Methodology in Architectural Research

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CONTENT

PREFACE

Many people view the architectural profession as biased towards artistic and intuitive solutions, but lacking in terms of evidence-based research and rigorous scientific inquiry. Such perception is understandable in view of the fact that architecture schools generally attract fewer research grants than other scientific and technologically-driven centres of education and is often rated lowly when compared to other faculties with respect to research activities and output. In most cases, design is arguably considered and promoted by architectural fraternity as a kind of research activity. Unfortunately, many non-architectural researchers tend to be sceptical on the link between design and research activities.

Nevertheless, architectural research has increasingly become an important area of inquiry due to many factors such as the rapid advances in technology and construction methods, speed of service delivery, changing public perception on the profession, emerging issues in education and quite significantly, an ever increasing concern on the effects of physical development on man's future well being and the sustainability of the environment.

For Malaysia, the mounting demand for educators within higher learning institutions to acquire PhD degree as minimum work qualification has indirectly promoted research activities and opened new chapters for many architecture schools to now offer postgraduate programmes by research as part of continuous professional development programmes. In view of a worldwide trend in the promotion and advancement professional postgraduate degree programmes such as the likes being implemented in the United States, Germany and more recently, in Australia, the Malaysian architectural education scene will most certainly see greater awareness on the parallel roles of design and research. This is particularly true as more schools of architecture are expressing interest in setting up similar postgraduate and professional architectural centres of education. Thus, the idea of design as a research activity is not so distant a concept after all.

With this latest scenario in mind, the publication of these book chapters is deemed timely. It is a compilation of various research methods that have been adopted and employed by the respective authors. These methodologies were based on their previous research works. The main intention is to share their experience in conducting research and promote the use of appropriate research methods. On many occasions, the authors would initiate research discourse by advocating comprehensive literature review on methods used and tested by previous researchers are excellent steps towards the development and improvisation of their own generic methods of inquiry, those that would suit different types of research problems, scopes and limitations.

The editors see that the 11 chapters compiled would be the first among many series of architecture research methods that would be primed for future publication. For the current compilation, we have included methods in environmental architecture or building science, architectural behavior, architectural theory, and building services and safety. Future series may include various approaches in dealing with architectural history, conservation and heritage, building materials, construction technology, sustainable planning, urban design, project management and many others.

The chapters in this book are arranged according to common research areas. The first area is in environmental architecture and building science. Chapter 1 and 2 are basically research methods used in daylighting while chapter 3 and 4 are for solar shading towards energy efficient building design. Chapter 5 talks about computer simulation method used in forced ventilation technique made possible by solar chimney. Further, chapters 6 and 8 concern physical measurement or field study methods with respect to indoor thermal comfort research.

The next area is in building services and building safety as presented in chapter 7, one that discusses the method applied in understanding the science and problem of fire and fire escape. The final area is on architectural theory and behavior consisting of three chapters. Chapter 9 is on architecture theory while chapter 10 and 11 deliberates on two different approaches to studying architectural behaviour.

It is hoped that this compilation will be a useful research manual for new and budding researchers. This book is also intended as a reference for postgraduate and undergraduate students as well as professional in the field of architecture and allied professions who are interested in making critical inquiries in similar areas of research. The chapters in this book are useful for a wide spectrum of research activities, from simple and generic ones to very specific and complex studies. Quite importantly, it should also generate the greatest of interest from amongst the current researchers, along with the supporting motivation and background materials that comes with this compendium of studies. In particular, it provides a comprehensive source from which interested parties may learn about a great variety of research methods, serving both students and instructors alike. In addition, the rigorous treatment, breadth, and extensive bibliographic material should make it an important point of reference.

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1

RESEARCH METHOD IN ATRIUM DAYLIGHT DESIGN

Mohd Hamdan Ahmad

INTRODUCTION

Recently, the atrium has become a common feature in a variety of building types. The primary role of a modern atrium is to enhance the aesthetic and visual quality of the building (Treado and Gillette, 1986). Very few of these new developments have used atria to incorporate passive environmental design principles. As a result, a majority is air-conditioned for year-long indoor comfort. However, fully air-conditioned grand atria are gradually coming out of favour probably due to the global recession and the recent energy crisis (Lomas and Eppel, 1994). Today, the trend is to incorporate atria as part of a design strategy in the development of energy efficient buildings, the 'green' buildings concept.

One of the many reasons that atria are well accepted is the additional commercial and community value that they can give (Harney, 1979). Another reason is that they can contribute to lower energy use in buildings (Saxon, 1983). However, it is a common misconception that the use of an atrium automatically provides benefits in the form of lower energy costs and therefore makes good commercial sense. In fact this is not so. Atrium buildings normally cost more to build than similar conventional buildings and are also difficult to maintain. Unconsidered uses of atria have led to some being considered as failures.

These misconceptions of the energy benefit of atriums, which have led to poor designs, have provoked various research programs on atria. The research is generally intended to assist building designers towards a better understanding of the effect of including atrium into any type of building, particularly non-domestic buildings. The development of a variety of predictive tools is another important research outcome. The outcomes of this research are normally summarised into simplified design guidelines or recommendations. Research on atria can be classified according to the research general functions. These atrium functions can be divided into two main categories: the non-energy related function and the energy related function (Usha,1990).

NON-ENERGY RELATED RESEARCH

The non-energy related work is concerned with the spatial expression and aesthetic value (Harney, 1979; Lehrman, 1984). Another topic of concern is the urban quality of atrium buildings (Hashimoto, 1989). The fire safety issues are also considered (Morgan, 1979). The economical performance of the atrium buildings as a marketing strategy (Portman and Barnett, 1976) can also be categorised into the non-energy related research grouping. Other areas may also include building appraisal (Neeman and Selkowitz, 1984), indoor landscaping (Navvab, 1990; Maddock, 1992; Watson, 1982) and building typology (Hawkes and MacCormac, 1978; Martin and March, 1966; Geist, 1983). Apart from the fire safety issue, the architectural and urban issues are very dependent on the design intentions of the architect. On the other hand, the economic function of atria is of greater importance to the owner or developer of the buildings. Because of these, the non-energy related research has not been an important factor which directly influencing decisions made by the designers. This is because, the non-energy related issues are very subjective to the designers' intentions, the goals set by the developers and the users' perceptions towards atrium buildings and have been seen as more important.

ENERGY RELATED RESEARCH

The energy related research is considered to be an important contribution to the architects (Atif, 1992). It is important because any design decision may directly affect the final energy use in buildings. It is most important during the initial design stages, as the architect needs to understand the implications of his or her intended design solutions, particularly towards the energy and environmental consequences when an atrium is incorporated. Architects should understand that the environmental performance of an atrium is directly influenced by its basic form and architectural treatments and not something that can be left later to be corrected by engineering means.

Research on energy related functions usually involves daylighting and sunlighting such as the work of Cole (1990); Atif and Boyer (1991), Kim and Boyer (1988), Boubekri (1995) and Usha (1994). The impact of atria on interior air stratification have been investigated, by Jones et al (1991) and Kainluri et al (1991) and the use of atrium as a passive feature for either cooling or heating can be found in the work of Kristensen et al (1991), Degelman et al (1988), Baker (1984a and 1984b) and Hawkes, (1983). The thermal performance of atria and the energy saving associated with the inclusion of the atrium form are considered in Watson (1982), Bazjanac, (1981), Atif (1992) and Gillette and Treado (1988).

COMMON RESEARCH METHODS AND EXPERIMENTAL PROCEDURES

At present, there is no single method available that can be used to give a complete analysis on every aspects of atrium design, whilst at the same time providing a measurable and useable result to designers and researchers (Navvab, 1990). However, a survey of previous works, suggests that in general there are three types of method that are often used in energy related atrium research. They can take the form of actual building measurement, simulation studies using physical scale modelling or computer modelling, simplified design and calculation tools, and a combination of any or all of these. Each has its own advantages and limitations. Choosing appropriate method usually takes into consideration the objective of the studies and the expected outcomes of the research.

a) Actual Building Measurement

The first method involves actual building measurements done on site (Baker, 1988 ; Kainlauri et aI, 1991 ; Jones et aI, 1991). Apart from scientific data collections, an actual building measurement method can also include an appraisal of the building made either by personal observation or user response study. The advantage of this is that it allows the real performance of the built atrium to be measured and analysed within its external climatic conditions. The daily changes of the internal environment can be monitored and recorded on site. Since measurements are made of the actual building which has already been built, the problem is that any improvements and corrections might involve alterations to the existing building which may not be feasible in construction or economic terms. Furthermore, it takes a considerable length of time to actually be able to assess the overall performance of the atrium.

Another constraint of using this method is that it involves various parties which include the building owner, the architect and the users. This has been particularly important in Malaysia because obtaining approval to use the building to study normally takes a lot of time and persuasion. The apprehensive attitude of the building owner and the architect may be due to their fear that the outcome of the research may have a negative impact on the building and on them even though this is not the intention of the research.

b) Simulation Studies

The second method is by simulation, utilizing scale models (Hopkinson, 1966; Moore, 1985; Robbins, 1986) or computer models (Ander, 1995) to predict the performance of the full scale building. Simulation methods are important as they can predict the performance of the atrium in the early stage of design before it is finalised and constructed. Alternative designs or corrective measures can be easily tested and compared. It is also important to note that simulation approaches can only predict what will happen if the atrium is built to the design investigated. It might not predict the actual values because in the event changes may be made later in the design and construction process.

i) Scale Modelling

The scale model is an important tool especially in daylighting research. The scale model measurement has been extensively used (Hopkinson, 1966; Robbins, 1986; Moore, 1985; Moore, 1993) and is popular as it can be accurate in predicting the actual building conditions (Navvab, 1990; Usha, 1994; Kim, 1987).The scale model can be tested under actual sky conditions (Usha, 1990; Cole, 1990) or in the artificial sky (Neales and SharpIe, 1992; Kim, 1987; Willbold-Lohr, 1989, Atif, 1992; Boubekri, 1995). The scale model placed outdoors is limited by the daily changes of the sky conditions. It is time consuming to wait for the right sky condition and to test the model for every possible condition. Using the actual sky in Malaysia is almost impossible as the sky condition can change within minutes. To avoid these problems, the artificial sky must be used. It is possible to simulate different sky conditions such as the clear sky or overcast sky condition in the artificial sky laboratory. There is no restriction on the number of points to be measured at anyone time as the sky condition is constant. The illuminance levels inside the model, as well as outside the model, for both actual and simulated sky can be taken and the results can be expressed in the form of Daylight Factor (Ne'eman and Selkowitz, 1986). However, only certain academic and research institutions can offer this facility. Furthermore, in Malaysia, no school of architecture yet has this facility.

ii) Computer Modelling

A major disadvantage of the scale modelling technique is that it cannot predict the average performance of daylighting over an entire year. In this respect the lighting computer model simulations at the early design stages are very useful (Navvab, 1990). It is also possible to use the same system for various performance analysis such as daylighting, HV AC (heating, ventilating and air conditioning) operation or for thermal modelling. However, the computer models also have their own limitations. Since there are various types of computer modelling systems, one needs to be very familiar with the operation of the system and their capabilities before using them. Some system can be very expensive and time consuming involving multiple and complicated calculations. Even though the computer model can simulate complicated geometry, this capability is still limited to powerful workstations only. The majority of users own a personal computer, therefore could not venture into more complicated daylighting programs. However, the use of computer in design and research is growing and becoming more popular as it is now designed to be more user friendly, cheaper and most important reliable (Ander, 1995).

c) Simplified Design and Calculation Tools

The simplified design tools are generally used for a quick assessment and simple prediction of daylight. They can be mathematical, graphical or tabular. They include simple equations, graphs, nomograms, charts and manual tools. All simplified design tools make reference to either uniform, overcast or clear blue sky conditions. The suitability of various simplified calculation tools varies according to the intentions and the reference conditions for which they were developed. Thus, which method is preferred will very much depend on the stages of the design, the complexity of the space, and the accuracy of the calculation required. Simple equation can be done manually. For complex calculation and algorithm, computer programs are available. In general the mathematical simplified design tools are dislike by architects as they require scientific knowledge and bias towards engineering. On the other hand, architects prefer generative design tools in the form of quick sketches and renderings which are also a simple method used to show design intentions and concepts, as well as the image of the expected final product. It is easier for client to relate to the sketches produced by the consultant for conceptual and aesthetic purposes; however the sketches do not convey the quantitative aspects of the environment.

d) Combined Method

As there is no single method at present that is capable of producing a complete and accurate analysis (Navvab, 1990), it is possible to combine different methods which were already discussed and explained above. This will allow the researcher to combat any shortcomings from a particular method (Everett and Baker, 1995). It also allows researcher to validate the results as well as correlate the findings (Mardaljevic, 1995; Kim, 1987). The following quote is from Navvab (1990), sharing his experience in combining the methods in one of his many studies, *'It is a back-and-forth process. First we use the scale model, then we make parametric studies with computer models. Then we go back to scale model to refine them .... After the completion of each project many site visits are made to take actual illumination measurements .... This provides data that allow researchers to validate the results of all the calculations made during the design process. There are always some differences, but that's is to be expected. After all, no modelling technique is perfect. '*

In principle, Navvab implies that using various methods should yield comprehensive and more accurate results. However, it is also costly, as each method uses different techniques and may involves various type of equipment. It is also time consuming. Hence, a combined method is more appropriate in a well-resourced programme.

USE OF CASE STUDY IN ATRIUM RESEARCH

In general, previous literature mostly cited and illustrated atrium environments in the context of the temperate climates, or for regions of northern latitudes. The information directly related to atria in tropical countries is very limited and insufficient. In this aspect, the case study is designed to address the local situation and at the same time supplement the lack of appropriate literature. Moreover, the case study assists in the understanding of the conditions of the existing atrium buildings, and thus directly highlights the Malaysian atrium characteristics and the consequent environmental and building energy issues. Review of the case study can be performed in variety of methods such as visual observation, photographic recording and lighting measurement. The outcome of the case study and the local information were essential factors in the construction of the typical model of the atrium space and its adjacent corridor way for subsequent daylighting experiment and analysis.

Another important subject which was found lacking in the literature review was local information on daylighting practices and day lighting design conditions in Malaysia. The understanding of the state of daylighting practice is considered essential in order to explain the prevailing state of the existing atria buildings, hence it can be included as part of the case study. It can be concluded that the main objective of the case study is to highlight the issues and conditions directly pertinent to the context and the scope of the research.

DAYLIGHTING EXPERIMENT

The information gathered during the literature review and case study are used to develop the research procedures in the daylighting experiment. The prototypical atrium forms found during the case study for shopping malls in Malaysia were drawn using selected AutoCAD program. The complexity of the models and detailing of the interior spaces are constructed in relation to the aim of the intended daylighting analysis. The main purpose of the experiment is to analyse the daylighting performance of both the typical top-lit atrium and the alternative side-lit design proposed. The emphasis is on the daylighting distribution and daylight levels falling on the atrium floor and on adjacent corridors. The effects of the physical proportions or degree of enclosure of the atrium space on the daylighting characteristics are investigated as well as the impact of various roof forms and the balcony sections. The impact of the application of horizontal shading devices is also suggested. In the early stage of the development of this research, the physical scale models and the use of artificial sky laboratory were contemplated as the method to conduct the daylighting experiments. The scale modelling techniques have been traditionally used by architects to predict available illumination in a building and for visualisation of the overall lighting quality. However, computer modelling offers some advantages with respect to the complexity of the experiments compared to physical scale model.

1) It is easy to construct and modify the model. The capability of the daylighting software to integrate with CAD programs means that the model tested can easily be drawn and modified as desired by the user. Thereby the user can freely select the required details to be included or excluded at any stage. In addition, the model can be very complicated and drawn either in two or three dimensional format. The materials data base can be edited to add new materials with user specified surface characteristics.

2) The advance daylighting program is flexible. Daylight calculation can be performed for a variety of sky conditions, for a given sun positions, geographical locations and user defined irradiance or radiance data.

3) The advance daylighting program is reliable and accurate. Grynberg (1989) has shown that the results of the computer studies when compared to the scale model studies and real building measurements studies illustrate good correlation with the measured data. In addition, the reliability and accuracy is due to the ability of the more advanced computer program to simulate various surfaces, materials and light sources characteristics (Lomas and Mardaljevic, 1994).

4) The computer program can provide additional data such as the luminance distributions within spaces and glare conditions. The computer results can also be linked easily to various energy calculation programs for energy saving calculations (Hitchcock, 1995).

5) The output of the daylighting analysis can be produced in text or graphic formats. The more advanced computer program can give photo-realistic results of the simulated space or buildings (Ward, 1994).

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2
METHODS AND TOOLS FOR DAYLIGHTING ANALYSIS

Gurupiah Mursib

INTRODUCTION

The intention of this chapter is to review the most suitable method of analysing daylight level and daylight distribution of a side-lighted room. Several methods and tools were analyzed to determine the most practical tool to investigate the effect of various design parameters for a given daylighting concept.

