Chapter 3 Verification And Testing Of New Simplified Thermal Design Tool

Extensive testing and validation of design tools is of paramount importance. It provides valuable information regarding the accuracy and capability of the tool. It further serves to increase the confidence and credibility in the use of the tool. Professional designers are unlikely to accept or widely employ tools that they are not confident in. An empirical validation study was consequently performed on the new simplified building thermal design tool. This chapter presents the results of this study.

NOMENCLATURE

ach : Air changes per hour

T : Absolute temperature, K

V : Velocity, m/s

Subscripts

i : Inside

o : Outside

3.1 INTRODUCTION

Validation and testing should form an integral part in the development of new design tools. It ensures that the underlying models and assumptions are error free and valid [1]. It further serves to substantiate that the tool produces satisfactorily accurate answers within its scope of application [2]. This is especially important for establishing confidence and credibility in the use of the tool. These are essential characteristics if the tool is to be applied to real-world design problems.

An empirical validation study was performed to ascertain the validity of the new thermal design tool. This required that the tool yield results that are within an acceptable accuracy range for a convincing number of case studies. One hundred and three verification studies from fifty-six different building zones were performed for this purpose.

3.2 VERIFICATION AND VALIDATION OF DESIGN TOOLS

Verification and validation of building analysis tools is generally neglected or only performed as an afterthought [1,3]. Lack of a well-defined methodology and difficulties in obtaining good data sets are often stated as the reasons for this [4]. Shortage of funds, time and published information also contributes to this problem [5]. Verification is however essential, especially since critical assumptions are made during the development of these tools. Some of these assumptions can only be proved valid by extensive verification.

Validation of design tools can be attempted by using either one or more of the following three techniques [3]:

- *analytical verification,* in which the model is tested and compared to exact solutions;
- *inter-model comparisons*, where predictions of different tools are compared;
- *empirical validation,* where the tool's predictions are compared to measurements taken on real buildings.

Irving [3] and Bowman et al [6] describe the advantages and disadvantages of these methods. Of these, empirical validation has the greatest potential. It provides a good indication of the validity of the tool compared to the physical reality. It is unfortunately also fraught with difficulties and uncertainties [6].

3.3 VERIFICATION OF THE NEW THERMAL DESIGN TOOL

The new design tool developed during this study uses a six node electrical analogue model developed by Van Heerden [7,8]. This model has been extensively tested. The input requirements for the new design tool have however been significantly simplified since it is to be used as a preliminary design tool. The data used by Van Heerden was consequently used again to test the validity of the simplified design tool.

Two tests were performed. The first analysis consisted of testing the simplified building shell in combination with the use of default load and ventilation profiles. During this test the internal load (a Watt per square metre value) was applied from 08h00 to 17h00. This load was taken to be 40 % convective and 60 % radiative. The same model used by Richards [1] and Van Heerden [7] was used to calculate infiltration, where

$$\text{ach} = 1.5(0.215 + .042V + .013|T_o - T_i|) \ . \quad (3.1)$$

No natural or mechanical ventilation was included in this study.

Indoor loads and ventilation do however have a direct influence on the indoor temperature node [9]. To isolate the effect of the simplified building shell a second validation study was performed. For this study the indoor loads, infiltration and ventilation were taken to be the same as used measured.

Both studies were performed using the actual measured weather data instead of the default design data. This was necessary since measurements were not taken under design day conditions. This does not compromise the validity of the study. It can be assumed that if the tool is valid for a range of different climatic data, it will also be valid for the design weather data.

The thermal properties of the building materials used in the analyses are presented in Appendix A. These properties, as used by Van Heerden, were obtained from tables available in the literature [10,11], and were thus not measured. Measuring these properties could have eliminated some of the inherent uncertainties of this validation study. This information is however usually available to designers and consequently used by them. These are also the default values used by the new thermal design tool.

Although most of the building zones formed part of multi-zoned buildings, only fourteen studies are listed as multi-zone experiments. The indoor air temperatures in these fourteen zones differed considerably from the air temperatures in adjacent zones. In all other cases, the assumption of similar temperatures in the zone under consideration and adjacent zones was acceptable. This is one of the primary assumptions used for the design tool.

These multi-zoned buildings fall out of the scope of the simplified design tool, and were therefore not included in the global evaluation of the tool. They are however included for completeness of this study and to determine the extent of this limitation.

3.4 DESCRIPTION OF THE 56 BUILDING ZONES

Validation studies were performed using 56 different building zones obtained from various types of buildings. To extend the study, some of these zones were modified by adding insulation, changing exterior colours, opening and closing windows, generating heat, and so forth. This section only describes the basic building zones, while the following section describes the modifications made to arrive at a total of 103 case studies.

