ahmad and Szokolay 1993; Clarke, Strachan et al. 1994; Lomas, Eppel et al. 1994; Meldem and Winklemann 1995; Guyon, Moinard et al. 1999; Moinard and Guyon 1999; Neymark, Girault et al. 2005; Agami Reddy 2006). As the data sets being analysed are either temperature or other environmental parameters, similarity in wave pattern and trends between the two data sets is a good indicator of the HER software's capacity to perform a meaningful thermal simulation (Dewsbury 2009; Dewsbury, Soriano et al. 2009). If the values are different but the pattern is similar, it could indicate a sensor calibration fault, or a fault in the software's algorithm.

This form of graphical analysis is also useful during the data cleaning stage, as it allows for the prompt detection of outlying data and their subsequent rectification. This form of analysis may be used to examine differences between:

- measured on site climate data versus TMY climate data;
- HER simulation types; and
- measured and simulated zone temperatures.

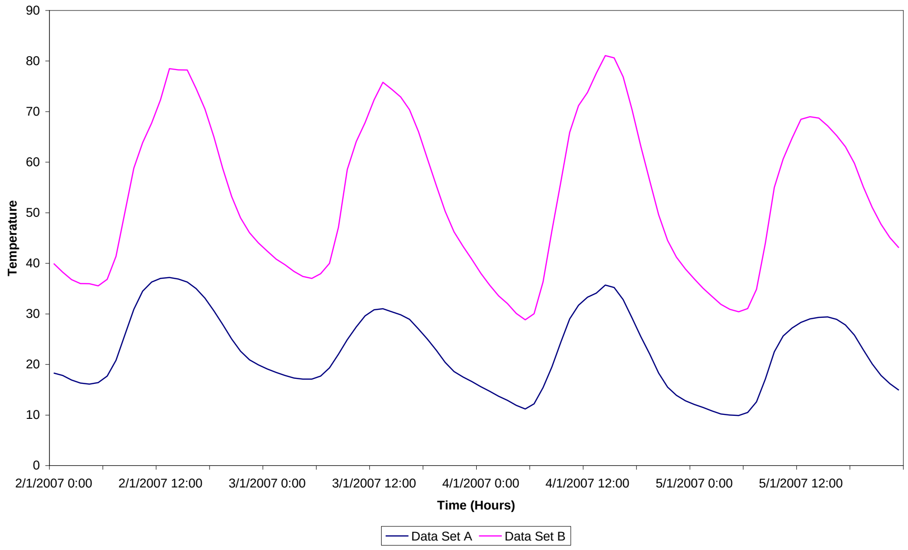

Figure 26 – Time-series based graphical analysis

7.2 Statistical Analysis

The linear graphical analysis discussed above is a simple method of detecting differences between data sets. However, this form of analysis only allows for small groups of univariate data to be compared visually. Further investigation requires a greater understanding of the difference between the measured and simulated data and the analysis of the interaction or non-interaction between the data sets (Palomo, Marco et al. 1991; Palomo del Barrio and Guyon 2002). Previous research projects have often referred to differences in mean averages (Lomas, Eppel et al. 1994; Travesi, Knabe et al. 2001) which is not suitable for this type of research (Dewsbury 2011). The primary purpose of the HER software is to calculate the amount of energy that would be required to maintain human comfort within prescribed habitation conditions (ABCB 2006; NatHERS 2009; NatHERS 2009). For many locations in Australia, the need for heating and/or cooling only occurs at the peaks or troughs in the daily temperature cycle. In this context the average temperature can misinform the capacity of the software.

In comparing time series data with similar patterns and trends, the error is the difference between the measured and simulated values at any particular time.

The error is normally referred to as the ‘residual’ value. The residual value is the portion of the validation data that cannot be explained by the model. Residual values are obtained by subtracting the simulated temperature from the measured temperature, as in Equation 4.