METHODS OF ANALYSIS

Daylight quantity can be analysed using three basic methods (Robbins, 1986):

1) Lumen method
2) Daylight Factor method
3) Flux Transfer method

These methods are applied in various analysis tools. The following review will explain the advantages and the disadvantages of several leading method and tool for the study.

1) Lumen Method

The Lumen method is adopted by the IES Daylighting Committee as the recommended method in design practice (IES RP-5, 1979). The method is based on a physics principle that illumination at a station point (E_{sp}) is obtained from a function of external illumination, net transmission and coefficient of utilisation. The basic equation is,

$$E_{sp} = E_e (NT)(CU)$$

Where,

E_e = external illuminance from either sky or reflected ground
NT = net transmission
CU = coefficient of utilisation

Effect of sky, opening, glazing, surface reflectance and room dimension can be included from an analytical formula stated as,

$$E_{sp} = (E_e) \times (A_g) \times (T_g) \times LLF \times CU$$

Where,
E_e = external illuminance from either sky or reflected ground
A_g = area of glazing
T_g = transmission of glazing
LLF = Light loss factor
CU = coefficient of utilisation

Although the equation is of simple algebraic form, the variables require very complex operations to determine (Mohd. Hamdan, 1997). The two coefficients of utilisations are determined from interpolation of test data from actual testing of room parameters made available in a series of tables and nomograms. As the result, limitations on room configuration, size, reflectivity, and opening shape are inherent, depending on coefficient of utilisation available for it (Robbins, 1986). Besides, this method produces illuminance at three station points only, thus, provide no information on the overall distribution and on the desired working station. The method of analysis has the disadvantage of producing inadequate output for the study and therefore, it is not applicable for this study.

2) Daylight Factor Method

The Daylight Factor (DF) method is also known as the Sky Factor method and the Split Flux method. Commission Internationale De l'Eclairage (CIE) has recommended this method for procedure in lighting calculation (CIE Publication No. 16, 1970).

The Daylight Factor (DF) can be defined as the ratio between the internal illuminance on horizontal plane and the unobstructed exterior illuminance on horizontal plane, expressed as follows:

$$DF\ (\%) = (E_i/E_e) \times 100$$

Where,

E_i = interior illuminance on horizontal plane

E_e = exterior illuminance on horizontal plane

As a relative measure of illuminance, the DF ratio is a good indicator to the performance of a given daylighting alternative in buildings (Robbins, 1986; Ander, 1995). The DF expresses the efficiency and effectiveness of a room and its window system as a natural lighting system (Love, 1992). Comparative analysis of daylighting systems can be made because DF value measured under an overcast sky is unaffected with time, window orientation, and sky condition. If outdoor illuminance for specific time and location is obtained, the DF value can be converted into an absolute illuminance value for that particular location, at specific time and days of the month (Mohd. Hamdan, 1997). Thus, the relative concept of DF is a suitable approach for evaluating and comparing the performance of daylighting systems. DF consists of three components:

1) The Sky Component (*SC*)
2) The Externally Reflected Component (*ERC*)
3) The Internally Reflected Component (*IRC*)

These three components are summed to determine the total DF:

$$DF = SC + ERC + IRC$$

The *SC, ERC* and *IRC* of the Daylight Factor can be determined either mathematically or by a variety of analysis tools. The *SC*, *ERC* and *IRC* are added algebraically to produce the total DF at a station point. The procedure will be repeated for many other points of the interior to determine the DF distribution. The process of determining the distribution in a room is a tedious routine if done manually. Alternatively, it can easily be obtained using widely available computer programs (Leite, 1986; Shankman, 1986).

Although Daylight Factor can be determined from photometry measurement, this approach has a few disadvantages. First, the measured DF is difficult to determine because the value fluctuates when direct sunlight is present (Love, 1992). Second, even under an overcast condition, the value shows variability over time (Love, 1993). Large magnitude of variation reported by Tregenza (1980) presents grave difficulties in comparing the performance of daylighting systems.

3) Flux Transfer Method

The Flux Transfer method is the most comprehensive daylighting analysis method (Robbins, 1986). The term 'flux transfer' means a radiative transport of a luminous flux from a source to a receiving surface. The visible flux transfer between a source and a receiving point or surface is determined based on the Configuration Factor *C* and the Form Factor *F*.

1) Configuration Factor *C* describes the flux transfer from a Lambertian source surface to a small target point of a receiving surface. It is the ratio of illuminance on an infinitesimal target point to the luminous exitance of a Lambertian source surface.

2) Form Factor *F* describes the flux transfer from a Lambertian source surface to a second Lambertian surface. It is the ratio of flux directly received by a surface to the total flux emitted by the Lambertian source surface. Thus, it describes the quantity of light reflected or emitted by one surface and reaching another surface.

The function of *C* and *F* factors describe the relationship between plane of the aperture and the workplane upon which the station point is located:

For illuminance at a receiving point (E_p),

$$E_p = MC$$

For illuminance at a receiving surface (E_{rs}),

$$E_{rs} = MF$$

Where,

M = diffuse exitance of the source
C = Configuration Factor
F = Form Factor

In a side lit-room, a window acts as a large diffused area source. The exitance M of the window is produced by light from the sky transmitted through the glazing of the window.

Thus, illuminance at a receiving point (E_p):

$E_p = (E_a \times T_g)C$

Illuminance at a receiving surface (E_{rs}):

$E_{rs} = (E_a \times T_g)F$

Where, E_a = illuminance striking the aperture
T_g = transmission of glazing
C = *Configuration* Factor
F = *Form* Factor

The direct and reflected components of the light flux are calculated separately and added for the total illumination value.

Thus, the total illumination is:

$$E = E_S + E_{SE} + E_{ERE} + E_{IRE}$$

Where,

E_S = direct illuminance from the sun
E_{SE} = direct illuminance from the sky
E_{ERE} = externally reflected illuminance
E_{IRE} = internally reflected illuminance

The externally reflected illuminance (E_{ERE}) can be determined if the luminous existent from the surface is established. Under an overcast condition (without sun), the existent flux at a first target plane using C factor:

$$E_{ERE} = (E_{SE} \times \rho_s \times T_g)\ C$$

Where,

E_{SE} = daylight from the sky
ρ_s = reflectivity of the surface
T_g = transmission of glazing
C = Configuration Factor

The flux received by a second surface can be determined using the same equation, replacing *C* with *F*. By means of either Configuration Factor or Form Factor approach, exterior shading devices such as overhangs, roof porch and fencing wall can be analysed.

The internally reflected illuminance (*IRE*) can be determined by estimating average *IRE* for the surface or by estimating *IRE* quantity at specific point.

For average *IRE,*

$$IRE_{avg} = \{[(E_1)(A_1)(\rho_1)] + [(E_2)(A_2)(\rho_2)] +\ldots+ [(E_n)(A_n)(\rho_n)]\}/(1-\rho_{avg})(A_r)]$$

E_n = centroidal illuminance striking a surface
A_n = area of a surface
ρ_{avg} = average reflectivity
A_r = total surface area of the room

In a point-specific method of determining *IRE*, each surface is considered as a source. The flux transfer equation for parallel and perpendicular surfaces will be used to determine illuminance from each source reaching a station point.

The Configuration Factor *C* and Form Factor *F* in the Flux Transfer method can be used to analyse almost any shape of daylight aperture and room configuration. They are applied either to determine the amount of light directly reaching the station point or the amount of light inter-reflected off exterior and interior walls, ceiling and floor to the station point. It can also be applied to both absolute and relative illuminance calculations. The contribution from the sun can also be included in the analysis. The method and calculation is most often incorporated into computer programs, such as the simple Lumen method or Zonal Cavity method and the more accurate Finite Surface method or the Ray Tracing method (Lupton, Lenns & Carter, 1996).

The advanced mathematical flux transfer method described above is preferable due to three reasons:

1) Its realistic modelling of light transfer that allows calculation of externally and internally reflected light,
2) Its applicability to complex building geometry and window system, and
3) Ease of application once aided by computer.

The room is described in terms of the initial luminance striking the ceiling L02, walls L01 and floor L03. The final luminance leaving each surface is described by L2, L1 and L3. The final luminance is greater than the initial luminance because of the inter-reflected light in the room.

The flux falling from a given surface A from surface B is equal to the flux on surface B times form factor between surface A and B (fAB). Therefore the flux falling on the floor from ceiling and walls is:

$$L3 = L03 + p3\ (L2f23 + L1f31)$$

The flux falling on the ceiling from the floor and walls is:

$$L2 = L02 + p2(L3f32 + L1f21)$$

The flux falling on a wall is:

$$L1 = L01 + p1\ (L1f11 + L2f12 + L3f13)$$

From the general equation, the luminance from any surface can be determined.

The total absolute illuminance at station point can be defined similar to daylight factor method of analysis:

$$E_{sp} = E_s + E_{se} + E_{ere} + E_{ire}$$

Where,

E_{sp} = Illumination at station point in lux
E_s = Illumination from the sun in lux
E_{se} = Illumination from the sky
E_{ere} = externally reflected illumination
E_{ire} = internally reflected illumination

The illumination at a station point is based on:

- the size and shape of the aperture
- the distance from the station point to a corner of the aperture
- the view of the sky from the station point or the illuminance from the plane of the aperture
- The climate, time of the day, and solar location.

DAYLIGHT DESIGN TOOLS

1) Simplified Design Tools

The simplified design tools can be classified into eight categories: Equation, Single Stage Method, Lumen Method, Tables, Nomograms, Protractors, Dot Diagrams and Waldram Diagrams. The major drawbacks of the simplified design tools are:

1) They offer limited application of window shape and position.
2) They offer application of simple geometry only. Most application is limited to rectangular form.
3) They produce component output of a point. Calculation of each component to obtain the total illuminance requires lengthy calculations.
4) The simplified methods involve reduced calculations and assumed conditions, thus are less accurate.

In conclusion, the simplified design tools and methods reviewed above are not suitable for this research.

2) Actual Building Measurement

If measuring instruments are accurate and handling is done as prescribed, an actual building measurement allows actual performance of interiors to be measured and analysed within its external climatic condition. Data collected in a real environment allows an accurate evaluation of a building performance. Since the measurement is subjected to variability of the external condition, strategy of measuring as Daylight Factor ratio or monitoring measurement extensively is required (Hamm & Mullican, 1997).

Limitation of photometer as a measuring instrument is among the disadvantages of this method. Daylight measurement involves a wide range of illumination and requires measures for controlling the sensitivity and accuracy of photocells (Pritchard, 1985). Although some photocells are relatively able to withstand temperature variation and wide range of illumination, the cells are subjected to ‘cosine error’ (due to high illuminance incident), to ‘drift’ effect (due to slow response during early exposure), and ‘fatigue’ effect (due to prolonged exposure to high illumination). The photocells can be damaged if exposed to damp and high temperature and excessive illumination.

Actual building measurement is not practical if the study involves large number of typology permutation to be investigated. First, changing the physical variables on actual building is costly and time consuming. In fact, such experiment is not viable in private houses. Second, to measure the actual house samples that represent particular daylighting systems involve measurements in large number of different houses. These measurements are subjected to field variables such as different type of furnishings, plantings and outdoor obstructions. It is hard to quantify the influences of these variables, thus comparison among different daylighting systems is difficult.

3) Physical Modelling

Daylighting analysis of a given system can accurately be done using a physical modelling (Kim, Boyer & Degelman, 1985). Physical modelling involves constructing a model to scale and measuring the illuminance under a real or an artificial sky. Due to the extremely short wavelength and high speed, visible light behaves the same way in a scaled model as it does in an actual room. Thus, a fully detailed scale model of a room gives a true photometric analogue (Chavez, 1989). A physical model can handle complex geometry and allows exploration of design alternatives by changing one variable at a time (Moore, 1989; Ander, 1995).

There are many factors that contribute to error in the estimation of physical model (Love, 1993). For example, a large diameter of sensor probe may influence the quantity measured. Thus, the size of photo sensors to the scale of the model is crucial (Chavez, 1989). Since more points or nodes need to be measured in order to establish a complete room illuminance distribution, this may not be feasible in small-scaled models because of the relatively large photocells used.

Testing physical models under a real sky condition is a difficult procedure (Love, 1993). First, if Daylight Factor value is to be measured, it is necessary to wait for an overcast sky. Even under an overcast sky, the values are not reproducible and fluctuate due to a constantly changing sky luminance and pattern (Tregenza, 1980). In Malaysia, the constantly changing sky luminance patterns due to cloud formation (Mohd. Hamdan, 1997) presents difficulties in determining Daylight Factor of a room.

The use of an artificial sky is recommended to test physical models (Robbins, 1986; Baker, Fanchiotti & Steemers, 1993). An artificial sky can provide the specified sky luminance distribution. This eliminates sky variables, which is necessary in comparing different daylighting systems. Unfortunately, the artificial sky is not available in this country. Since the construction of an artificial sky is costly, no school of architecture in the country has this facility (Mohd. Hamdan, 1997). However, there is one currently under construction in the Department of Physics of Universiti Kebangsaan Malaysia (Azni, 1998).

Although physical modelling has several advantages in evaluating building performance, it is not a practical for this study. The care and precision that are required in measuring procedure could be tedious for large number of models involved. The large number of models and their variations can also be costly to construct. While artificial sky is not available, the fluctuating sky characteristic prevents Daylight Factor value of a particular system to be accurately determined.

4) Computer Simulation

Computer simulation is the growing trend of simulating luminous environment because of various benefits (Shankman, 1986). Accessibility, ease of application and quick feedback contribute to its popularity among designers (Stix, 1988; Simpson, 1971). With CAD interface, architectural input can be directly transferred to the program. Programs for personal computers are widely available at reasonable prices (Baker, Fanchiotti & Steemers, 1993; IESNA, 1996; Ander, 1995). Furthermore, programs can be linked to thermal or energy analysis for a more extensive evaluation.

The advance light modelling technique involves a large number of difficult computational problems, which is ideally done by computer. The computer is able to perform fast and accurate calculations, and these save time on difficult and tedious, routine calculation (Leite, 1986). The algorithm has been improved and the software is regularly verified (Bellia, Cesarano & Sibilio, 1994; Mahdavi, 1992; Tragenza 1983; IESNA, 1996).

The computer program is a useful tool to predict design performance and to investigate the effect of different systems (Stix, 1988; Selkowitz, 1985b). Design models can easily be constructed, changed and modified for any parameter of design. The numeric and graphical outputs produced by the computer can be scrutinised much closely (Davis, 1986). This allows for both quantitative and qualitative evaluation of a daylighting system. It can help designers determine if the required illuminance level is met at specified reference point. The isolux contour plan, graph section and three-dimensional graph illustrate characteristics of pattern, shape and direction of light penetration. A virtual walk through graphic offered in a more sophisticated program can serve as a replacement for experience.

The computer programs adopt various calculation methods for modelling the flux transfer. Three common methods of modelling flux transfer used in interior lighting simulation programs are the Lumen Method, the Finite Element Method and the Ray Tracing Method (Lupton, Lenns & Carter, 1996). These methods are explained in detail and compared in Table 3.6. It is found that programs incorporating the Lumen Method are useful for quick prediction of average illuminance, but does not produce detail room distribution or illuminance at a reference point. This method is widely available for free (Baker, Fanchiotti & Steemers, 1993). The more rigorous Backward Ray Tracing method such that used in RADIANCE combines the Monte Carlo Method (Tregenza, 1983) and the Finite Element Method (Lupton, Lenns & Carter, 1993). The program calculates reflections from any surface characteristics and produces a virtually realistic graphic representation. However, this sophisticated program operates under a mainframe and requires users with an excellent computer background (IEA-Task 12, 1996f). Detailed and tedious data input and long computing time (Ander, 1995) is impractical for studying a number of different design solutions.

The Finite Element Method is a realistic and relatively accurate program compared to the Lumen Method due to the ability to simulate inter reflected light, light that originates from a particular light source to various surface planes before finally reaching a station point. It is a far more efficient method for calculating a complex room and window geometry with assumed diffused surface (Tregenza, 1983). This method has been used as a research and design tool for a number of years, and claims reliable results (Lupton, Lenns & Carter,1996). An example of a program that incorporates the Finite Element Method is SUPERLITE (IEA-Task 12, 1996e).

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3

BUILDING SIMULATION TO DETERMINE SELF-SHADED FORM FOR HIGH-RISE BUILDINGS

Chia Sok Ling
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INTRODUCTION

The chapter discusses the methodology used in investigating the optimum geometric shape high-rise built form and effectiveness of self-shaded high-rise built form for hot and humid climate. The discussion is divided into two phases. Phase one consists of case study of the generic high-rise building shape in Kuala Lumpur and adaptation of self-shading strategy in high-rise built form. Three base models are developed based on the above said studies. Second phase reviews the research methodologies used by previous researchers. The justification of the selected methodology of this study is elaborated. Finally, the experimental procedures, limitations and overall sequence of the experimental method are discussed.