Experim 1 ***(Study 1, -5, -9, -13, -17, -21, -25)*****, Experim 2** ***(Study 2, -6, -10, -14, -18, -22)*****, Experim 3** ***(Study 3, -7, -11, -15, -19)*****, and Experim 4** ***(Study 4, -8, -12, -16, -20, -23, -24)*****:** These single-zone experimental huts are all situated in close proximity and it can be assumed that they are subjected to approximately the same outdoor environment. The buildings are surrounded by a few other low-rise buildings on a fairly open test terrain of the National Building Research Institute in Pretoria. The construction of the huts is nearly identical except for the roofs. The first two huts have identical corrugated iron roofs, the third hut has a tiled roof, and the fourth hut has a high-mass concrete slab as a roof. Various studies were conducted in the buildings by modifying the construction, exterior colour and window operation. The buildings were not furnished.

Bedroom 1 ***(study26 to study31)*****:** This furnished room forms part of a townhouse in a residential area in Centurion. The adjacent rooms are a study and a dining room. The door leading into the rest of the building was left open while measurements were taken. The room was not occupied.

Bedroom 2 ***(study32)*****:** This furnished room forms part of a house in a residential area in Wingate Park, Pretoria. The adjacent rooms are a living area and another bedroom. The exposed facade is shaded by a big tree. The door was closed and the room was unoccupied during the validation study.

Bedroom 3 ***(study33)*****:** This furnished room is situated on the first floor of a house in a residential area in Moreleta Park, Pretoria. The adjacent rooms are two bathrooms. The door was closed and the room was unoccupied during the validation study.

Bathroom ***(study34)*****:** This room forms part of a house in a residential area in Faerie Glen, Pretoria. The adjacent rooms are a bedroom and living area. The door was closed and the room was unoccupied during the validation study. Plants cover the exposed southern wall. Large mirrors are attached to some indoor surfaces.

Dormit 1 ***(study35 to study37)*** **and Dormit 2** ***(study38 to study40)*****:** These pre-cast concrete units form part of an arrangement consisting of twenty units. The buildings are situated in the Negev desert in Israel. Indoor partition walls divide the units into four smaller zones. Indoor temperature measurements are however representative of the whole unit. The large windows are fitted with externally adjustable PVC louvers acting as a shading device. During monitoring the units were unoccupied.

Prefab ***(study41 to study43)*****:** This low-mass prefabricated unit is situated in an open area in the Negev desert in Israel. The building consists of two similar zones, separated by a dividing wall without a door. Only one of the zones was monitored. During monitoring the units were unoccupied. The building is placed on steel beams approximately 20 cm above the ground. Windows are fitted with external shading devices consisting of adjustable PVC louvers.

Garage ***(study44 and study45)*****:** This empty garage is attached to a townhouse similar to the description given for Bedroom 1. No ceiling is provided and the southern wall consists mainly of a steel door.

Shop ***(study46 to study48)*****:** The vacant shop is located in a single storied shopping mall in the low-rise city centre of Centurion. Exposed glazing is well protected by building eaves. The interior walls are shared by an adjoining restaurant and a loading zone.

School 1 ***(study49 and study50)*****:** The monitored classroom is on the third floor of a school situated in a residential area in Menlo Park, Pretoria. The adjacent rooms are another classroom and a storeroom. Measurements were taken during the holidays and the rooms were therefore not occupied. The room is furnished with school desks and chairs.

School 2 ***(study51)*****:** The walls of this single-storied classroom are made from prefabricated asbestos cement panels. An adjacent classroom was occupied during validation but the room under consideration was used to store various pieces of furniture. The school is situated in a residential area in The Willows, Pretoria.

Store 1 ***(study52)*****:** The storeroom is attached to another storeroom and a classroom at the same school described as School 2. Clothing was stored on shelves against the walls and on parts of the floor.

Store 2 ***(study53)*****:** This single-zone corrugated iron store is situated on an open area in the industrial area of the rural town of Volksrust. The store was vacant and closed during the validation study. Ventilation was achieved by means of ventilation openings in the roof.

Studio ***(study54)*****:** The southern and western external walls of this studio consist of very large glazing areas allowing solar penetration. Walls are fairly high and a ventilation opening is located in the roof. Interior partition walls form a smaller zone inside the main building. The studio is used as a showroom for furniture and is situated in a residential area in Brooklyn, Pretoria. Validation was done on a Sunday when the building was closed.

Church ***(study55)*****:** The church was designed with the aim to achieve sound human comfort and hence incorporates various techniques enhancing natural ventilation. The main zone of the church can be considered as a single zone with fairly high walls. It is situated in a residential area in Arcadia, Pretoria, and is surrounded by various high trees. Monitoring was done on a Sunday and consequently includes church services in the morning and in the evening.

Factory ***(study56)*****:** The building is situated on an exposed terrain in Groenkloof, Pretoria, with no surrounding buildings. It is naturally ventilated by means of roll doors at ground level and roof-mounted ventilators. The factory was used for the assembly of mechanical components with no significant heat generation during monitoring. At least half of the roll doors were kept open during the day. The south wall is a partition between the zone under consideration and another factory.