Equation 4 – Establishing Residual Values for a Test Cell Zone

$T_r = T_o - T_s$

Where:
T_r = Residual Value C^0
T_o = Measured Temperature C^0
T_s = Simulated Temperature C^0

A positive residual value indicates that the HER software has under-predicted the zone temperature, whereas, a negative residual value indicates that the HER software has over-predicted the zone temperature.

The exposition of data relationships through statistical analysis can uncover valuable insights regarding the meaning of the data and direct further statistical or other forms of research (Palomo, Marco et al. 1991; del Mar Izquierdo, Lefebvre et al. 1995; Palomo del Barrio and Guyon 2002; Ahmad and Culp 2006; Dewsbury 2009; Dewsbury, Soriano et al. 2009). Compared to linear graphical analysis, univariate and multivariate statistical analysis tools such as histograms, time series plots and scatter plots can provide a more profound understanding of the source of differences between measured and simulated temperature values.

Table 10 lists the statistical tools and their application in analysing empirical validation data.

Table 10: Univariate and Multivariate Analysis Tasks Completed

Statistical Analysis Type	Elements Compared	Purpose
Scatter-plot diagram - Measured / Simulated	All test building zones	To show correlation between the calculated and measured temperatures
Residual Histogram Show	All test building zones	To show zone residual values
Residual Time Series Plot	All test building zones	To show zone residual values based

		on time
Scatter-plot diagram – Zone A residual / Zone B residual	Adjoining test Building zones	To show correlation between zone residual values
Scatter-plot diagram – Zone residual / Climate variable	All test building zones	To show correlation and/or sensitivity between zone residual values and measured climate variables

7.2.1 Histograms

Residual histograms provide an understanding of the frequency distribution of the differences between simulated and measured data (Anderson 1989; Rees 1989; Ramsey and Schafer 2002). As shown in Figure 27, the histogram allows for the assessment of normality, skewness or kurtosis of temperature residuals (Mansour, Jutten et al. 1998).

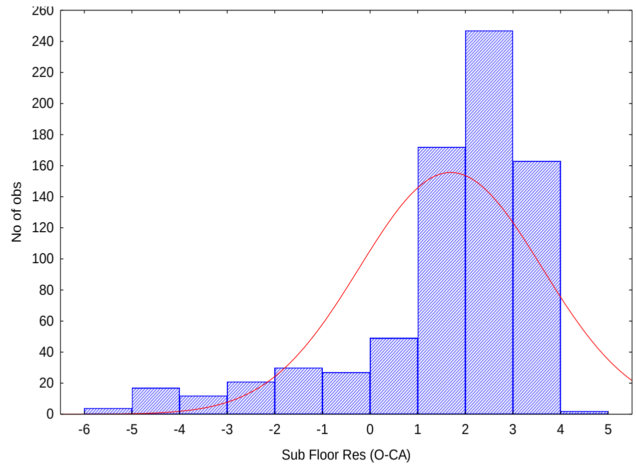

Figure 27 – Example of residual histogram analysis

7.2.2 Residual Time series Analysis

The time series plots of residuals show data trends over short and long time periods as shown in Figure 28 (Clarke, Strachan et al. 1994; Jimenez and Madsen 2008; Jimenez, Madsen et al. 2008). A greater understanding of the residual values can be gained through the observation of patterns relative to climatic inputs. In cases where the trend and/or pattern behaves in an unexpected way, this can be compared to the residual time series graphs of adjoining zones in the same test building, or other nearby test buildings.