There is lack of research on the solar radiation prevention especially in equatorial tropics. The development of self-shaded high-rise built form to achieve maximum reduction of solar insolation on its external exposed surface is crucial. Impact of solar radiation on the external surfaces of high-rise is important to determining the optimum geometric shape and adaptation of self-shading strategy into high-rise building design. The shading strategy is more efficient if able to apply at the early stage of high-rise building design. Since it is in the early stages, the most significant decisions are easily and appropriately made regarding sizing, form, placement and orientation of the building volume.

EVALUATION OF SOLAR RADIATION IN BUILDING

The purpose of this section is to evaluate the available methods of solar radiation in building. Surveys on previous works suggested that generally there are three methods often used in researches related to solar radiation. They are manual calculation, field experiment and computer simulation.

Choosing an appropriate method needs to take into consideration the objectives of the study and the expected outcome of the research. Understanding the nature of every method helped the author to decide on the best selection of the method required. The following sections discuss the advantages and disadvantages of the above said methods.

a) Simplified Design and Calculation Tools

The simplified design tools are generally used for a quick assessment and simple prediction of solar radiation (Hamdan, 1996). It can be in the form of mathematical calculation, graphic or tabular. Most manual calculations are based on steady state conditions, where factors influencing the solar radiation are considered under constant state. For example, solar radiation calculation by ASHRAE (1997) is calculated under clear sky condition. Therefore manual calculation approaches frequently leads to over-estimating the availability of solar radiation. It is based on average conditions and does not account for day-to-day weather variations.

Architects prefer generative design tools in the form of graphical diagram or tabular which is more visual oriented. Olgyay (1963), Brown and Dekay (2001) suggested passive solar design strategies using sun path diagrams to predict the position of sun in the sky dome, estimation of hourly solar radiation available and period of overheating or under-heating. Similar to manual calculation, this method is based on rules of thumb and does not rely on day-to-day weather variations. Therefore, it is not reliable for complex building or detailed simulation.

b) Field Measurement

Meteorological station in Malaysia started its measurement of daily total horizontal solar radiation since 1975. Long-term measurement data of direct and diffuse solar radiation are needed. The availability of hourly direct and diffuse solar radiation data is rare. Reliability of solar radiation data is obtained by accurate measurement. According to Donald, et al (1984), studies on the solar radiation measurement data in Malaysia are often used for atmospheric science studies, meteorological forecasting and application for purpose of energy conversion, but applications in designing for energy efficient building is still not widely used.

On the other hand, measuring station was set up in Hong Kong to measure horizontal hourly solar radiation and vertical global solar radiation on four cardinal surfaces (Lam and Li, 1996). This study involved large amount of equipments, data collections, quality control and data processing through computer simulation. There are greater demands for the knowledge of solar radiation on vertical surfaces particularly for high-rise building with substantial glazed area. The data collected from this study reflect more accurate condition compared to other methods.

Data measurement is regarded as the most effective and accurate method of setting up solar radiation database (Li and Lam; 2000). But not every researcher has sufficient time and financial support to run the field measurements. It is very time consuming for every experiment needing appropriate period for data collection. It is also very costly in preparing sufficient equipments and labour on site to run the experiment. Sometimes field measurement is too complex and hardly understood by architects and designers.

c) Computer simulation

Review of the above said methods informed that simplified design and calculation is unreliable and does not represent real-world complexity. While field experiment requires complex and comprehensive procedure in methodology, limitation in available equipment, limited budget and time consuming. Therefore, computer simulation is an alternative method for this study.

Over the past 50 years, literally hundreds of energy programmes have been developed, enhanced and applied in the building energy community. New design tools approach enable all simulation model being simulated under virtual condition. Computer simulation tools developed by scientist and researcher provide accurate result and the models in simulation adequately represent real-world complexity (Sonia, 2005). However they require extensive training, for learning on how to use them, preparing input, running and interpreting the result to the requirement of the research.

Technology and information today allow scientists and researchers to bring computer simulation tools to implementation in actual building design and construction (Kristensen, 2003; Garde F. et al, 2001; Shaviv E., 1998). Study from Garde F. et al (2001) demonstrates the methodology of the above methods. Firstly, identify the specifications needed to consider in the building design and complete the simulations for each specification. Then, implement the solutions on real projects and finally have the experiment validated.

SELECTION OF COMPUTER SIMULATION PROGRAMME

Sonia (2005) recognizes the need for building simulation or performance tools that can be integrated into the building design process. The complexity of simulation tools created by scientists, who are more technically oriented, discourages architects or designers who are more visually oriented people to use them.

The selected computer simulation programme must provide a design tool that is user-friendly and easy-to-use. Sonia (2005) describes the following factors to be integrated into the programme:-

a) Provide designers with a building performance tool that would aid in the design process.
b) Provide a front-end that supports AutoCAD so that the building information can be assigned to the drawings.
c) Develop a graphical user interface where the mode of output is both graphical and numerical.
d) Provide designers with building design information tool that requires the least amount of training and yet is very easy to learn and use.
e) Provide designers option to create their own custom databases of building components.
f) Allowing researchers to expand or further their study to widen perspective and scope (expandable design tools).

EXPERIMENTAL REQUIREMENT

The purpose of this study is to understand the impacts of solar radiation on high-rise building shape in minimising the total solar insolation on the exposed external vertical surfaces. The selected computer programme should be able to analyse effect of any building shape variation on solar radiation and simulate any possibility of self-shading design strategy. Therefore, the computer simulation programme must fulfil the following criteria:

a) Provide required climate condition and weather data for the specified location of the study being carried out.

b) Provide detailed weather data input for hourly horizontal global solar radiation.
c) Provide editable modelling features, for example options in creating various generic high-rise building shapes and further modification it into self-shading building shape.
d) Provide solar insolation analysis that enables distribution of computation at required time-step.
e) Simulate the impact of incident solar radiation impinges on the external surfaces of any building shape in both numerical and graphical output.

REVIEW OF ENERGY SIMULATION PROGRAMS

Sonia (2005) explained those most available simulations programmes were originally developed by researchers to have extremely sophisticated analysis tools. It requires significant amount of detailed information about the building and its context. The input requires mechanical engineering data that comes at the end of the design process and the output is largely numeric or text. It becomes difficult for architects to incorporate the analysis results during the process of designing. Building designers require energy analysis tools that are quick to use and produce result that are easy to understand. Gratia E (2002) believes that user interface tool for architects should be very user-friendly and uses visual language of architects based mainly on illustrations.

The comparative surveys of twenty major building energy simulation programme developed by Crawley, et al, (2005) became the reference of many researchers. Availability of the comparative analyses provides immediate information for researchers to have a quick view and precise assessment.

From the comparative survey, the following simulation programmes fulfil the required criteria of this research: ECOTECT, Energy Plus, e-QUEST, IES <Virtual Environment> (IES <VE>) and TRNSYS. The five selected simulation programmes have their own unique ability. ECOTECT is the ideal simulation programme for this study that can fulfil all experiment requirements and can easily be integrated into the building design process. A generative design tool is suitable for complex and expendable models.

THE ECOTECT V5.2B COMPUTER SIMULATION PROGRAM

ECOTECT is unique within the field of building analysis in that it is entirely designed and written by architects and intended mainly for use by architects. This energy analysis tools enable architect to design building that is more responsive in the initial stages of design (Sonia, 2005).

The original ECOTECT software was written as a demonstration of some of the ideas presented by Andrew Marsh (2000). Its modelling and analysis capabilities can handle geometries of any size and complexity. Its main advantage is that it focuses on feedback during conceptual building design stages. The intention is to ease design process to create a truly low energy building. Analysis results can be mapped over building surfaces or displayed directly within spaces that generate them. It provides the designer the best chance of understanding exactly how their building is performing and deriving basis that make real design improvements.

It is an environmental design tool which couples an intuitive 3-dimensional modelling interface with extensive performance analysis functions covering shading, thermal, lighting, acoustic, energy, resource use and cost aspects. ECOTECT provides performance analysis which is simple, accurate, interactive and visually responsive (Crawley, et al, 2005).

SIMULATION PROCEDURE

This section will outline the sequence of the simulation approach, from the required data and the construction of geometric models to the output of the results.

i) Data Requirement

Provide required climate condition and weather data for the specified location of the study. All simulations are calculated based on the Malaysian climate data. The calculated data were obtained from the ECOTECT 5.2v -weather file for, Subang Jaya, Latitude: 3.10; Longitude: +101.7; Time zone: +8. The weather data were obtained for the year 2000.

ii) Preparation of Geometric Modelling

In earlier design stage, minimum data input and various geometric variables are needed to provide more design option for architects. The very nature of the architectural design process is visual. This is especially true of the early stages of design where the building geometry itself is still being established. The ability to visualize a geometric model in three dimensions is therefore considered very important.

In order to create various generic high-rise building shapes and then further modify them into self-shading building shape, generation of flexible and editable basic geometric modelling is very important such as creating and editing objects according to size for base models 1, 2 and 3. Two ways for creating the base models are by importing the building geometry from AutoCAD drawings or creating new objects in ECOTECT window application.

iii) Simulation Parameter and Performance

Analysis grid represents a grid of points within the model at which light, solar insolation and thermal comfort values can be calculated. Grid analysis can be divided into 5 components which include grid setting, grid data & scale, grid position, grid nodes and perform calculation as follow:

a) Displaying grid setting on various base models.

- The grid can be displayed in four ways: single grid, horizontal grid, vertical grid and box grid. However, curve surface can only be displayed in vertical and box grid. Analysis display for flat surface is straight forward. Box grid is chosen and every single grid represents 1m x 1m (width x height) on the flat surface.
- Curve surface for circular shape depends on the division of perimeter length on analysis grid.

b) Grid position

- Insolation analysis can be mapped over the external surfaces of high-rise building and displays directly the impacts of solar insolation in various colour effects.
- Grid form fit the grid to current axis according to the selected surfaces. This function enables grid for curve surfaces to be formed accordingly.

c) Grid nodes

- Visible node affects the analysis result. Numbers of visible nodes on analysis grid bring effect to the analysis grid result.

d) Perform solar insolation analysis calculation

- Grid analysis enables the calculation of insolation level, lighting level and spatial comfort
- Calculate cumulative incident solar radiation on building surface for a period of time or insolation level on yearly, monthly and daily basis for selected surfaces.

iv). Review Simulation Result

The output of the result can be generated either in text format or graphic format or also as 3-dimensional pictures. The output analysis can be mapped over building surfaces and can be viewed as OpenGL visualisation option or a freeware Virtual Reality Modelling Language (VRML) plug-in. Both viewers can display interactive 3-dimensional models that can move around in real time and also display a range of analysis results overlaid upon the model.

v). Simulation Limitation

The performance of the simulation program is bound to have few limitations as discussed below:

a) The programme only considers two types of solar radiation on external vertical surfaces, directly from the sun (direct solar radiation) and directly from the sky (diffuse solar radiation), or diffuse irradiance on the building components.

b) Only incident solar radiation falling on external vertical surfaces is calculated (excludes horizontal surfaces such as exposed roof and floor surface). Reflected solar radiation from the ground and neighbouring buildings are not considered in the calculations.

c) ECOTECT version 5.2b is unable to build up convex surface. Therefore, cylinder shape is generated by 36-segmented flat surfaces.

d) Analysis grid (1m x 1m) shows the pattern of solar insolation distribution on the selected surface.

vi). Simulation Design Conditions

This section discusses the preparation of the basic condition of different variables for the simulation. The design conditions to conduct the simulation were adjusted based on the literature review (Marsh A., 2002 and 2000; Ossen, 2006; Stasinopoulos, 1998):

a) Outdoor condition: Refer to weather data from ECOTECT.

b) Solar collector material (from default library) has been applied on all vertical surfaces for high-rise building shape. All interior spaces are applied the same material for all base models.

c) Solar insolation analysis is influenced by four factors: solar geometry, atmosphere condition, incident surface properties and ground reflection

d) The three design-days were selected according to the seasonal profiles of each characteristic day. The impact of solar insolation received by each vertical surface on three design-days represents the solar extreme condition that happened on each surface during equinox and solstices.

e) Assume that all base models are the same in the application of interior space, building system and occupancy load for high-rise office building. These conditions will have great impacts of energy load if energy use is the main concern for this study.

ADAPTATION OF SELF-SHADING STRATEGIES TO HIGH-RISE BUILDING DESIGN

Since Malaysia is in the tropical region (located between 1-7^{o}N and 100 to 120^{o}E), it is undeniable that we are facing lot of problems in terms of solar radiation. This emphasize the importance of prevent solar radiation from overheating the external surfaces of buildings.

Due to their height, building envelope of high-rise building experiences the full impact of external temperatures and global solar radiation than low-rise or medium-rise buildings, which can be easily shaded by the roof and vegetation (Ismail, 1996). Matus (1988) carried out a study on the relationship between building form and orientation. He stressed that high-rise building form is more sensitive to orientation than low-rise building form. The studies above stress on the importance of determining the optimum geometrical shape and placing the right building orientation for high-rise building before applying self-shading strategies.

Possible Adaptation

Application of self-shading strategies in medium-rise building can not be literally applied to high-rise buildings. The main problem is due to the building heights. Theoretically, an inverted cone may be the ideal form for self-shaded high-rise building. Its surface to volume ratio is the lowest and the solar radiation falling on its vertical surface can be minimized constantly. However, it is structurally a challenge in constructing a self shaded high rise form.

The main draw back of using self-shading strategies for high-rise building is the low solar altitude, which creates a very inclined wall. Modification on self-shading strategy is needed, so that it can be applied for high-rise building design. There are two design strategies, namely the inclined wall and stepped inverted geometry. These proposed design strategies may enable building forms to be self-protected from solar radiation during a required period.

Development of Self-Shading High-Rise Form

The methods of self-shading are adapted from several solar shading methods including solar envelope (Knowles, 1981; Capeluto and Shaviv, 2001) and shadow umbrella (Emmanuel, 1993). Solar envelope and shadow umbrella are known as shading strategies for urban fabric. Their application on individual or isolated building is yet to be found. Capeluto (2003) modified the solar collection envelope (SCE) method and applied it for self-shading strategies for application in medium-rise office building. He proposed a few modifications on the self-shading strategies to avoid inclined wall while still allowing daylight penetration into internal spaces.

The determination of the cut off time and self-shading protection angle of the sun path are crucial. This is the fundamental variables for self-shading strategies. Based on the solar position, this section generates and modifies self-shading strategies for high-rise built forms in hot humid tropics. There are four main steps defined by the author that can generate self-shading high-rise built form and yet still fulfil other design issues.

Step A: Generation of base model for self shading strategies

The schematic diagram in figure 1 shows the first main step on generation of the base model.

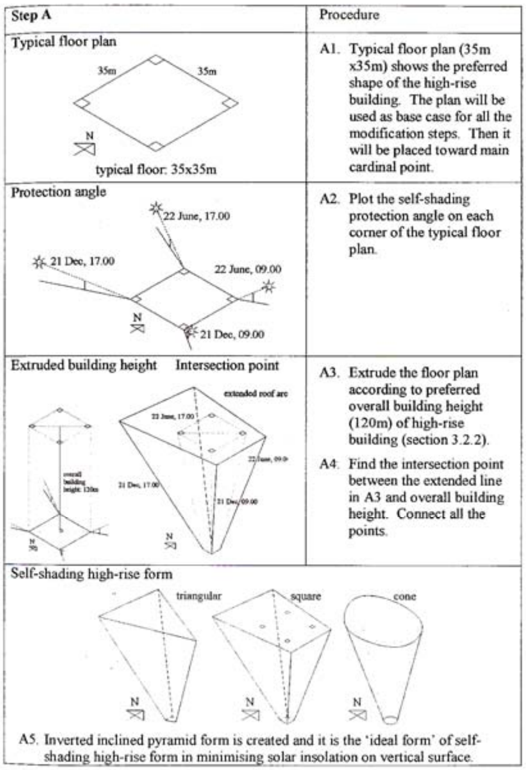


Figure 1: Generation of base model for self shading strategies

Step B: Segmented high-rise form into smaller vertical groups

In order to minimise the roof surface area, 120m high high-rise built form is segmented vertically into smaller groups. Each group consist of 5-storeys with total height of 20m.

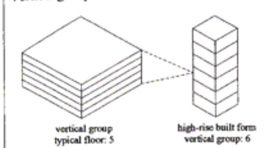
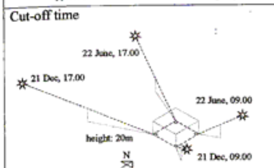
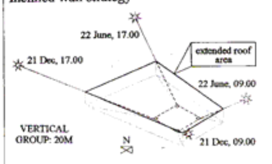
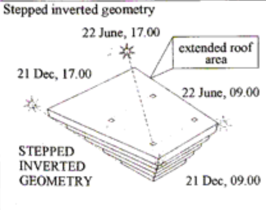
Step B	Procedure
Vertical group 	B1. Segmented the high-rise form into smaller vertical group, for example: 30-storey high-rise building can be divided into 6 groups, which means 5-storey height per group.
Cut-off time 	B2. Each level within the group will be generated according to relevant cut-off time and protection angle on its vertical wall. o Solar azimuth and solar altitude are plotted on each corner of the typical floor plan.
Inclined wall strategy 	B3. Inclined wall strategy increase the area of exposure area to sun. o Height for each group is 20 m. o Depth of self-shading projection depends on the protection angle and VSA of each wall orientation (table 2.2).
Stepped inverted geometry 	B4. Stepped inverted geometry strategy minimizes the exposure area of vertical wall. o Typical floor plan mentioned on B2 will be located on the centre of the vertical group. o every floors will be stacked up and cantilevered out above each other for a typical vertical group o Typical floor-to-floor height is 4m.