Office 1 ***(study57 and study58)*****:** This office is on the second floor of a naturally ventilated office block on the grounds of the Council for Scientific and Industrial Research in Pretoria. The building is situated on an open terrain but is sheltered by other buildings. High-mass beams are located in the roof. The office was vacant during monitoring.

Office 2 ***(study59)*****, Office 3** ***(study60 and study61)*** **and Office 4** ***(study62)*****:** These three adjacent offices are on the first floor of the air-conditioned G H Marais building in the city centre of Pretoria. Office 2 faces east, Office 3 is on the corner of the building facing north-east, and Office 4 faces north. The floors of Office 2 and Office 4 are exposed to an open parking area, while Office 3 is above the air-conditioning plant room. The offices were furnished but vacant, and closed during monitoring. The air-conditioning was also inoperative for validation purposes.

Office 5 ***(study63)*****:** This office is in the naturally ventilated Central Governments Office building in the city centre of Pretoria. The office was occupied during the day.

Office 6 ***(study64)*****:** This office is on the 22^{nd} and top floor of the Liberty Life building in the city centre of Pretoria. The office was occupied during the day but air-conditioning equipment was inoperative.

Office 7 ***(study65)*****:** This office is on the 16th floor of the Poyntons building in the city centre of Pretoria. The office was furnished but vacant and closed during monitoring. Air-conditioning equipment was inoperative.

Office 8 ***(study66)*****:** This office is on the fourth floor of the UNISA building near the city centre of Pretoria. The office was furnished but vacant and closed during monitoring. Air-conditioning equipment was in operation.

Office 9 ***(study67)*** **and Office 10** ***(study68)*****:** These offices are on the 9th floor of the air-conditioned Engineering Tower Block on the campus of the University of Pretoria. The offices were furnished but vacant and closed during monitoring. Air-conditioning equipment was inoperative.

Office 11 ***(study69)*** **and Office 12** ***(study70)*****:** These offices are on the second floor of the J G Strijdom building on the campus of the University of Pretoria. Office 11 was empty and Office 12 was furnished but vacant and closed during monitoring. Air-conditioning equipment was inoperative.

Lightweight ***(study71 and study73)*** **and Heavyweight** ***(study72 and study 74)*****:** These are two buildings at the Desert Architecture Unit of the Jacob Blaustein Institute for Desert Architecture at the Ben Gurion University in Israel. The lightweight building is a prefabricated building. The heavyweight building is a demonstration building of heavy construction.

The next 23 studies were conducted at animal laboratories on the Onderstepoort campus of the University of Pretoria. Three separate facilities on the campus were included in the case studies namely, the conventional laboratory-animal facility, the infectious-diseases facility and the metabolic facility.

Room 1-79 ***(study79)*****, Room 1-80** ***(study80)*****, Room 1-82** ***(study81)*****, Room 1-83** ***(study82)*****, Room 1-90** ***(study76)*****, Room 1-91** ***(study75)*****, Room 1-93** ***(study78)*****, Room 1-94** ***(study77)*****:** These rooms housed cats, dogs and rodents and were supplied with two constant volume direct expansion units. The supply airflow rate and temperature were measured and entered as the ventilation data for these rooms.

Room 1-122 and 1-123, Room 1-125 to 1-127, Room 1-141 to 1-143 and Room 1-145 ***(study83 to study91)*****:** These are the infectious-diseases laboratories. The laboratories were all supplied with air from an evaporative cooler. The temperature after the evaporative cooler and the flow rate to each room was again measured and used in the program as input.

Room 1-7 ***(study93 and study95)*****, Room 1-9** ***(study92 and study94)*****:** The metabolic facilities were supplied with fresh air, and conditioning of the air was performed by ceiling-mounted cassette units. Each room was also equipped with a heater bank.

Sasol E ***(study96)*****, Sasol F** ***(study97)*****, Sasol N** ***(study98 and study99)*****, Sasol S** ***(study100 and study101)*****, Sasol W** ***(study102 and study103)*****:** The zones make up an administrative building of SASOL II located in Secunda. These specific zones were only serviced with mechanical ventilation.

It is quite clear that a wide range of building types and construction techniques are covered. A validation study of these buildings should thus help to achieve a high level of confidence in the applicability of the design tool in practice. The following section describes the 103 validation studies carried out in these buildings.

3.5 DESCRIPTION OF THE 103 VALIDATION STUDIES

A summary of the 103 validation studies is provided in Appendix B. The building zone names, location and date of each experimental study, and additional information are listed. Detailed information of each zone can be obtained on the attached disk. The building zone names correspond to the descriptions given in the previous section. The following discussion describes the modifications to obtain 103 case studies. Studies not described here were handled as described on the attached magnetic disk.