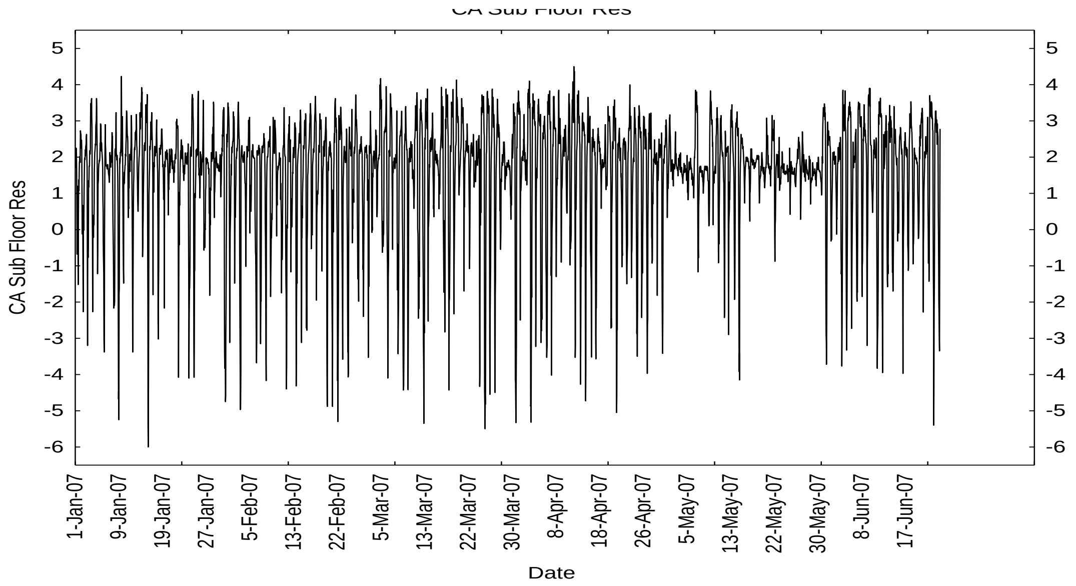

Figure 28 – Example of residual time series analysis

7.2.3 Scatter-plot Diagrams

The previous forms of analysis are univariate, that is, involve a single variable. The scatter-plot diagram, as shown in Figures 29 and 30, allows for both preliminary and in-depth bivariate analysis methods to examine correlations between two variables (Palomo, Marco et al. 1991; Agami Reddy 2006).

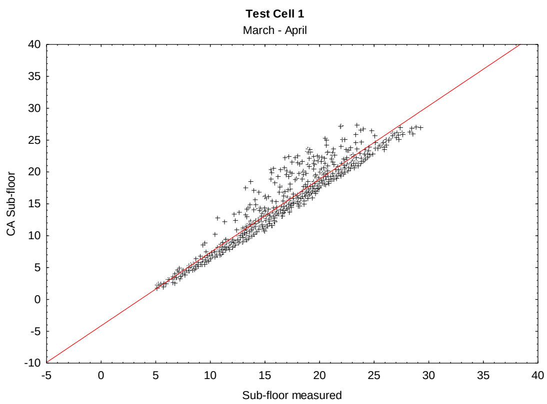

Figure 29 – Example of scatter-plot diagram illustrating correlations between measured and simulated zone temperature

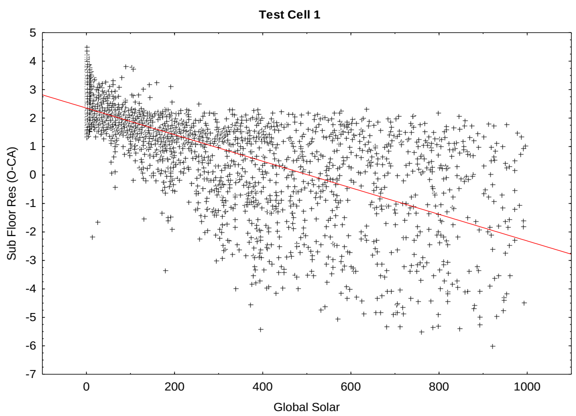

Figure 30 – Example of scatter-plot diagram illustrating correlations between measured zone temperature and global solar radiation

7.2.4 Other Methods of Analysis

The methods listed above are by no means the only useful forms of analysis for empirical validation studies. They may be considered as basic, but can provide a starting point for more complex analysis. Residual regression analysis allows for a deeper drilling down of correlations between variables, which can lead to a more informed understanding of algorithms that may require calibration. Williamson (1995) and ASHRAE have published methods of data analysis for empirical validation.

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