Figure 2: Segmented High-rise form into smaller vertical groups

Stepped inverted geometry is more relevant in high-rise built form compared to inclined wall strategy. Further modifications will be discussed in step C.

Step C: Modification on the self-shading projection depth

Modification on step C will concentrate on the adaptation of high-rise building design consideration in the modified model. Stepped inverted geometry illustrated at step B4 in figure 2 is more relevant for high-rise building design and this model is selected for further modifications based on the sun path and solar intensity. In order to investigate the effectiveness of stepped inverted geometry, each typical floor within the vertical group will be self-shaded by the same projection depth regardless of the wall orientation. Application of equal self-shading projection depths for all vertical walls may cause over-designing or under-designing for certain vertical walls. Therefore, series of self-shading projection depths is further explored. Self-shading projection ratio (SSP ratio) is introduced to show the relative relationship between the projection depth and typical floor-to-floor height. This ratio can be easily understood and applied for all dimension of projection depth and floor-to-floor height.

Positioning the service core is a fundamental aspect in high rise design and in a self shaded strategy the service core can be used more than just providing vertical accessibility. Centre core and side core are commonly applied in high-rise building design. The positioning of the service will determine which part of the building peripheral walls will have window or wall. Step C2 in figure 3 shows the application of the side core affecting the simulation results because the side core by itself already functions as solar buffer. High-rise built form with centre core will experience the full impact of solar insolation.

Step C3 shows the combination of stepped inverted geometry and the proposed core position. High-rise built form with side core only allows two sides stepped inverted geometry to be applied. The side core will protect the other two sides of the wall orientation. Placing service core at the centre exposes external walls to the sun. This compels all sides of the building to be designed as stepped inverted geometry. Therefore, the effectiveness of varied self-shading projection ratio (SSP ratio) can be performed and explored in this method. This modified self-shaded built form is chosen and developed as the base model 3 for examining the effectiveness of varied SSP ratio.

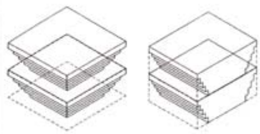
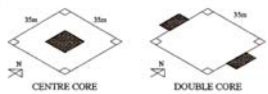
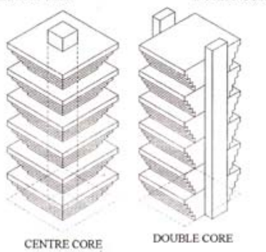
Step C	Procedure
Self-shading projection ratio (SSP ratio) 	C1. Equal self-shading projection depth on all wall orientation will be proposed. Each typical floor within the same vertical group will be self-shaded by the same projection depth. The relationship between projection depth and typical floor height is called self-shading projection ratio. There are five SSP ratio applied in this study: 0, 0.25, 0.50, 0.75 and 1.00.
Core position 	C2. Side core and centre core are placed on the typical floor plan. Side core produce a very deep parameter depth (35m from glass to glass). The centre core design produces 10.5m of parameter depth (glass to core).
Centre Core Double Core 	C3. High-rise built form with two side stepped inverted geometry and side core is produced. The built form can be placed facing north-south orientation and the side core will face to the east-west orientation. Thus, the impact of solar insolation can be minimized. The full side stepped inverted geometry with centre core is formed. Each wall orientations will face equal SSP depth. The effectiveness of each wall orientation is depended on its capacity to minimize the impact of solar insolation and proposed SSP ratio

Figure 3: Modification on the Depth of Cantilever

Step D: Additional Design Alternatives

Modifications from step A to step C completed the self-shaded built form, which will be used as base model for computer simulations. Step D will propose additional design alternatives to further minimize the solar insolation on its external wall.

Application of fully shaded and partially shaded strategies is depended on the solar altitude incident on certain wall orientation. The lower the solar altitude the longer depth of self-shading projection needs to be applied. Application of equal self-shading projection depths for all vertical walls in step C1 may cause over-designing or under-designing for certain vertical walls. Therefore, combinations of fully shaded and partially shaded strategies on one built form not only minimize the depth of self-shading projection, but also prevent unwanted solar radiation penetration into the internal spaces. Selection of SSP ratio for fully shaded north and south walls will partially shade the east and west wall.

Positioning side core on hotter sides (step C2) of the building is effective way to reduce solar heat gain. Besides installing additional external shading devices, internal shading devices and placing some vegetation at the balcony or sky court are also relevant for the above said purposes.

DEVELOPMENT OF GENERIC GEOMETRIC SHAPE FOR HIGH-RISE BUILDING

Development of simplified generic high-rise building form for building simulation is necessary, so that it can be easily integrated into the building design process. During the preliminary stage, building simulation on a simplified building form can shorten the time for simulation. It can predict the performance of various generic building forms and can lead to better informed design decisions.

In general, base models used in the experiment are generated from the typical geometrical characteristic and dimensions of the existing high-rise buildings in Kuala Lumpur, as described earlier in section. Selection of conceptual model is based on its relevance to high-rise building design. For this study, climate impact is the main concern and other considerations such as its buildability, typical floor efficiency and perimeter depth can not be neglected. The base case building form is developed into three base models to investigate the impacts of solar insolation on vertical surfaces.

Base Model

Figure 4 illustrate the design variables for base model A and B with variable plan form ratio and orientation. There are total 21 variations can be created from this base model. W/L ratio and building orientation are the independent variables for base model A. The impacts of solar radiation on three basic geometric shapes with varied plan form ratio (1:1, 1:1.7, and 1:3) are investigated.

Two commonly used generic geometric shapes including square and circular forms are used for the base models. All geometric shapes have similar height and typical base floor area respectively. In each geometrical shape, the volume is also the same but the exposed surface area is different, thus giving different values for the 'exposed surface area-to-volume' ratio. Its capacity to receive solar insolation depends on the total exposed surface area, which varies in every building shape.

The main outcome of this simulation is to determine the optimum shape on minimising total insolation on vertical surfaces. The characteristic of optimum shape can be studied in the next experiment of the base model.

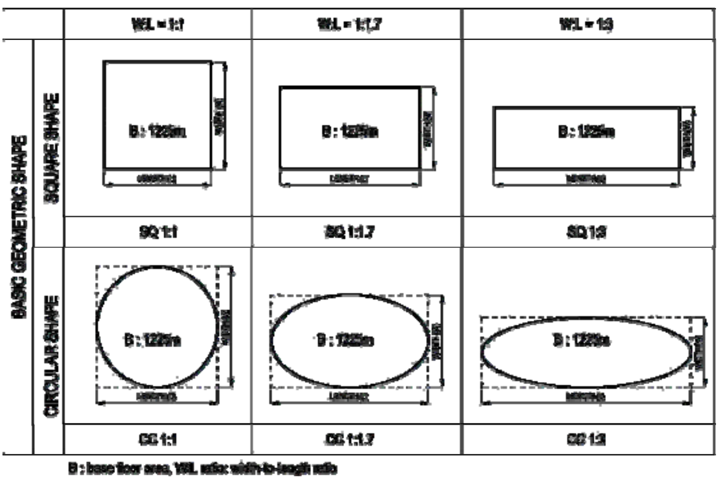


Figure 4: The geometric proportion of two basic geometric shapes.

Stepped inverted geometry is a self-shading strategy. It is more suitable for high-rise building design compared to the inclined wall strategy. Base model A and B are conducted by two optimum shapes, circular shape with W/L ratio 1:1 (CC1:1) and square shape with W/L ratio 1:1 (SQ1:1).

A study conducted by Chia (2006) suggested circular high-rise shape (plan form 1:1) as the optimum shape in minimising impacts of solar insolation on the vertical surfaces in the tropics. The approach of applying self-shading strategies on cylinder shape is less flexible compared to the preferred square shaped form.

Base model A: CC 1:1	Base model B: SQ 1:1
	

Figure 5: Base model A and B

Self-shading projection ratio (SSP ratio)

The self-shading projection ratio (SSP ratio) is the primary independent variable in this study. The main purpose of this study is to determine the effectiveness of the use of self-shading strategy in term of minimizing the incident solar insolation on the exposed vertical surfaces. Table 8 presented the self-shading projection configuration to be tested and the respective self-shading projection ratio (SSP ratio) in the study.

Self-shading projection ratio,

$$\text{SSP ratio} = \frac{\text{SSP depth [D]}}{\text{Floor-to-floor height, }[H_F]}$$

COMPARISON OF SOLAR RADIATION DATA BETWEEN WEATHERTOOL AND METEOROLOGICAL STATION (MS)

A major draw back in using meteorological parameters is its scarcity and unavailable detailed climate data. Obtaining daily measurements are also time consuming and location wise is dispersed. Unfortunately, accurate weather data only really exists for sites where there is a local meteorological station, and cannot readily be interpolated between sites. As a result, climate data has only been provided for a number of major towns and cities. As an alternative, numbers of climate prediction models have been recommended to estimate different climatic parameters with varying degree of details and accuracy. Comparison between the measured data from Subang Meteorological Station (SMS) and weather data from computer simulation needs to be evaluated.

Muneer et. al (1998) evaluated horizontal solar radiation data from both weather files by employing a statistical analysis. The Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) are the most commonly used indicators in examining the model performances. The MBE indicates whether the trend under predicts or over predicts its modeled values. The result is expressed as percentage. He also suggested that the accuracies of the order of 2-3% (MBE) are acceptable for daily summations of radiation and hourly summations may have error of 5-11% (RMSE).

$$\text{MBE} = \sqrt{\frac{\Sigma\,(\text{estimated value} - \text{measured value})}{\text{No of measurements}}} \quad \ldots (3.1)$$

$$\text{RMSE} = \sqrt{\frac{\Sigma\,(\text{estimated value} - \text{measured value})^2}{\text{No of measurements}}} \quad \ldots (3.2)$$

Comparison between the measured data from SMS and weather data from ECOTECT indicates a closer and similar pattern of horizontal solar radiation of the location for Kuala Lumpur. Basically both weather data would be evaluated in three ways. Firstly, comparison between the monthly averages is made, followed by the hourly data of four design-days. Finally, the frequency distribution of number of days for global solar radiation is checked.

Relevant data of weather elements can be extracted from ECOTECT version 5.2b and weather tool files for Kuala Lumpur (latitude: 3.120N, longitude: 101.60E). 'The Weather Tool' files are binary files used to store annual hourly climate data for a single location. This weather data consists of monthly statistics on temperature, rainfall, humidity, solar radiation daylight hours, and so on.

SIMULATION ANALYSIS CRITERIA

The analysis of the study is based on the output data obtained from the simulation for the tested generic geometric shape and self-shading strategies options. The output results were obtained in two stages.

a. The output results for the tested generic geometric shape obtained based on annual total values.

b. The output results for the tested self-shading strategies options also obtained in two forms:
   - o Average daily total values on three specific design-days.
   - o Solar insolation index, μ-index

The annually results were only obtained for total solar insolation on the entire external surfaces of generic geometric shapes and it has been totalled up as the annual total solar insolation (MWh). Results obtained from comparison between the annual total values of the simulated building shape to the selected optimum shape, gives better understanding of the capacity of each building shape to receive solar radiation. The results of annual total solar insolation and comparison between building shape were combined into a single graph on respective geometric shape, W/L ratio and building orientations.

Average daily results obtained the performance variable for direct, diffused component of solar insolation on self-shaded building shape. The results of direct, diffuse and total (direct + diffuse) average solar insolation (Wh/m2) are performed in graphical indication based on the analysis grid discussed in previous section. To get a better understanding of the SSP ratio on the performance variables, the results of each direct, diffuse and total components of solar insolation with the solar insolation index are illustrated in a single graph on respective dates and for orientation.

Solar insolation index, μ-index is introduced by Stasinopoulos (1998); it is defined as the ratio of the average solar irradiance on any surface to that on the horizontal surface. μ-index indicates the efficiency of a form or surface by comparing ratio of received average solar insolation to available solar insolation at the same time and place. So as surface or form is transformed to become flat and horizontal, its μ-index tends towards 1.00 or 100%. Assuming that horizontal surface (flat roof) of building shape always received maximum intensity of solar insolation. Thus, other vertical surfaces will received less than 100% as compared to the horizontal surface depending on the degree of solar exposure over the specific time.

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4
BUILDING SIMULATION FOR ENERGY EFFICIENT SOLAR SHADING

Dilshan Remaz Ossen

INTRODUCTION

The external horizontal shading device is an important climatic design element in the tropical climate. According to the review, little is known about the influence of external horizontal shading device on reducing the solar heat gains, daylight penetration and the building energy consumption. Another important aspect is that the review on energy audits indicated a high intensity of energy consumption (an average of 269kWh/m^2) for office buildings in Malaysia. However, significant energy savings can be achieved in buildings if they are properly design and operated. Therefore, it is important to investigate the above interrelated issues to determine appropriate solar shading design strategies for the correspondence climate conditions. Also, early design decisions are the most effective than making changes at later stages after construction, which is time consuming and costly.

According to the literature review, energy performance of high-rise building is influenced by several design variables. The best option to optimize the total building energy consumption is to test the number of design alternatives, which is time consuming and laborious approach. The other way of dealing with the problem is by varying one variable at a time and keeping the others fixed at reasonable practical values in order to determine the effect of the particular variable on the energy performance of the building.

Therefore, it is necessary to find a compromise that best matches the priorities and objectives of the study.

The main aims of the experiment are:

a. To assess and compare the impact of external horizontal shading device geometry in reducing the unwanted solar heat gain and the amount of daylight penetration into the building.

b. To compare the potential trade-off involved between the solar heat gain and daylight penetration for determining the optimum overhang depth to achieve optimum energy consumptions.

METHODS OF ENERGY EVALUATION

Different interrelated issues influence the energy consumption in buildings. Awareness in energy issues and energy management are important measures that can play a significant role in the building design process. According to Al-Homoud (2001), energy analysis in buildings is important to achieve the following:

- To determine the alternative energy efficient design options, systems, sub-systems and equipments
- To allocate an annual energy budget
- Compliance with energy standards
- Economic optimization
-

The procedures for estimating energy requirements vary considerably based on the complexity of the analysis. In general they can be categorized as simplified energy calculation methods and detailed energy calculations methods.

a) Simplified Energy Calculation Methods

The most commonly used simplified energy estimating methods are degree-day method (DDM), modified degree-day methods (MDD), variable based degree-day methods, bin-method and modified bin methods (ASHRAE, 1989).

The degree-day and modified degree-day were single measure steady state methods that can be used only for heating calculation in small buildings. The results were based on the average conditions and out door weather variation were not accounted. Also, these methods cannot be used for cooling load calculations therefore not applicable for building energy calculation under the tropical climate conditions. The variable based degree-day method uses the same concept of DDM, but counts the degree-day based on the ***balance point temperature*** for the building. According to the ASHRAE (1989), the balance point is the average out door temperature at which the building requires neither heating nor cooling. The variable based degree-day method considers all factors that influence the balance temperatures, such as indoor temperatures, thermal properties of building elements, heat gain from appliances and solar radiations. Although this method can be used for both heating and cooling load calculation, generally the cooling load calculation are difficult compared to heating load calculations (Al- Homoud, 2001). This is mainly due to the complexity of heat gains in buildings, infiltration and the effects of humidity.

The bin-method and the modified bin-methods consist of performing instantaneous heating and cooling energy calculations at many different outdoor dry bulb temperature conditions. This method involves making instantaneous energy calculations at several different outdoor temperatures. The bin method only uses peak loads to establish a load profile. It accounts on hourly weather data rather than daily averages. The modified-bin method allows off-design conditions which calculate diversified load values rather than peak loads. The diversified load profile is characterized by average solar gains, average internal loads profile, secondary systems and plant equipment effects. Some of the constraints in using the bin methods are: not reliable for buildings with complex high solar radiation effects and with high thermal mass loads and also the building size is limited between 500-2500m^2 (Al- Homoud, 2001).

b) Detailed Energy Calculation Methods

Assessing building energy performance is a complex process. Each system is (building design and envelope, mechanical system and management system) inter-related and each set constraints on one or more of the others. Furthermore, each system may consist of several subsystems, for example the building design and envelope designs relate in minimizing heat gains, maximize daylight utilization, achieving high thermal comfort satisfaction, controlling air movement. The unsteady climatic excitation is another major parameter affecting the building energy performance. Therefore, building energy performance is inherently a dynamic as well as a complex process in which many parameters change over time and at different rates (Clarke, 1993; Hong et al, 2000; Bouchlaghem, 2000).