Forty-four studies were monitored with open windows. The natural ventilation rates in these studies are determined by the procedure given in ASHRAE [10], except for studies 71 to 74. The model presented by Rousseau [12] was used for these studies. The infiltration rates in the other studies are determined by means of equation 3.1. Six studies are listed as YN, indicating that the windows were opened and closed during monitoring. The window operation of these six studies is discussed later in this section.

The heat generation column lists forty-seven studies that included interior heat generation by means of small domestic heaters. Solar penetration occurred in most of the 103 studies and is thus not listed here under heat generation.

Twenty-five validation studies were performed on the experimental huts. Studies 1 to 4 were carried out in the huts without any change to the construction. In studies 5 to 8 the floors of the four huts were insulated with 25 mm thick expanded polystyrene. Studies 9 to 12 were again carried out in the buildings without any change to the construction, but the windows were open as opposed to the closed windows in studies 1 to 8.

In studies 13 to 16 the windows were again open, but the floors were insulated with 25mm thick expanded polystyrene. The floors were not insulated in studies 17 to 20, but the ceiling was insulated with 25mm thick expanded polystyrene. No floor or ceiling insulation was incorporated in studies 21 to 25, only the exterior colours of the buildings were modified. For studies 21 and 23 the roofs were painted black and the walls painted dark brown. The colour of the huts in studies 22, 24 and 25 was unchanged from the descriptions on the magnetic disk.

The validation studies carried out in the Negev Desert were a joint project between the University of Pretoria and the Desert Architecture Unit of the Jacob Blaustein Institute of Desert Research [13]. Primarily, the twelve studies differ only in window operation. For studies 35, 38 and 41, the windows were closed for the whole duration of monitoring. The windows were however open for the whole period in studies 37, 40, 43, and 71 to 73. For studies 36,39, 42 and 74 the windows were opened during the night from 20h00 to 08h00 and closed for the rest of the period.

Study 56 involving the factory also employs open and closed window operation. Although the building did not have windows that can open, some of the doors were kept open during the day between 07h00 to 19h00. Ventilation was achieved by means of these open doors and roof-mounted ventilators.

3.6 EVALUATION OF THE PROPOSED DESIGN TOOL

It is impractical to consider each case study individually when validating the new design tool. Criteria therefore need to be established to facilitate the evaluation of the tool. In this section several global parameters are defined (following the approach of Richards [1] and Van

Heerden [7]). This enables us to evaluate all the data at once, and to make comparisons between different models.

Five global thermal parameters are defined, i.e. the mean-, maximum- and minimum indoor temperature, the indoor temperature swing, and the phase shift between the measured and predicted indoor air temperatures. The mean indoor air temperature is simply the mean of the 24-hourly values. Maximum and minimum indoor temperatures are the comparison between the predicted maxima and minima relative to the measured values. The temperature swing is determined by taking the difference between the maximum and minimum indoor temperatures.

In this study the phase shift is determined by first calculating the difference in time between the measured and predicted indoor maxima. Secondly, the difference in time between the measured and predicted indoor minima are determined. The phase shift is then the mean of these two values. The phase shift lags when the difference is negative and leads if positive.

Figures 3.1 to 3.10 show the results of the global parameters for both tests. The correlation coefficients for each of these parameters are also presented on the respective figures. The correlation coefficients are a good indicator of how closely the predicted values relate to the measured data. However it does not give any idea of how that data is dispersed or the size of the error band. Average error and standard deviation for the mean temperature, temperature swings and phase shift were therefore also calculated. These results are provided in table 3.1

	Means		**Swing**		**Phase shift**	
	Average °C	**St. dev. °C**	**Average °C**	**St. dev. °C**	**Average hours**	**St. dev. hours**
Test 1	1.5	2.9	1.1	3.6	0.7	1.4
Test 2	0.4	1.5	1.5	1.8	0.3	1.4

Table 3. 1 - Average and standard deviation for the global parameter

Although global parameters can be considered representative of the thermal response of the indoor temperature, hourly values were also compared, but in an aggregated form. Detailed comparisons are provided in Appendix C. The cumulative error distribution of the differences between the hourly measured and predicted indoor temperatures of both studies are shown in Figure 3.11.