These complex processes of the real system is abstracted and implemented in a detailed simulation model with reasonable assumptions. Simulation models are flexible performance tools used to produce a set of selected measures that reflect the performance of the simulated system (Al- Homoud, 2001). A series of mathematical models are developed for building and its energy system representing the following:

a. Thermal behavior of the building structure
b. Thermodynamic behavior of the air-conditioning delivery system
c. Mathematical relationship between loads and energy requirements of primary equipments

d. Relationship between the daylight and artificial lighting energy requirements

These models are logically linked with each other to obtain an overall energy performance of the correspondence system or in the building design. Al- Homoud, (2001) points out that there are two modeling strategies being used in evaluating the building energy performance. They are the sequential approach and simultaneous solution approach. In the sequential approach, the loads are calculated in step by step in following order. First the space loads, then the secondary system loads followed by the primary system loads and finally the energy cost. The output of each step is used to execute the next step. According to Al- Homoud, (2001) this approach lacks interaction between the loads, system and plants which may produce questionable results. For instance, when the equipment capacities cannot meet the required load, this will effect on the ultimate result.

In the simultaneous approach, the loads, systems and plant models are solved simultaneously at each time step (Al- Homoud, 2001). This provides more accurate results compared to sequential approach, but the simulation process is a complex mechanism.

Due to the complexity, detailed energy evaluation methods are incorporated in computer programs to conduct the calculations. This enables to effectively analyze the building energy performances with accuracy and faster. However, single measure simplified calculation methods can be carried out by hand.

METHODS OF STUDYING ENERGY IN BUILDINGS

A literature survey of previous work suggested that solar shading has a direct impact on building cooling load, heating load, electric lighting load and daylight distribution. Various experiments have been carried out to analyze and evaluate the impact of solar shading on above aspects separately. Previous works suggested three types of experimental methods commonly used in energy related research on shading devices. They are actual building measurements, simulation studies and use of simple calculation methods. Choosing the appropriate method to meet the objective of the studies and the expected outcome of the research will save a great deal of time and effort (Hamdan, 1996).

Intended primary objective of the present study is to determine the cooling and lighting energy balance due to daylight utilization as a function of external solar shading device. To consider the correlation between above parameters in the design of shading devices is to study their impact on building energy use (Dubois, 2000; Shaviv, 1999; Lee, 1998).

a) Manual Calculation Methods

Traditionally manual calculations using pre-selected design conditions and 'rule of thumb' were applied throughout the design process (Hong et al, 2000). Most manual calculations are based on steady state conditions, where factors influencing the heat transfer are considered under constant state. Therefore, manual calculation approaches frequently led to oversized plant and system capacities and poor energy performances. Also, it is based on average conditions and does not account for day-to-day weather variations. Another constrain in manual calculations is the difficulty to evaluate the effects of natural lighting and artificial light integration.

b) Field Study or Full Scale Method

The main constraints to carry out experiment in real building or using scale model are complex and comprehensive procedure in methodology, limitation in available equipment, limited budget, time consuming and limited man power. Moreover, to obtain approval to use the building and to obtain information takes longer time and persuasion due to the attitude of the building owner, architect and the builder (Hamdan, 1996). Also at present there is no building built for low energy performance except for the Multimedia Low Energy Office (MEWC-LEO) building in Putrajaya. It is the first building which integrates comprehensive features of energy efficient features, built in Malaysia. The building was under construction during the present study. Hence, the performance of the MEWC-LEO building is still under investigation and thus the results are still limited during the present study was conducted.

Well equipped research laboratory or full scale mockup experimental rooms for energy experiments are not yet available in any architectural school or in any other research institutes in Malaysia. However, combined experiments were carried out to overcome the shortcoming from any particular methods stated above and to verify the findings (Dubois, 2001; Abdullah-Abdulmohsen, 1995; Chavez, 1989). Since each method uses different techniques and uses various equipments, the combined research methods are costly, time consuming and only appropriate in well resourced programs (Hamdan, 1996).

c) Computer Simulation

Due to above stated complex process of building energy performances, limitations and constraints, the only alternative method that is possible to explore is to depend on computer simulations. The advantage of using a dynamic energy simulation is that complex daylight, thermal and radiative processes between the building, shading device and the out door environment are considered in the calculations. Thereby any design short comings can be reviewed before finalizing the design.

Another advantage is that the detailed energy simulation programs can provide hour-by-hour extensive out-put data. However, they require some time in learning how to use them, preparing the input, running them and interpreting the results to the requirement of the research. The accuracy of the programs depends on the accuracy of modeling building components and on the program input assumptions.

The MEWC-LEO building also optimized the effects of applying the main energy saving features using the Energy-10 computer software before they were implemented in the actual design and construction (Kristensen, 2003). This indicates that optimizing the energy saving features and calculating the energy balance of the building using computer simulation is an acceptable method in designing energy efficient buildings.

SELECTION OF COMPUTER PROGRAM

Energy simulation in buildings offer a valuable tool for architects and engineers to evaluate building energy consumption before the building is built. In recognition of the significance of energy use in buildings, large and complex energy simulation programs have evolved. At the core of all simulation models is a mathematical representation of the thermal and optical transfer processes occurring within the building and plant systems (Clarke, 1993).

Though there are more than one simulation programs that meet the requirement for any given problem, there is no single program that can perform all kind of simulation (Hong et al, 2000; Hamdan, 1996). According to Hong et al (2000) there are three important factors to consider in selecting an appropriate simulation program:

a. Purpose of the study: Understanding the nature of the problem expected to solve with the use of the simulation program.
b. In terms of cost: Includes software cost, cost of the computer platform, user training cost should be within the study budget and period.

c. Available facilities: Selected program should be able to run on existing computer facilities, especially in personal computer (PC).

Balcomb (1998) describes that the following factors should be part of the simulation program to make the program easy and faster to use:

a. The building should be described graphically using CAD tools or user friendly interfaces.
b. Automatically modifying the design description to effect the application of energy efficient strategies.
c. Estimating the size of the HVAC equipment requirement to meet design day loads.
d. Option of evaluating various parametric schemes.
e. Displaying results in an understandable way either graphically or in spread sheets (tabulated).

a) Requirement of the Study

The purpose of the study is to understand the interaction between the solar shading, solar heat gain, daylight and energy needs of high-rise office building. Therefore, any simulation program chosen should be able to analyze effect of building design features on solar radiation, daylight, cooling load, lighting load and calculate saving due to daylight utilization. Thus, the software must have following criteria:

a. Provide required climate condition and weather data for specified location.
b. Estimate the incident solar radiation, heat transmission and resultant daylight levels.
c. Provide daylight/ electric light control strategies and estimate the electric lighting trade off due to daylight utilization.
d. Provision for parametric evaluation, e.g. options in creating different geometry of external solar shading devices

e. Provision and easy construction of the required building configuration, operating schedules, HVAC system and plant sizing etc.
f. Simulate hourly values of required parameters and annual energy calculations to evaluate the trade off between cooling load, lighting load and the total energy consumptions due to daylight utilization as an effect of external solar shading system.

b) Review of Energy Simulation Programs

Marsh (2002), Hittle (2001), Crawley (2001), Hong (2000), Balcomb (1998), James J. Hirsch (2000), Pasqualetto (1997) and McHugh (1995) have investigated some commercially available energy simulation software. However, the following simulation programs enable to fulfill the required criteria of research and was further reviewed; Building Loads Analysis and System Thermodynamics (BLAST), BSim 2002, ECOTECT, Energy-10, Ener-Win, Energy Plus, IES Virtual Environment, Power DOE and eQUEST-3 DOE 2.2

According to the review, the Radiance-IES module in the IES Virtual Environment (IES VE) simulation program creates a better daylight modeling capabilities with photo-realistic pictures and contour of illuminance than other programs discussed. The Energy-10 and DOE 2.2 includes the daylight calculations simply to estimate the savings due to dimming and capture the thermal effects of the natural lighting for energy calculations. It is important to understand that Energy-10 or DOE 2.2 is not daylight design tools but structured for complex energy calculations. The DOE 2.2 calculation engine incorporates the daylight results directly into the control schedule for lighting, thus models cooling loads reduction or gains and demand savings in lighting, cooling and total energy consumption. The DOE 2.2 program also provides a larger range of simulation variables. Apart from above capabilities, the required criteria of the research and considering the financial constraints, the eQUEST-3 user interface of the DOE 2.2 is a capable software to analyze the impact of solar shading integrated with daylight on the building energy performance. The building simulation procedures are further elaborated using the e-QUEST 3 program as an example.

THE e-QUEST-3 COMPUTER SIMULATION PROGRAM

The simulation "engine" within eQUEST-3 is derived from the latest official version of the DOE-2.2. However, eQUEST-3's engine DOE-2.2 extends and expands the previous version of DOE-2 capabilities in several ways. This include HVAC plant operations, interactive operation between daylight and thermal loads, dynamic default calculations and selection of energy conserving or peak demand reduction alternatives.

The eQUEST-3 energy simulation program is in the process of being submitted for certification as Title-24 (California's Energy Efficiency Standards for Residential and Nonresidential Buildings) compliance software (Shank and Lunneberg, 2003). Shank and Lunneberg, (2003) and Brown et al (2003) reported that this software is proven reliable and validated for evaluation of energy efficiency measures of typical building forms.

The DOE-2 program for building energy use analysis provides the building construction and research communities with an up-to-date, unbiased, well-documented computer program for building energy analysis. The DOE-2 is a portable FORTRAN program that can be used on a large variety of computers, including PC's. Developments and updates of the DOE-2 program have continued since the first version. Each new version of the program is denoted by appending numbers and letters for major and minor changes, respectively (Al-Homoud, 2001). Since its first release in late 1970's the DOE-2 has been widely reviewed and validated in the public domain{Meldem, R. & Winkelmann,1998; Holz et.al, 1996 (DOE-2); Kannan, 1991(DOE 2.1C); Reilly et al,1995; Pasqualetto et al., 1998; Lam & Li, 1999 and Carriere et al., 1999 (DOE2.1E)}. Based on the DOE-2 engine there are several interfaces developed by the resellers. The main difference between each interface depend on their licensee and simulation cost. The freely available programs only provide access to selected modeling capabilities.

a) Simulation Procedure

This section will outline the sequence of the simulation approach, from acquiring the required data and the construction of the model to the output of the results. According to the program description, the DOE-2.2 has one subprogram for translation of input data (BDL processor) and three simulation subprograms (Loads, HVAC, and Economics).

The loads simulation subprogram calculates the sensible and latent components of the hourly cooling or heating loads for the each user design spaces in the building. The loads program sums the loads from each type of heat gain into a total load, which it passes to the HVAC program. The building cooling/heating load is responsive to weather and solar conditions, lighting and equipment, schedule of people, infiltration, heat transfers from building envelope elements and to the effects of buildings shades on solar radiation. Daylight calculation of the program is incorporated with the specific lighting load calculations. The calculations were performed by applying a room weighting factor to the heat gains to determine the loads.

The overall simulation procedure is performed in four steps. The detail explanations of the steps are as follows:

Step I: Data Requirement

Initial step involves preparation and gathering the required data to develop the simulation model. The approach has to focus on the design questions intended to solve using the simulation model.

For example; to achieve research objective as stated in previous section a single zone primary unit office room can be selected for further investigation. The geometry and characteristics of the typical office room model is developed based on the analysis of the high-rise office buildings in of a particular location or climate condition with following assumptions:

a. The typical office room is in the perimeter zone with a single window. Hence, assumptions are made that heat gain through the window system is significant compared to the heat gain through wall, floor and roof area in high-rise office buildings.
b. Heat transfer from internal walls, ceiling and the floor are constant for all tested cases.
c. The prototype office room can be accumulated to create perimeter office buildings facing the main cardinal orientations.

Use of perimeter office room will avoid the calculations of the energy consumed by the building's deeper spaces and core spaces, which are largely depending on artificial means for cooling and lighting. These spaces are also independent from the effects of solar radiation and shading strategies.

Step II: Preparation of the Models

The required building model can be created using eQUEST-3's building wizard (figure 1). This wizard allows all the data gathered prior to the simulation under specified dialog boxes to be incorporated. The models were generated for six horizontal overhang options on the east and west orientations, five horizontal overhang options for the north and south and for two natural-light design criteria. The following details are required by the wizard to generate the specific models for simulation:

a) General information

This section includes building type, weather file coverage, overall size of the building, utility rates, cooling equipment and option of daylight utilization. Depending on the building type, set defaults for the HVAC system, construction materials, operation schedules and loads will be selected by the program. These default values are derived from the up to date simulation program library. These values are based on the ASHRAE supported research projects. However, these values are tested and validated for temperate climate conditions, e.g. HVAC system details, construction materials and operation schedules. In such cases the program allows for user input values and set up the simulation conditions to represent the corresponding simulation condition.

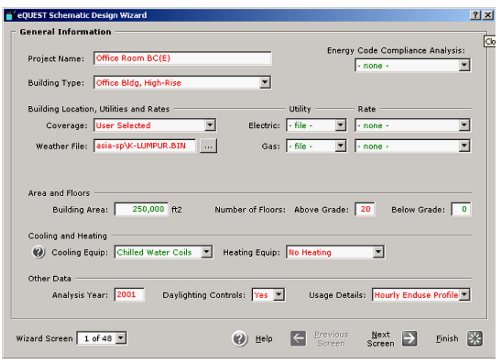

Figure 1. Typical eQUEST-3 building wizard screen

The weather file coverage, region and city option enables the user to specify the required climatic weather file for a specific location. The program allows three choices of climatic data; 16 California climate zones, several other cities in United States and from the standard DOE-2 weather files which includes weather data for Kuala Lumpur. Having the option of selecting required climatic data and the HVAC system detail (cooling/heating) as well as the option of daylight utilization, enables the program to be used in any climatic condition for load calculations. In the tropics, the cooling and daylight components are more important than heating.

b) Building Description

The building description section allows establishing the building foot print, building orientation, building construction and door-window detail options. Shape and size of the building model is created using the data input of building foot print dimensions. However, the program allows creating custom made building shapes using a Cartesian co-ordinate's screen. Default values are given for exterior and interior surface constructions (roof, wall ceiling finishes and colour) based on the building type. The program also allows adiabatic wall surfaces to be created if necessary. The detail section provides flexibility to incorporate user define values if necessary.

The doors and windows are selected according to the orientations of the wall surface. For each orientation, required number of door and window elements can be selected based on the length and height of the wall. A percentage value can be suggested for the window as compared to external wall surface or internal wall surface (within floor-to-ceiling of the wall with the window). Two options of windows are generated; identical windows divided within the wall space and a single window to cover the entire window area specified. Materials and glass types are selected from the default library or user can create his/her own library of materials.

This screen also includes external shading device dimension for relevant windows. Only two types of external shading devices are included in the program; horizontal overhangs and vertical fins. Additional requirements if necessary such as changing length, width and angle of correspondence devices can be adjusted in the detail section.

c) Daylight Utilization

The daylight input screen is displayed if only the daylight option in general information screen was selected. Two daylight concepts are allowed in the daylight modeling; sky light and side light options. For multistory buildings, three daylight zones were allowed, ground floor, typical middle floor (all middle floor zones were summarized into one typical floor) and top floor zone. In non daylight utilization option, internal illuminance is provided by artificial means. Hence, the building will be converted into a daylight-rejecting building type.

d) Activity Area and Occupied Internal Loads

Heat gains from internal loads (people, lighting, equipment) contribute significantly both from their direct power requirement and indirect effect on cooling/heating requirement. Internal loads are specified based on user input for activity area. The program load schedules are based on two levels of activities, during occupied and unoccupied hours. According to the type of building being analyzed, the activity areas are allocated by percentage value. Preferred occupancy density and out side ventilation rate (per person) were also included to the program. Then the program allocates these loads to each HVAC zone for calculations.

e) Building Operations and Schedules

The program permits up to two building usage schedules, a main schedule and an alternate schedule. The alternate schedule is to be used if there is different schedule for a second season. Apart from two schedules, it also gives the option of three day types; five week days, two weekend days and a holiday. This enables to specify usage of building for three different activity patterns, if required.

f) System and Plant Information

Zone cooling, heating and ventilation loads are transferred to the HVAC module to model the performance of the loads. The transfers of energy to these systems are dynamic in nature and the loads are calculated in hourly basis. Undersized equipment may affect the zone temperature and thereby affect the load calculations (Hittle, 2001). Therefore, proper control modeling is an essential part for arriving at better simulation and correct system loads. However, default system types are based on the building type and the coil types selected under general information screen.

Primary equipments such as chillers, cooling towers and boilers also influence the energy consumption of the building. General understandings of their functions are required. Selecting a plant type and the capacity is based on survey done on buildings and chosen from most commonly used system.

Step III: Detailed Interface-Selecting Simulation Parameters and Perform Simulation

The detail interface option allows you to further refine and edit the input data to suit the requirement of the study. The energy efficiency measures (EEM) wizard in detail inter face allows to select ten design alternatives to the base building description. However, alteration to the building made in the detail interface will not be communicated back to the 'building wizard'. Therefore, the EEM wizard can be used only for buildings described by the 'building wizard'. The detail interface also allows monitoring the building in three-dimensional form.

Modifications in detail interface allows for alterations in two methods: using “spreadsheets” and “detail tabbed dialogue box”. These spreadsheets and dialogue boxes can be used to review, input or modify general features related to the respective components. Buildings with alterations and modification in detail interface enables design alternatives to be analyzed and simulated for energy consumption to the base case model only.

Within detail interface, user is permitted to select simulation parameters up to 60 variables from the following tables; global weather data, building loads, space loads, external wall loads, window loads, zone loads, system loads, and plant loads. Based on the selected variables the hourly reports were calculated for every hour of the day, daily summary, monthly summary and yearly summary for the correspondence year. These reports can be used for detail analysis of the expected out come or results of the simulation.

Once the descriptions of the preferred building are completed, the simulation can be performed by pressing the run simulation button. The simulation is performed for the designated annual year. Overall numbers of simulations permitted to be performed were 52.

Step IV: Review Simulation Results

The program provides a graphical simulation output in two forms; single run report and comparison report. These results only present monthly and annual energy consumption by endues, utility bills and peak demands. The hourly values are written in text form; therefore the required data need to be transferred to excel work sheets to obtain graphical descriptions.

SIMULATION LIMITATIONS

The performance of the simulation programs are bound to have few limitations. Understanding the limitations will help to perform the simulation accurately and to justify the results with proper reasons. These limitations vary between different simulation programs.

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5

USE OF COMPUTATIONAL FLUID DYNAMIC SIMULATION IN SOLAR INDUCED VENTILATION STRATEGIES

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INTRODUCTION

Various models and tools have been invented to fulfill the different needs in natural ventilation study. Models and methods ranges from a very simple empirical algorithm to calculate airflow rate to a sophisticated computational fluid dynamic (CFD) techniques, in solving the Navier-Stokes equation. Yogou Li (1994) classified the available methods to estimate air flow into three categories. They are analytical method, use of a full scale model and CFD technique. Heerwagen *et. al.* (2000) classified the available methods into four categories which are field measurement, physical modeling, computer simulation and simplified methods. Wang (1996) categorized the main method for studying natural ventilation due to temperature difference through two main methods. They are physical and virtual experiment methods. The physical experimental method includes scale measurements or field experiment. Meanwhile, virtual experimental method is referred to as CFD modeling base on numerical equation.

The main aims of this research is to estimate the internal temperature difference caused by solar induced at solar chimney model and to predict the internal air velocity of the proposed solar chimney. Consequently, this will determine the performance and effectiveness of the solar induced ventilation at proposed solar chimney in achieving thermal comfort ventilation. Therefore, the appropriate methodology to be used is the two steps method. The first step is to estimate the temperature difference over the internal solar chimney model. The second step is to apply the temperature difference obtained from the sealed building to the openings using flow rate methods. This method is adopted from Awbi (2003).

THE PHYSICAL EXPERIMENTAL METHOD

Full-scale measurement can be used to judge the actual performance of a building, a system or a technology. In natural stack ventilation study a scale or field measurement is intended to measure the profile of the wind approaching the site, the temperature distribution and the vectors of wind (Wang, 1996). These techniques can be applied either to an existing or new buildings and to estimate the temperature difference. According to Wouters, *et. a!.* (1998) full scale measurement is the best way to obtain better understanding and evaluate the building performance and its function. It is also the best technique, because it can provide actual experimental condition, this can be used to compare the agreement between the predicted performance and the actual performance.

However, the procedures are very complex and involve comprehensive experimental methodology, experiment equipments, cost, manpower and man-hours. Moreover, the results can be applied only to a specific site and conditions (Wang, 1996). This will limit the contribution of the findings. Due to these reasons, the proposed research is not viable to be carried out using this method.

a. The Physical Experimental Modeling

When considering the free convection, the Grashof number is always used, which is the ratio of the buoyancy to viscous force.

$$\mathrm{Gr} = g\beta\Delta T l^3 / \upsilon^2$$

where, g is the acceleration due to gravity (m/s^2); β the thermal expansion coefficient (1/K); ΔT the temperature rise (K); l the characteristic length (m); and υ is the viscosity (m/s). Actually, it is almost impossible to preserve the Grashof number in the reduced scale model and the full-scale building. However, it is found that even for the free convection, as long as the turbulent intensity of the flow is over some value of the Grashof number, the basic characteristic of the flow becomes independent on the Grashof number. For natural ventilated space, most of the flow region can be regarded as such state (Takashi, 1981). Therefore, substituting the turbulent viscosity υ_t (it is proportional to the product of the local velocity U and length l for the Grashof number),

$$\upsilon_t \; \alpha \; Ul$$

$$(\mathrm{Gr})_t \; \alpha \; g\beta\Delta T l^3 / U^2$$

Considering $\Delta T_M = \Delta T_F$, then

$$U_M / U_F = (l_M / l_F)^{1/2}$$

Where, M indicates model and F indicates full-scale. Basically, the Grashof modelling mentioned above can be used to establish relations between the reduced scale model and the full-scale prototype. (Ding, 2004)

b. The Physical Experimental conditions

Under real context, physical experiment creates restriction which may be considered as disadvantages (e.g. the existence of air movement around the model which will have an impact on the measurement) and advantages (e.g. potential of the model to be improved). This emphasizes the need for a clear experimental procedure and a more flexible design of the models. It is important to anticipate and minimize the influence of the environmental conditions at the experiment location, which could result in a biased result. The site environmental constraints will enable to re-configure the model so that an optimum ventilation performance could be obtained (Satwiko, 1994). To realize preferable airflow throughout the building, setting of openings should be reasonably planned. Measurements of the temperature and pressure difference are used to assess the natural airflow conditions through the mode. Incense sticks are used to judge the airflow direction near the openings. Data loggers are positioned at the testing points and data were recorded in short time intervals (Ding, 2004).

THE VIRTUAL EXPERIMENTAL METHOD

Compared to physical model testing, results obtained using CFD codes (numerical methods to simulate real conditions) have been regarded with skepticism. As it is a virtual simulation, the CFD codes have been viewed as producing unrealistic results. It has been difficult for these codes to be accepted as imitating real conditions. CFD was originally developed by L.F. Richardson in 1917. Its codes consist of equations, known as Navier-Stokes equations, which are highly non-linear and cannot be solved using simple algebraic methods. As a result, this method has only recently become fully developed, with the technological ability of personal computers, which are more powerful, faster, and more economical (on time and labour). Computers enable experts to solve Navier-Stokes equations iteratively. CFD methods have several advantages over traditional, analytical and physical model measurement methods. A CFD model, compared to a full-scale physical model, is easier to set up, less costly, consume less time to run, while simulating boundary layer wind profiles with greater accuracy and ease (having no building size limitations). It is easier to investigate, parametrical changes in the building's design, and provides valuable output (eg. detailed air flow patterns around the building). Analytical methods have suffered from severe simplification of assumptions and simplistic designs. Though full-scale physical model measurements provide the most reliable data, they are expensive and difficult (mostly impossible) to do. Nielsen, in 1974, was the first person who used CFD codes to study air motion in rooms. Since then, experts from various countries have vigorously conducted research on the application of their CFD codes to building environmental studies.

a. The Virtual Experimental Modeling

In experiments using Virtual Codes, the pre-processing (or preparation phase, i.e. transforming the real model into integer space representation, preparing the grid, etc.) consumes most of the time required. Compared to pre-processing, the calculation process consumes less time. However, once started, the processing step continues to completion with no interaction possible, if for example, the calculation showed a difficulty in convergence. The pre-processing, on the other hand, can be run in an interactive mode which gives two advantages: instant verification of the validity of the command (syntax and logic) and the flexibility to terminate and resume at anytime. The same sequence as in the physical experiment can be illustrated when the model configurations were analyzed using virtual experiment. Unlike in the experiment using physical models, in the experiment using a computer program, the geometry of the model can easily changed by redefining the position of points. Transforming the model with grid strategy is the division of the flow domain into small parts as required by the finite elements method as the basis of CFD calculation. The form of the grid is dictated by the geometry of the flow domain.

Grid strategy is important to achieve an optimal balance (or composition) between the validity of result and the efficiency of the calculation. Small cells and an overall fine grid means that the accuracy of solution is much greater, but costs more in calculation time. In practice, not all parts of the flow domain need to be divided into fine grids. Only in areas where high fluctuations of variables occur the fine grid is required. In general, non uniform grids are preferable to uniform ones. In non uniform grid, a fine grid is applied at locations such as in and around diffusers, heat sources, obstacles, and walls. Hence, intuition or experience is needed to predict the likely air flow pattern so that the finer grids can be located at the right places (Satwiko, 1994). Additional grid points are embedded near the walls, around the openings to enable better resolution in these areas (Ding, 2004).

In the virtual experiment the air flows were assumed to be laminar, the Rayleigh number could be taken anywhere between 10^3 and 10^6. When the preliminary tests found that taking $Ra = 10^6$ had resulted in a convergence difficulty, then we can use two solutions. Firstly, a special solution technique called *acceleration factor could* be applied. Secondly, smaller *Ra* numbers could be used. If the preliminary tests found that taking $Ra = 10^s$ could solve the problem (a convergence could be achieved in 4 to 5 iterations) and no acceleration factor was needed. Thus, the reasons why a Rayleigh of 10^5 was chosen there was a problem of convergence of the CFD calculation if a higher Ra# than 10^s was used. A *Ra* 10^5 was considered tolerable since it is close to the transitional flow range (*Ra* 10^6 to 10^9). With this number, a convergence problem could be avoided and a reasonable result could be achieved (Satwiko, 1994).

b. The Virtual Experimental Condition

The virtual experimental conditions data specify the constant value of certain nodes. These data, together with the grid strategy, form the logical boundaries of the flow domain. Velocity boundary condition data, for example, define the air velocity on surfaces as zero. Thermal boundary condition data define the location and magnitude of heat release in the space from occupants, lighting, and possible heat generating equipment. Boundary condition data are also known as constrained nodal data. There are two types of boundary condition: flux type and nodal point type. Flux types specify conditions such as boundary stresses and heat fluxes. Nodal point types specify boundary conditions directly to nodal points in the mesh; e.g., specified values of velocity, temperature, pressure. Initial conditions data specify initial values for certain nodes. These data are applied to the nodal points in the mesh. For a transient analysis these values are used as the initial conditions at the initial time, while for a steady state analysis they are used as the initial guess for the nonlinear iterative solution method. In general for stack induced ventilation experiment, two boundary conditions were involved, i.e. temperature and velocity boundary conditions. Both were applied to all surfaces of the model. Surface temperatures were taken from the solar radiation calculation. These results were normalized. Velocities at all surfaces were set to zero. This meant velocities at given nodes (which were occupied by the surfaces) were zero. Its value would be calculated by the computer program. It started from zero and increased incrementally until all the equations (which were used in the program) were satisfied. Initial values could be given as a first estimate to speed the calculation (Satwiko, 1994). Fluid property data specified the fluid properties such as density, specific heat, and viscosity. To simplify the calculation, all values were normalized. Using dimensionless values, the density became;

$$\rho = (Ra.\mathrm{Pr}^{-1})$$ [5]

And the specific heat became the Prandtl number,

$$C_p = Pr$$

Other properties such as viscosity, thermal conductivity and volume expansion became unity. For the natural ventilation prediction, the flow is considered to be a low level of turbulence and an indoor zero-equation model is used where eddy viscosity is given from an analytical equation without involvement of transport equations. Density variation caused by temperature rise is expressed using Buossinesq approximation, which takes air density as constant and considers the buoyancy influence on air movement by the difference between the local air density and the pressure gradient. The upwind scheme has been used in the calculations (Ding, 2004)

CFD SIMULATION

However, although it has now been twenty-five years since Nielsen first applied CFD codes to indoor air motion study, issues of validation are still debated. Many research reports have been published, but the majority discusses validating the codes using simple room geometry. Of thirty-two such papers, three (9.4%) discuss purely theoretical aspects (eg. Baker), sixteen (50%) discuss validation processes (eg. Williams), eleven (34.4%) report on the use of CFD codes for practical design purposes (eg. Kolokotroni), and two (6.2%) report on the use of CFD for actual construction projects (eg. Kent). It seems that experts are still unsure about completely relying on CFD codes as a design tool. Moreover, 80% of the papers present advanced mathematics equations, which require a reasonably high skill level in mathematics for understanding. CFD solutions are based on the closure of conservation equations relating to mass, momentum, and energy. As the number of unknowns is larger than the number of equations, more equations are needed for closure. Usually, two equations are use, one concerned with turbulent kinetic energy (k) and another relating to kinetic energy dissipation rate these are popularly known as the k-ε equations. The accuracy of CFD depends very much on the accuracy of the turbulent models. Turbulent modeling expresses Reynolds stress, turbulent heat flux, and turbulent diffusion flux. The accuracy of an iterative solution depends on such variables as grid resolution (i.e., number of grid points) and convergence criterion used. From a computational perspective, interior airflows are complex and generally turbulent. Predicting airflow within buildings is more difficult when buoyancy is involved. In terms of the closure the Partial Differential Equations (PDE), buoyancy terms, being non-linear, are the most difficult to handle. Moreover, improper selection of the reference velocity for scenarios involving natural convection in enclosures can cause considerable numerical problems, and hence, inaccuracy. CFD also overestimates flow rates through windows, especially in buoyancy driven flow. The root of this problem lies in a velocity profile through the opening, not accounted for in the CFD simulation. The k-ε model assumes that eddy viscosity is the same for all Reynolds (Re) stress (isotropic eddy viscosity) and is restricted to flows with high Re. This method has been developed and modified. There are still some different opinions about CFD validity based on concerns about the k-ε methods used by the codes.

CFD prediction produces detailed information on the distribution of air velocity, temperature, turbulence quantity, contaminant concentration, humidity, and wall surface temperatures, which can be used in airflow design. CFD codes (combined with physical modelling) have been used to study the natural ventilation system (large thermal chimney) of the School of Engineering at De Montfort University in Leicester, UK. This is one of the Europe's largest naturally ventilated buildings. Computer simulations were deficient in coping with thermal stratification and the complex internal geometry, which needs a physical model to compensate for missing information.

CFD SIMULATION PROCEDURE

a. Modeling Methods

CFD is a modeling technique. CFD modeling is the process of representing a fluid flow problem by mathematical equations. The mathematical equations are phased on the fundamental law of physics. For building application, the parameters of interest would include velocity, pressure, temperature, turbulence intensity and possibly concentration of smoke and contaminations. Therefore, the set of equation in CFD are related to those variables.

In general, the equations involved are those for conservation of momentum, which are sometimes referred to as the Navier-Stokes equations, the conservation of mass and the transport equations for turbulent velocity and its scale (Awbi, 1991). In solving these equations, computer calculation technique is used. Due to this process, the method is also known as computational fluid dynamic (Razak, 2002).

Those "conservation laws" may each be expressed in term of partial differential equations (PDE's). Each PDE describes the conservation of one dependent variable within the flow field. This provides a basis for a flow field in CFD model simulation. Usually in wind engineering or building studies the flow field in real situation is turbulent. If a turbulent flow is required in order to represent the real situation then, a "turbulent model" must be used. This will involve solving further equations.

The term "turbulence" is used to describe the apparently random "particles" of fluid, which can occur under certain flow condition. Broadly speaking, the flow which is usually referred to fluid dynamic theory can be described as being either laminar or turbulent, or when between these two states, as transitional (Schlichting, 1979). In fluid dynamic, Reynolds (Re) number is observed to be increasing as a result in an increase in flow velocity, until a certain velocity was reached. At higher velocity, turbulence resists distortion (increase in velocity) to a greater degree than laminar flow. Resistance to flow resulted in the formation of viscous forces and inertial forces. Reynolds number (Re) is a dimensionless number to describe the fluid flow. At low Re number the laminar flow tends to be greater than at higher Re number. However, the tendency for sudden shift from laminar flow to separated flow is greatly increased. Separation causes a great deal more drag than transition from laminar to turbulent flow.

Reynolds number is proportional to (inertia force) - (viscous force) and is used in momentum, heat and mass transfer to account for dynamic similarity. It is normally defined as:

Re = (U x L)/ υ

Where:

U = proposed simulated wind
L = characteristic length of flow system
υ = kinematics viscosity (u/p), air kinematics viscosity lower troposphere = 14 x I0^{-6} m/s
ρ = air density (at = 25°C ambient air temperature, the air density is around 1.225kg/m^3)

The aim of turbulence modeling in CFD is to represent the diffusion influence of fine-scale turbulence effects. The turbulence diffusion coefficient is added to the laminar coefficient (laminar viscosity) to yield the combined effect. In turbulent flow the diffusion forces are very much dominated by turbulent mixing. Therefore, the laminar viscosity is usually negligible.