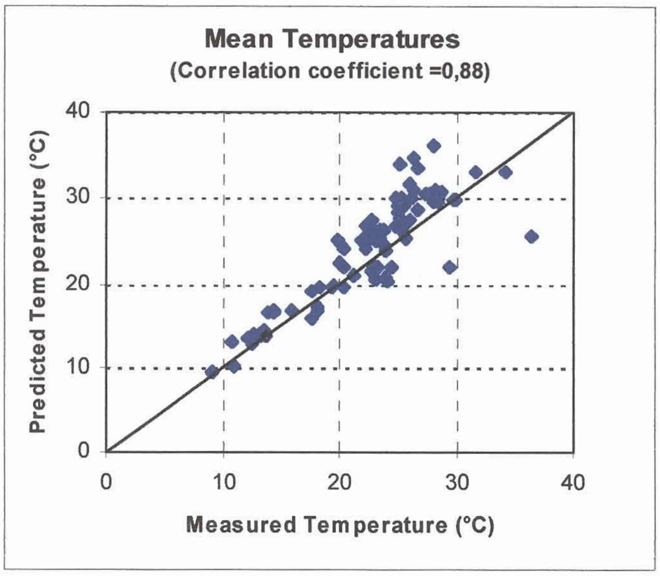

Figure 3.1 - Comparison between measured and predicted mean temperatures for Test 1.

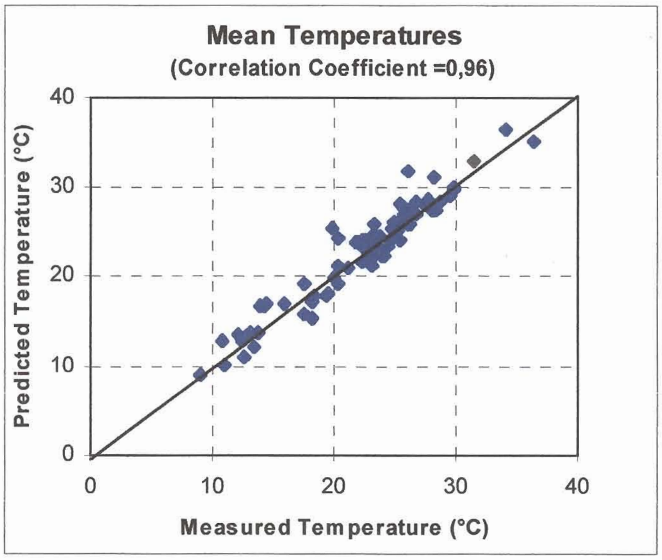

Figure 3.2 - Comparison between measured and predicted mean temperatures for Test 2.

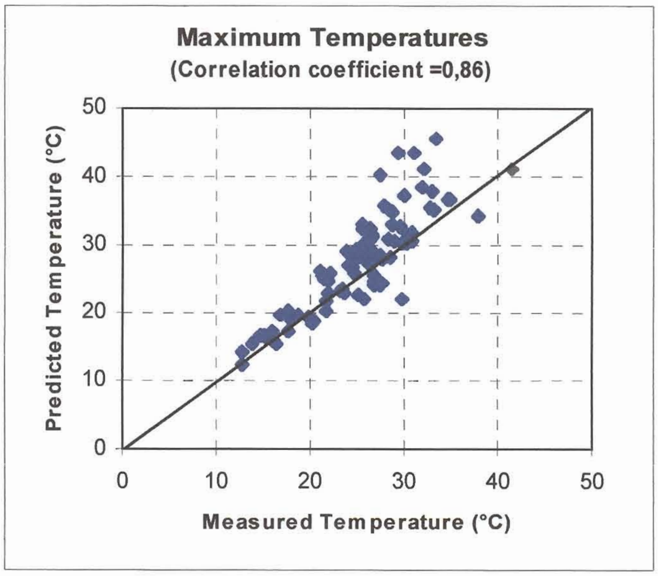

Figure 3.3 - Comparison between measured and predicted maximum temperatures for Test 1.

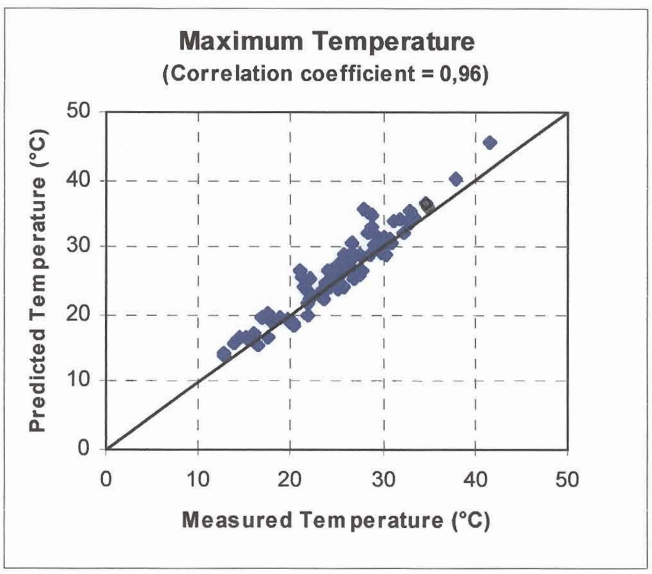

Figure 3.4 - Comparison between measured and predicted maximum temperatures for Test 2.