In CFD there are three major turbulence models. They are Large Eddy Simulation (LES), Full Simulation and Reynolds-averaged *(k-ε)* models (Jones and Whittle, 1992 and Murakami and Kato, 1999). In LES model, the Navier-Stokes equations are averaged over a small spatial region. This method enables the simulation of a fluctuating turbulence flow field. The full simulation is the numerical solution of the exact Navier-Stokes equation. The length scale is usually very small. Thus this method requires a very small mesh system and is therefore difficult to apply to analysis of airflow. Reynolds-average models approach is by averaging the Navier-Stokes equations, which governs the fluid motion. The averaging process of the Navier-Stokes equation includes the unknown averages of the products of actuating velocities. Reynolds stress as explained above is one of the fluctuating velocities. In comparison among the three methods discussed, the Reynolds-average model is the most commonly used (Malsiah, 2001;

Loomans, 1998 and Murakami and Mochida, 1989). It is recommended due to its efficiency and reliability (Jones & Whittle, 1992; Murakami & Kato, 1999 and Satwiko et. al, 1998). Therefore, it is relevant to adopt the LES method of designing the turbulence intensity for this research.

b. Solution Method

The main process in CFD is to solve the equations that have been mentioned earlier in this section. The solution method of solving the required equations involved is by using the domain of integration of solution domain. The solution domain is actually the region of space within the differential equations are to be solved. The solution approach in CFD is to represent the differential equations in numerical forms, linearise the equations and then solve them using numerical analysis techniques. This approach is known as "discretization method" (Awbi, 1991).

c. Numerical Procedures

The **discretized** form of equation can be solved by one of the well-established numerical procedures such as "finite element" method (FEM) or "finite differences" or known as "finite volume" method (FVM) (Awbi, 1991). The selected methods relied on the accuracy of the solution and the computer efficiency. The FVM is more popular then FEM in CFD because it is generally more economical in computational time. The majority of the commercially available CFD computer codes used the FVM solution techniques.

In both methods, the equations are solved on a grid. They are mapped to a computational grid, which forms three dimensional (3-D) volumes or control volumes of space. These grids need to completely fill the enclosure to be modelled. The computational grid is also known as a mesh. The control volume is Renown as a "cells", in FVM or "elements" in FEM. These FVM or FEM models use selected grid types. They are solved in a CFD modelling by an iterative manner. This is to generate field values for all dependent variables. The iterative solution will continue until the imbalance or error in the equations is sufficiently small to be considered negligible. The data obtained from simulation will be used to calculate the values of all dependent variables, such as air velocity, temperature distribution, pressure distribution, concentration of chemical, smoke, etc. for each computation control volumes.

d. Computational Grid

In CFD application, the computational grid cell defines the solution domain. Number and size of cells represent the level of resolution that the calculation can be achieved. Smaller grid cells are normally defined in areas where large gradient of solution variable are evident. Failure to provide enough mesh in these areas will result in the supply jet or boundary layer flow being insufficiently resolved. Hence, this resulted in an unrealistic local situation. For economic purposes (in term of computing time), it is usually to expend the grid, in the spatial sense, in area remote from those of interest and importance. Figure.1 shows the example of the grid layout that is uniform in sizes. The computational grid is having a total of 224 (=7x8x4) cells. Two main types of computational grid can be applied in CFD (Jones and Wittle, 1992). They are rectilinear (Cartesian) grids and curvilinear body fitted coordinate (BFC) grids. The grid is rectilinear (Cartesian) when the cells are formed as rectangles. The advantages of the Cartesian grid are that it is easy for the user to specify and generate the grid. FVM is performed very efficiently using this type of grid. For curvilinear body fitted coordinate (BFC) grids, the x, y and z structures of the Cartesian grid are retained. However, the cells are formed from four-sided (2-D) or six-sided (3-D) elements, which can be distorted to follow irregular boundaries. The BFC forms of the equations are much more complex and computations on these.

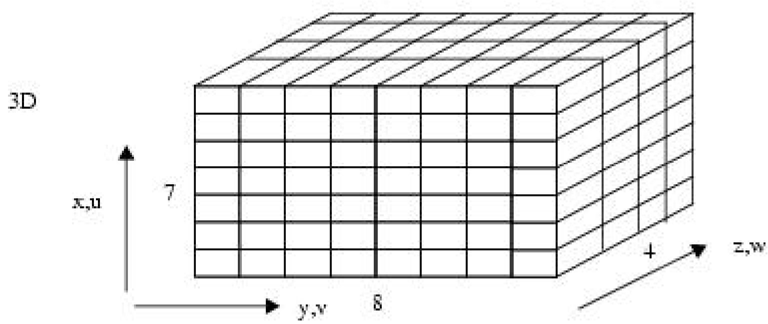


Figure 1: The example of the cartesian grid layout (Flomerics, 2000)

The most widely used methods in solving the numerical form of differential Ration is SIMPLE (Semi-Implicit Method of Pressure-Linked equation) (Awbi, 1991). Patankar and Spalding developed this method (Jones and Whittle, 1992). FSIMPLE method links velocity to the pressure in order to satisfy continuity. CFD commercial codes of FVM usually employed this method as a pressure if correction algorithm is required. This method uses the staggered grid (Jones and Whittle, 1992). This method enables the velocity component to be corrected using the pressure values at the neighbouring grid nodes. To achieve this, the positions of the velocity components must be displaced from the grid nodes (pressure positions) so that the pressure forces act at the surface of the velocity control volumes.

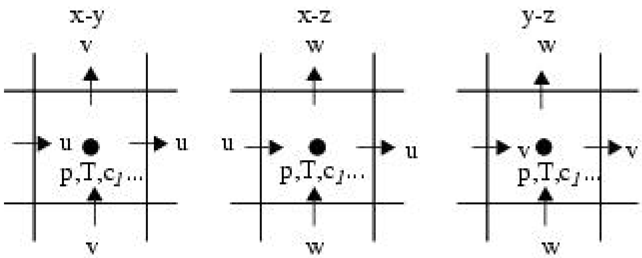


Figure 2: Simple method. Methods of solving the numerical form of Differential equation Using Staggered Grid (Flomerics, 2000)

e. CFD Solution Procedures

The CFD method involves an iterative procedure as solution procedures. This involves solving each equation separately for the whole field. This means, in an iteration, the equations are assembled and a solution is obtained for each velocity component (up to three), pressure, temperatures and turbulence quantities. This procedure is repeated until a converged solution is obtained. In general, the CFD solution procedures are summarized by the following example for a 3D simulation of flow and heat transfer:

Stage 1, initialise the fields of pressure, temperature and velocities,
Stage 2, increase outer iteration count by stage 1,
Stage 3, set up coefficients (i.e. the Cs) for temperature field, T,
Stage 4; solve linearized algebraic equations for the value of T in each cell by performing a number of inner iterations,
Stage 5, repeat stage 3 and 4 for field variables u, v, w, k,ϵ, and c_1, c_2, ... for concentrations,
-Solve the continuity equations in a similar manner and make any associated adjustments to pressure and velocities,
-Check for convergence and return to stage 2 if required.

f. Selection of Software

The rapid development in computer technology especially with regard to the computer-processing unit (CPU) led to the extension in CFD capabilities. Today, there is a lot of CFD software available. There are two categories of CFD software available for airflow modeling. They are categorised as general purpose CFD software and specific airflow modeling software. General purpose CFD software is usually used in fluid engineering application. The CFD software is used to predict the pipe size, duct size, heating and cooling loads, fire and smoke spread etc. (Jones, 1997). Razak (2002), Malsiah (2001) and Lam and Wong (1999) have investigated some available commercial CFD software specifically for airflow modeling. Table 1 shows the summary of the software.

Table 1: Computer Software for Ventilation and Air Quality Analysis Source: Lam and Wong (1999), Sapian (2004)

<table>
<tr><th>Name</th><th>Software Developer</th><th>Description</th><th>Output</th></tr>
<tr><td>1.
COMIS</td><td>Lawrence Berkeley Laboratory, Building 90, Room 3074, Berkeley, CA 94720.</td><td rowspan="2">-Based on multi-zone network model.
-Coupled to a pollution migration model
-Incorporation of a statistical algorithm to compute Cp values at any point of the building envelope (COSMIS)
-Incorporation of a simple HV AC module for the consideration of HVAC effects.
-Rudimentary Graphical User Interface (GUI)</td><td rowspan="2">-Air change rate for each zone
-Ventilation and infiltration rale (mechanical & natural)
-Rate and direction of airflow through individual openings
-Pattern of flow between zones
-Internal room pressure
-Pollution concentration for each zone
-Pollution flow between zones and between inside and outside of bull dings</td></tr>
<tr><td>2.
CONTAM</td><td>National Institute of Standards and Technology (N1ST), BR/A 313, Washington DC 20234.</td></tr>
</table>

3. PHEONICS	Concentration, Heal amd Momentum Limited, Bakery House, 40 High Street, Wimbledon Village, London SW19 5AU, UK	-Computational Fluid Dynamics (CFD) Models. -Normally requires the use of Pre-processor for geometry definition and -Post-processor for processing the data output -Rudimentary Graphical User Interface (GUI)	-Room air flow -Airflow in large enclosures -Air change efficiency -Pollution disposal pattern -Pollution removal effectiveness -Temperature distribution -Air velocity distribution - -Turbulence distribution -Pressure distribution -Fire and smoke movement Airflow around building.
4. FLUENT	Fluent Inc. USA. Worldwide Corporate Headquarters, Central Resource Park, 10 Cavendish Court, Lebanon, NH 03766-1442		
5. FLOVENT	Flomerics Limited. S 1 Bridge Road, Hampton Court, Surrey KT89HH, UK.		

Since this research is intended to study the solar induced and to estimate the air velocity inside solar chimney model, the temperature differences values needs to be converted into values for input data in the stack effect method in order to predict the internal air velocity. Therefore, in selecting the appropriate software certain criteria of the research parameters should be met by the software. In general, the software should be able to;

- Act as a virtual atmospheric boundary layer real condition.
- Represent the turbulent characteristics of airflow. In CFD it is usually represented through the k-ε method.
- Estimate the pressure distribution at the surface of the building.
- Provide with the Atmospheric Boundary Layer (ABL) generator so that the required wind profile can be simulated.
- Construct the required building configurations easily.

Due to the limitation of the study, time and cost, the software should also be able to fulfill some other factors such as;

- The software should be able to be installed in a personal computer (PC) using user-friendly operating system such as windows base application. Some software used complicated operating system such as DOS as an operating system (Malsiah, 2001).
- The user interface should be intuitive and easy to navigate around. For example, in building a model, the drawing should be easily edited like the CAD software
- The post-processing facilities should enable the user to communicate his results easily and effectively
- The most important factor is that the software should be user-friendly. Technical support after sales also should be able to provide training, assistance and support efficiently
- In term of cost, the software should be economical. The cost for the software license period should be within the study budget and period.

The above criteria and factors led to the selection of FloVent version 3,1 software developed by Flomerics Ltd. UK. Flomerics Pte. Ltd. (Singapore) distributes the software for South East Asia, The description of the software is explained in Abdul Razak (2002); Baskaran, A. and Stathopoulos, T., (1989) and (1992); Murakami, S. and Mochida, A., (1989) and Murakami, S, *et.* |; *al,,* (1999); reported that this software is proven reliable and capable to simulate stack airflow and estimate the air velocity.

CFD SIMULATION CONDITION

This section explains the setting-up and procedures of conducting the CFD simulation. The simulation conditions used are also deliberated in this section.

Position of Solar Chimney Model in the Overall Domain Solution

Using FloVent version 5.1 programs, the simulation models are created directly using the drawing board window provided with this software. This is to give more accurate representations of the buildings. Like CAD software, the building created in this CFD software is to 1:1 scale. The model was placed inside an overall domain solution size of 40m x 40m x 20m high. The position of the model inside the overall domain solution was at 20m from x-plane, 20m from z-plane and 1m from y-plane. Figure 3 shows the overall domain solution and the position of the model inside the overall domain solution. Figure 3 can also be considered as an overall setting-up.

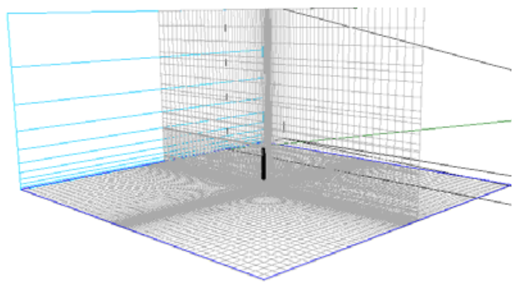


Figure 3: Overall simulation modeling setting up for solar chimney mode

Monitor Point

The main objective of the simulation is to estimate the air velocity inside of the solar chimney model. Therefore, monitor point represents the velocity tapping point was placed at the mid point of both inlet, middle of model and outlet openings. The exact location of the monitor point determines the accuracy of the predicted internal air velocity. The total monitor point used in solar chimney models is 3 numbers (figure 4).

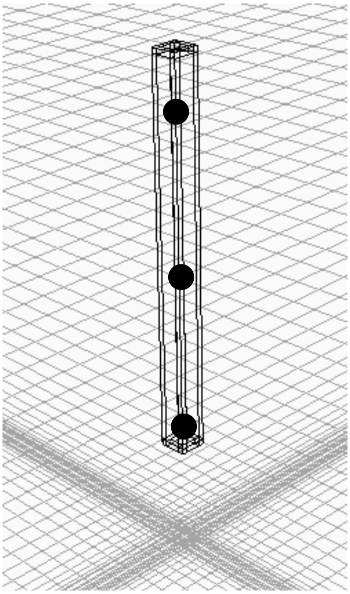


Figure 4: The position of monitor point in relation to the position field measurement and size of model

a. Grid System

The simulation used Cartesian type of grid system. Figure 4 shows the grid setting for the solar chimney model, where the grid was defined x, y and z direction. The x-direction grid was further defined into 3 grid constrain, the y direction into 3 grid constrain and the z-direction into 3 grid constrain as shown figures 5. Each grid constrains form a cell. The total number of cell produced from this system grid is 48 numbers (x-direction) x 40 numbers (y-direction) x 48 numbers (z-direction). This gives a total of 92.160 cells all together. Therefore, 92.160 control volumes carry out the numerical solution for this building. Grid distribution is very important as it affects the numerical accuracy. In determining the number of grid, start with a coarse grid and refine it in region of; complex flow, high gradients and particular interest. The more detailed the grid, the more trade-off between accuracy and computing time required.

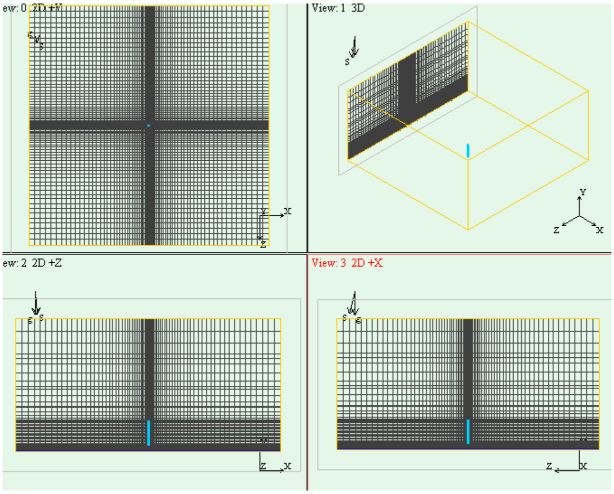
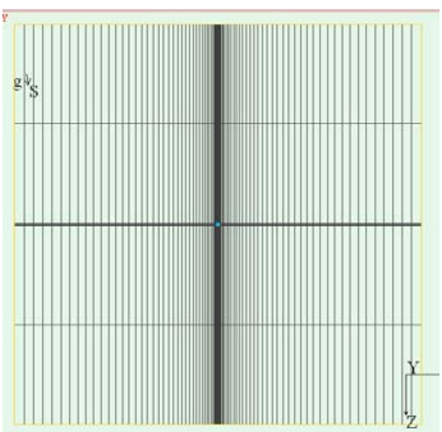


Figure 5: The grid setting for basic of solar chimney model in the Flo Vent

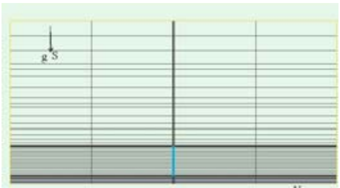


Grid constrain #1:
- Start location: 0 m
- End location: 19.875 m
- Nos. of grid: 20
- Type of grid distribution: decrease

Grid constrain #2:
- Start location: 20.125 m
- End location: 40 m
- Nos. of grid: 20
- Type of grid distribution: increase

Grid constrain #3:
- Start location: 19.875 m
- End location: 20.125 m
- Nos. of grid: 8
- Type of grid distribution: uniform

Figure 6: The grid setting for basic of solar chimney model at x-direction

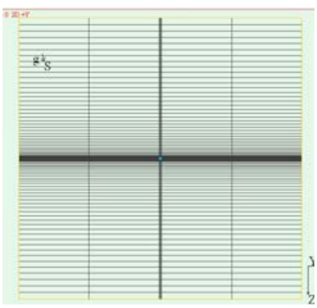


Grid constrain #1:
- Start location: 0.01 m
- End location: 1 m
- Nos. of grid: 8
- Type of grid distribution: decrease

Grid constrain #2:
- Start location: 1 m
- End location: 4.5 m
- Nos. of grid: 17
- Type of grid distribution: uniform

Grid constrain #3:
- Start location: 4.5 m
- End location: 20 m
- Nos. of grid: 14
- Type of grid distribution: increase

Figure 7: The grid setting for basic of solar chimney model at y-direction



Grid constrain #1:
- Start location: 0 m
- End location: 19.875 m
- Nos. of grid: 20
- Type of grid distribution: decrease

Grid constrain #2:
- Start location: 20.125 m
- End location: 40 m
- Nos. of grid: 20
- Type of grid distribution: increase

Grid constrain #3:
- Start location: 19.875 m
- End location: 20.125 m
- Nos. of grid: 8
- Type of grid distribution: uniform

Figure 8: The grid setting for basic of solar chimney model at z-direction

b. Boundary Condition

In ventilation study, the major variables are site, wind data or reference wind speed, wind profile, solar radiation and atmospheric boundary layer characteristics. For example, site conditions for Johor Bahru sub urban hot and humid climate is considered in order to further elaborate the use of CFD technique;

- The location of the study is Universiti Teknologi Malaysia.
- The latitude is 1° 08' N and the longitude is 104° 42' E of Greenwich.
- The height above sea level is 37.8 m.
- The nearest meteorological station is located at Sultan Ismail (SI) airport known as Senai meteorological station, approximately 20 km from centre of Johor Bahru.
- The average ground characteristics of on site weather station area are considered as a combination of flat terrain and low-rise buildings. This gives the empirical exponent (a) value of 0.22, the roughness length (Z0) value of 0.25 m and the gradient height (Zg) value of 370 m (ASCE, 1999).