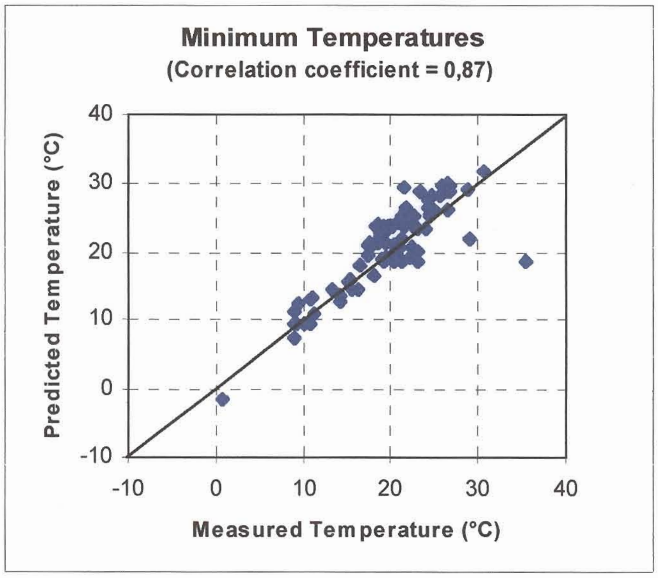

Figure 3.5 - Comparison between measured and predicted minimum temperatures for Test 1.

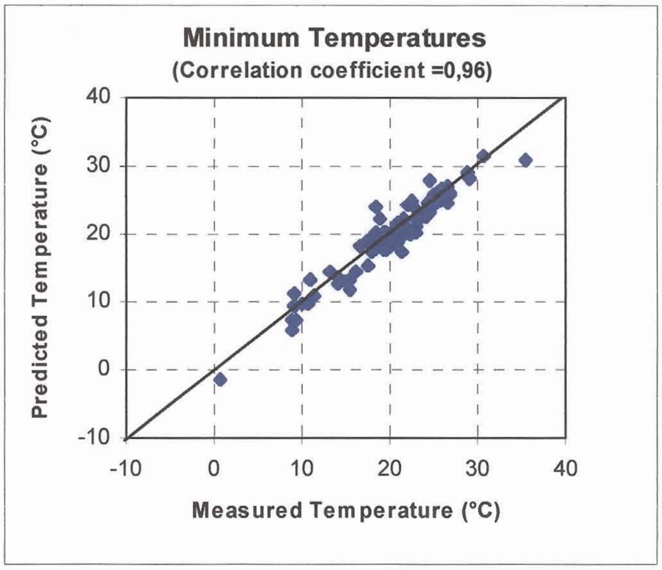

Figure 3.6 - Comparison between measured and predicted minimum temperatures for Test 2.

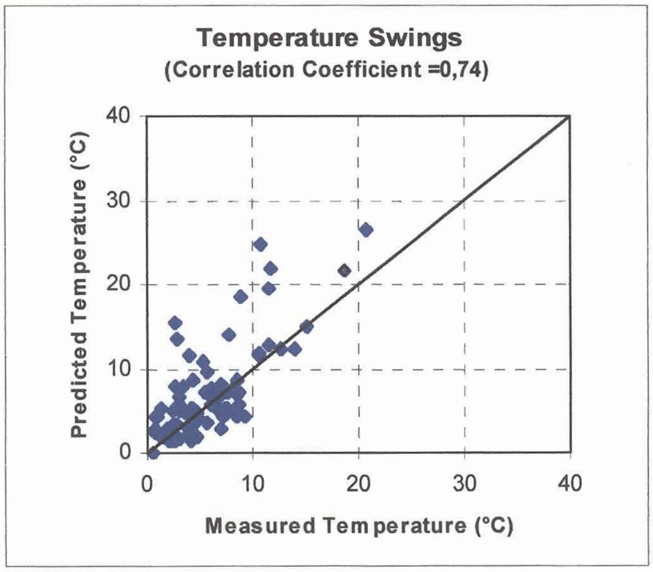

Figure 3.7 - Comparison between measured and predicted temperature swings for Test 1.

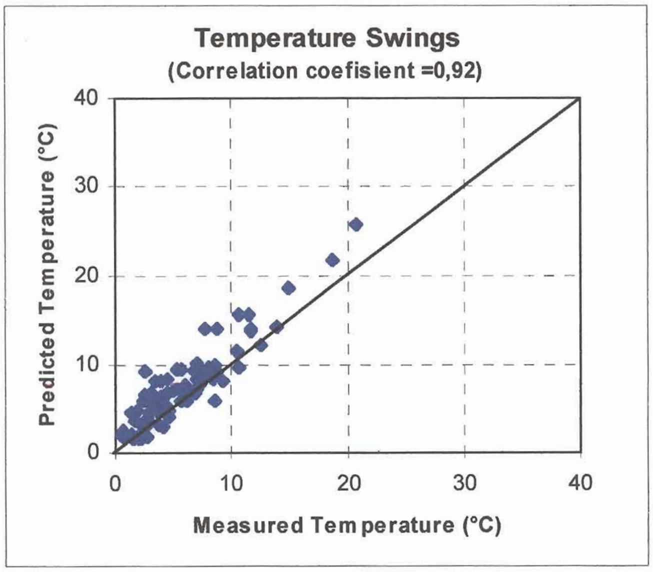

Figure 3.8 - Comparison between measured and predicted temperature swings for Test 2.

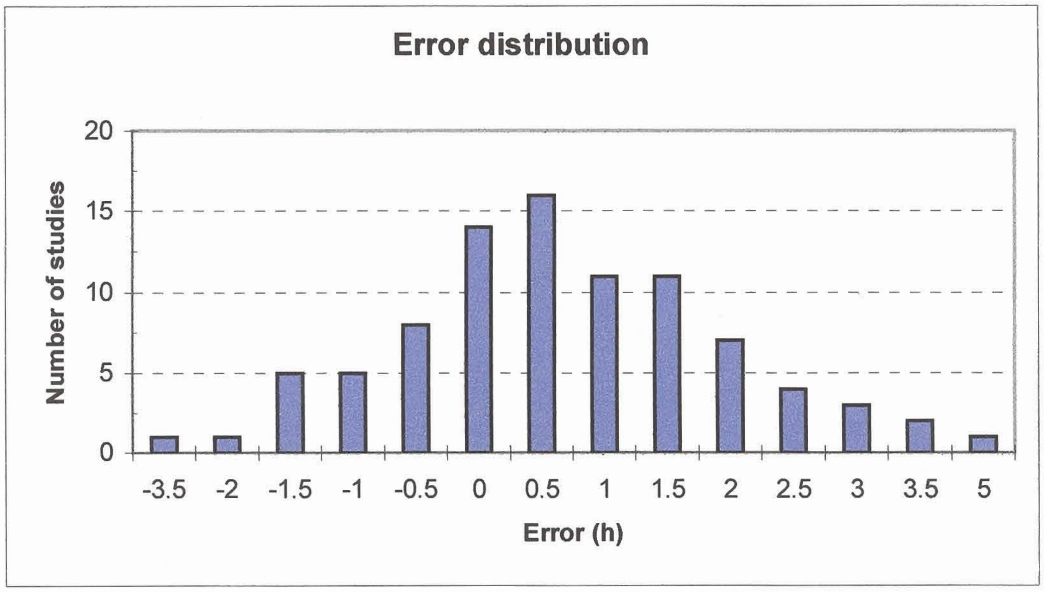

Figure 3.9 - Distribution of the indoor air temperature phase shift errors for Test 1.

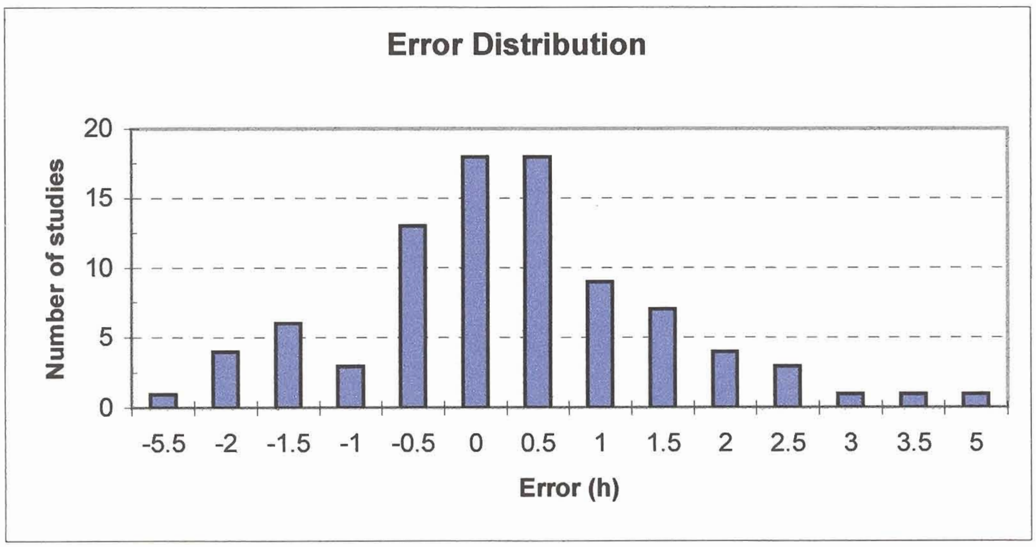

Figure 3.10 - Distribution of the indoor air temperature phase shift errors for Test 2.

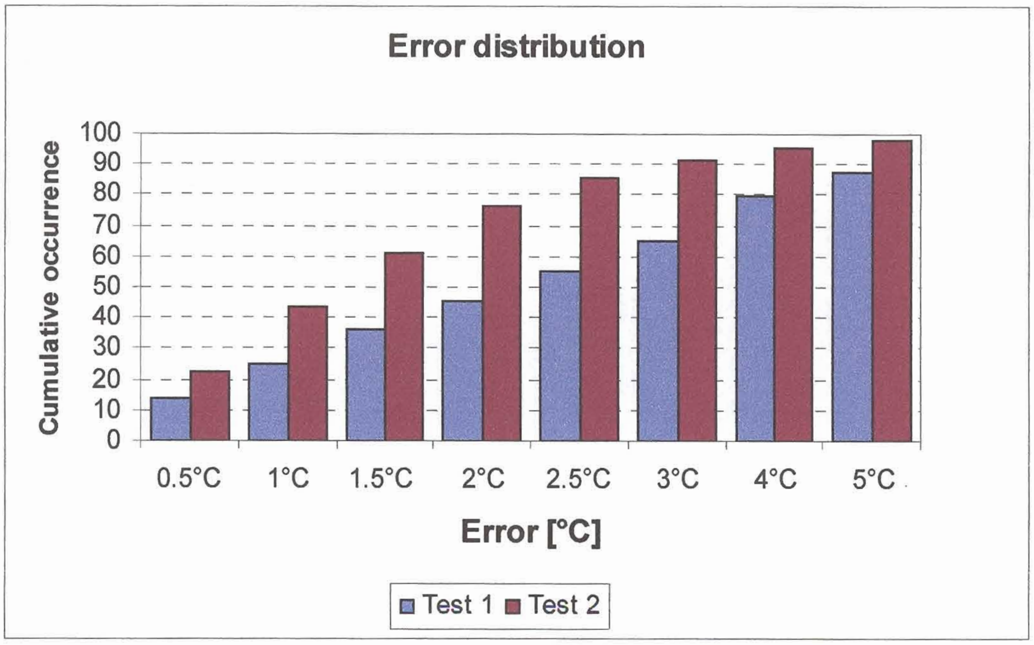

Figure 3.11 – Cumulative error distribution for the difference between hourly measured and predicted indoor air temperatures for both test cases.

It can be seen that there is a fair correlation between the mean, maximum and minimum temperatures in test 1. The temperature swing correlation however is not so good. This is to be expected since it depends on both the predicted minimum and maximum temperatures. It is therefore twice as sensitive to errors. Indoor temperatures were predicted within 3°C for 65 % of the time.

These results are quite acceptable considering the significant assumptions made for test 1. As expected, there is a marked improvement in the results of the second test. These results compare favourably with the actual data. Predicted indoor temperatures are within 2.5°C for 85 % of the time, and within 3°C for 90 % of the time. These results are exceptionally good considering that the tool was developed as a preliminary design tool. These results show that the new design tool, using the simplified building shell data, delivers satisfactory results and can thus be used with confidence.

The result of the first test seems a little disappointing at first. It should however be seen in context of the second test. In test 2, acceptable answers for a range of different ventilation and load profiles were obtained. It is thus safe to say that similar results would have been obtained if the default load and ventilation profiles, as used in test 1, were exactly the same as those of the actual buildings. The tool can therefore be used with the same confidence to evaluate the thermal performance of different building shells using the default load and ventilation values.

3.7 LIMITATIONS OF THE DESIGN TOOL

Fourteen of the case studies were identified as having multi-zone characteristics. The results of these studies were not included in the evaluation of the tool. As expected there were considerable differences between the predicted and actual temperatures. Differences in excess of 10°C were obtained for most of these studies.

This limitation is however usually only restricted to zones next to unconditioned areas such as kitchens, bathrooms and stairways. Major differences in temperatures however rarely occur. The new tool further aims to evaluate the total building shell rather than single zones. The average temperature of all the zones is therefore used. These variations must however be taken into consideration when sizing ventilation and air-conditioning equipment.

External or suspended floors are a second limitation identified. Currently the tool only makes provision for internal and ground contact floors. Seven case studies however had suspended or exterior floors. These floors were simulated as interior floors. Acceptable yet marginal results were obtained with this assumption. However, significant errors can be obtained if the climate differs significantly from the indoor air temperatures. This is a typical problem encountered in air-conditioned buildings.

3.8 CONCLUSION

The new thermal design tool was extensively tested using 103 actual building case studies. These buildings comprised of a wide range of different construction types, internal loads and ventilation requirements. Results gained from the tool using the simplified building shell were comparable to those obtained with more detailed design tools. The predicted temperatures were within 2,5°C for 85 % of the time.

It is clear that this tool can be used with confidence to evaluate and compare the performance of different building shells during the preliminary design stage. The results indicated that the tool also has the potential to be used in sizing HVAC systems. The current tool will need to be modified slightly to allow the user to provide detailed ventilation and load profiles as input. The tool will also need to address the two limitations identified during this validation.

3.9 BIBLIOGRAPHY

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