Due to its geographical location, Johor Bahru receives winds from almost all directions. However, the northerly winds that prevail from November until April, and the southerly winds that prevail from around May to September, are the main prevailing winds. The secondary winds come from the north-east during the months of November to April and from the south-west in the months of May to September. The mean surface wind fluctuates between 0 m/s and 1.43m/s. The mean maximum surface wind fluctuates between 13.4m/s and 19.0m/s. The percentage of calm period is about 31.6%, and 48.1%. Figure 3.9 shows the annual wind rose for Johor Bahru which exhibits the intensity and various percentage frequencies of wind speed and direction. The occurrence percentages of the northerly and southerly winds are amongst the highest. The northeasterlies and northwesterlies are the secondary winds (Kubota, 2006)

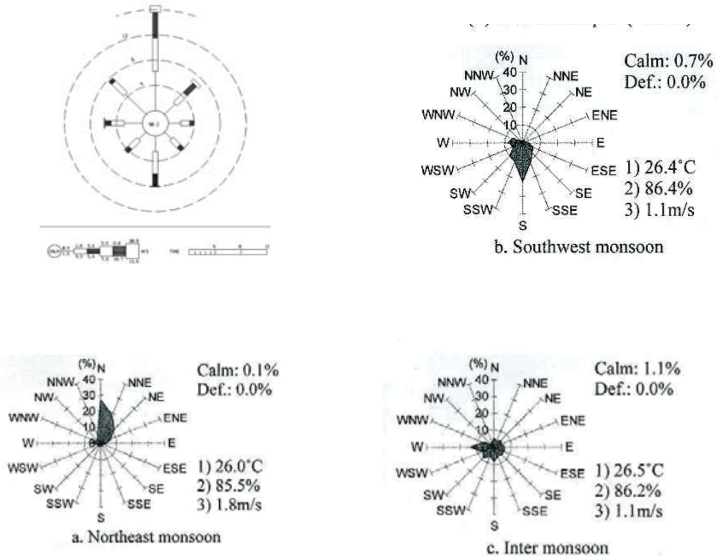


Figure 9: Wind rose and climate summary in Johor Bahru 1988-2002 (Kubota, 2006)

On the whole, the winds progressively pick up in speed during the day. Starting from about 7:00 am in the morning, the speed increases and reaches its peak at about 2:00 pm, and then starts decreasing until it reaches the lowest steady speed at about 10:00 pm. From 10:00 pm to about 7:00 am, the wind speeds are relatively low or calm (Malsiah, 1998). In Johor Bahru, the mean wind velocity in the northeast monsoon period (1.8m/s) is slightly higher than that of Kuala Lumpur, and the wind velocities both in the southwest monsoon period and the inter monsoon period (l.lm/s) are a little lower than those of Kuala Lumpur (Kubota, 2006). However, the data was taken at 17.4 m high (height of anemometer head above ground). In this research, the international standard reference height for mean wind at 10 m above ground is used. Therefore, the wind speed has to be corrected to a wind speed that refers to the international standard reference height. The

Atmospheric Boundary Layer ABL generator was downloaded from FloVent website. The ABL generator provided by FloVent used Log Law model to create the required wind profile- Johor Bahru can be described as a sub urban with high crops and residential suburban; therefore, the roughness length (Z_0) equivalent to 0.25 as proposed by ASCE is used. Table 2 shows ASCE (1999) ABL layer characteristics for different terrain roughness.

Table 2: ABL characterictics for different terrain roughness (ASCE, 1999)

Class	Terrain Description	Zo (m)	α	*Iu* (%)	Exp.	Z(m)
1	Open sea, fetch at least 5 km	0.0002	0.10	9.2	D	215
2	Mud flats, snow; no vegetation, no obstacles	0.005	0.13	13.2		
3	Qpen flat terrain; grass, few isolated obstacles	0.03	0.15	17.2	C	275
4	Low crops; occasional large obstacles	0.1	0.18	27.1		
5	High crops; scattered obstacles, residential suburban	0.25	0.22	27.1	B	370
6	Parkland, bushes; numerous obstacles	0.5	0.29	33.4		
7	Regular large obstacle coverage (dense spacing of low buildings, forest	1.0-2.0	0.33	43.4	A	460
8	City centre with high and low-rise buildings	≥2.0	0.40~0.67			

Correction can be done using the log law equation and the ABL characteristic is selected from table 2 Consequently the mean wind speed of UTM sub urban terrain condition can be predicted using the same log law equation.

Log Law model:

$$V_z = V_{ref} [\log (Z / Zo) / \log (Z_{ref} / Zo)]$$

Where:
V_z = the mean wind speed at height (gradient wind)
V_{ref} = the mean wind speed at some reference height
Z_{ref} = the reference height
Z = the height for which the wind speed V_z is computed (gradient height)
Zo = Roughness length or log layer constant

According to the description given by ASCE (1999) as shown in table 2, Senai meteorological station ABL characteristics can be described as open terrain (grass and few isolated obstacles). Therefore, its mean wind speed exponent (a) can be assumed as 0.15, the roughness length (Z_0) is 0.03 and the gradient height (Z) is 275 m. Using the same log law equation, gradient wind for UTM can be obtained. Before that, UTM ABL characteristic has to be determined. Referring to table.2, UTM terrain condition can be described as an area with high crops; scattered obstacles, residential suburban. Observation shows that although UTM is approximately $\pm$ 6 km from Senai, this area is denser compared with Senai. Therefore, its mean wind speed exponent (α) can be assumed to be as 0.22, with the gradient height of 370 m and the roughness length (Z_0) of 0.25 (ASCE, 1999).

As discussed in above section, the *k-ε* method of designing the turbulence intensity for the simulation is adopted. In this CFD software the *k-ε* model define the turbulent viscosity at each point from two additional variables that characterize the local state of turbulence, viz;

- the kinetic energy of turbulence *(k)*
- its rate of dissipation (ε)

In the k-ε model adopted by this FloVent version 5.1 software, the turbulence kinetic energy and the dissipation rate of turbulence are automatically set by the program based on average inlet velocity values as 0.1 J/kg and 0.l W/kg respectively. These automatic boundary settings are usually suitable because the generation of turbulence within the calculation domain is usually sufficiently high to make precise settings of the inlet values inconsequential (Flomeric, 2000). Other defaulted basic references values that are used throughout the simulation are;

- Datum pressure, this variable is set as a gauge pressure. It is used to calculate the absolute; pressure values for use in variable density models. For most calculations, the default; value of standard atmospheric pressure of 1 arm is appropriate (Flomeric, 2000).
- Air temperature, temperature around 33.2 °C was used as a constant temperature outside the enclosure. Air temperature around 33.2 °C was selected based on the mean air temperature for respectively day (21 March 2005) at 12:00 pm. This temperature is used by default for fluid temperature at the inflow boundaries and reference temperature in the buoyancy force.

CFD Simulation Analysis

In general, for simulation analysis and assessment, these research principles apply: qualitative analysis, quantitative analysis, comparison with previous studies, comparison with real world conditions and statistical (Satwiko, 1998). Firstly, the qualitative analysis for secondary problems is made. These include issues that should be accounted for, but should not be the major consideration. Some research is full of philosophy and not be easily linked to building science scenarios. To determine the relevance of a philosophical thought to building science, a logical qualitative analysis is conducted. This usually precedes a quantitative analysis. Second, the quantitative analysis for simple problems is conducted. People demand different indoor air conditions to keep comfortable, depending on their activities. In many cases, recreation and behaviour are culturally determined. This kind of relationship is discussed quantitatively and checked using the ASHRAE Thermal Comfort Program. Third, comparison with previous studies is sourced in research reports for complicated numerical problems. Computational fluid dynamics codes involve complex mathematics. Since this research focuses on the application of computational fluid dynamics codes, any issues raised by the numerical are referred to the relevant experts or, if appropriate, compared to results found in other research reports. Fourth, the comparison with real world conditions is made. Rather than simply adjusting the computer simulation to imitate real conditions, it quickly identifies suspicious or *strange* results that may indicate the existence of flaws. These flaws can be caused by various problems from false data input to improper computer programming configuration. Last, Statistical analysis is used particularly for interpreting weather data. In this research Excel version XP software is used.

To calibrate the program, the results of experiments using CFD-Flo Vent were compared to pilot testing experiments. The reliability of the results was determined, and input adjusted to produce results reflecting real situations. The graphic comparison used Excel XP software. The air temperature and velocity calibrations use, velocities and non-dimensionalised temperature as parameters. The solar chimney calibration compared two sets of data: pilot testing data and CFD-Flovent results from eight different experiments. The tolerance range can be derived from Selvam's report. He confidently states that his CFD experiment has a good agreement with the field data. Selvam allows up to 7% deviation for the average windward between his CFD calculation and the real condition. In a separate case study, another CFD expert, Shao, accepts 20% tolerance for a *good agreement* between his CFD codes' Cp results and field data. Expecting a complete match between CFD results and field data is not only difficult but also misleading. Airflows around and inside buildings are turbulent and always changing with time. Therefore, any measurements of airflow variables are generally noted as average values. CFD programs, on the other hand, tend to calculate the flow based on a particular set of steady state condition. Thus, a certain degree of deviation (between CFD results and the field data) can be tolerated (Satwiko, 1998).

The analysis of the study is based on the output data obtained from the simulation for the tested solar chimney configurations. The output results were obtained in two forms: the configurationally results for the selected time and the hourly values for the designated year. The configurationally results by end users are analyzed for the following performance variables:

i. Temperature Differences
ii. Air velocity
iii. Air Flow Rate

The suggested air velocity standard for indoor residential buildings is 0.25-1.5 m/s and it is used as a bench mark in describing the air velocity requirement of the configurationally tested solar chimney models. The analysis of each tested solar chimney configuration models will be evaluated with the maximal performance variables values for base-case model (pilot testing). Also, all the performance variables were correlated with solar chimney geometry ratio (SCGR) of the tested solar chimney models. The hourly results were obtained for the following performance variables:

iv. Air velocity
v. Air Flow Rate
vi. Air Temperature

The hourly data for respective days (21 March, 22 June, 24 September and 21 December) were chosen three times within hours chosen (8:00, 12:00, and 16:00) for analysis. The selected time was based on different position of the sun within the activities schedule. The results of the air velocity and air flow rate were combined into a single graph on respective dates and orientations. Likewise, the air velocity and air temperature were also illustrated in a single graph on respective dates and orientations. This is to get a better understanding of the influence of solar chimney over and on the performance variables. The maximum, minimum and mean activity plane air velocity, air flow rate and air temperature are used to describe general performance of the models tested.

Most results can be presented and interpreted graphically. Evaluation during interpretation need to be guided by logic informed analysis and assessment. Any unexplained results should encourage repetition of the experiments. Graphical presentations, plots and linear probes, are used to analyse results. Plots are defined in vertical, horizontal sections (cutting planes), or any defined surfaces.

A linear probe shows the values at points (locations) in a line.

-Vector plots. These plots show the airflow patterns around and within the models, including wake formations and stagnation locations.

-Velocity (V) plots and linear probes. Velocity plots allow for easy visual detection of low and high air velocity as well as stagnant locations. The velocity variable is used in the comfort equations to calculate the comfort level of a given location.

-Temperature (T) plots and linear probes. Temperature plots make the study of air temperature distribution easy. These plots show warmer and cooler locations within the house caused by radiation and convection heat transfer from the warm roofs.

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6

MEASURING INDOOR AND OUTDOOR THERMAL ENVIRONMENT IN TERRACED HOUSE

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Tetsu Kubota

INTRODUCTION

This chapter discusses the methodology employed to conduct the field experiment to measure indoor and out door thermal environment of a typical Malaysian Terraced house. Following sections elaborates the methods used to select the case study houses, an outline of the experimental conditions, and the details of measurements of indoor and outdoor thermal environments.

SELECTION OF CASE STUDY HOUSES

Survey Methods

According to the Malaysian housing census (Malaysia, 2005), the number of terraced house units nationwide had increased from 1.1 million units in 1991 to 1.8 million units in 2000. Moreover, the percentage distribution of housing units in urban areas in 2000 were as follows: i) 44% terraced house units, ii) 23%

detached house units, iii) 19% flat and apartment units, and iv) 9% semi-detached house units (Malaysia, 2005). This implies that terraced house is by far the most common type of residential building in Malaysia.

A primary survey of terraced houses in Johor Bahru city and its conurbation was carried out first. The purpose of the survey was to select two case study houses that represent the typical Malaysian terraced houses in terms of building design, construction and materials. Two adjacent case study houses with close resemblance were needed for this research so that the thermal environment measurements in both houses could be compared validly.

According to a recent Malaysian residential property stock report (Malaysia, 2006), terraced house units accounted for more than 50% of the existing residential units in Johor Bahru, followed by flat and apartment units (22%), detached house units (6%) and semi-detached house units (4%). Since the majority of the housing developments in Johor Bahru consist of terraced houses, it is appropriate to be used as a case study area for this housing pattern survey.

On the whole, the survey included three main steps. They were i) sampling, ii) classification, and iii) selection of the case study houses (Table 1). Relevant information was obtained through observation and compilation of building design documents acquired from local authorities as well as housing developers.

Table 1 Types of information acquired during the survey of terraced houses.

Survey Step	Type of Information	Details
1) Sampling	Development information	Development year Developer Completion status House type Number of house units
2) Classification	Building design and construction information	Basic building data Basic design drawings Building structure and materials Window and opening design Room height / ceiling height
3) Selection	Other building information	Physical condition Surroundings Any renovation made House occupancy / availability Design features e.g. openings for ventilation and window shading

CLASSIFICATION OF TERRACED HOUSES

A sample of 93 terraced houses from 24 housing estates in Johor Bahru was surveyed and used for the classification of terraced houses. It should be noted here that the sample has two limitations. One is that the sample size is relatively small compared to the population of terraced houses in the survey area (Table 2). The other limitation is the lack of building design documents on early terraced houses. This means that the early terraced houses are probably under-represented in the sample. Nevertheless, the classification of the sample served to provide a good overview and basis for the selection of the case study houses.

Table 2. Population of terraced houses in the survey area.

Authority Area	Total Housing Units	Terraced House Units
MBJB [1]	159822	64714
MPJBT [2]	94376	80962

Source:
[1] MBJB (2001); [2] MPJBT (2006)

In general, the survey reveals some distinguishable but non-drastic changes in terraced house design which began in the 1960s until present. One of the obvious development trends is the shift from building mostly single-storey terraced houses to building more double-storey terraced houses. Another significant difference in terms of architectural design elements is the window type and opening for natural ventilation. It is found that the air-well, operable louver window and ventilation blocks were commonly used in early terraced houses but much less used after mid-1980s. On the other hand, single-glazed casement windows are quite common at present. As the main intention was to select the typical house design, several attempts were made to classify the sample into relevant groups.

Firstly, the development years of the sample were categorized into the following periods 1960s, 1970s, 1980s, 1990s and 2000s for practical analysis. Table 3 lists the profile of the house sample according to development year and house type. The highest number of sampling units (38) is from housings developed in the 1990s. Only two sampling units from the 1960s period were analyzed due to limited available documents. Both 1960s sampling units are single-storey terraced house. In all, more double-storey terraced houses were sampled compared to single-storey terraced houses (Table 3).

Secondly, the sampling units were compared and analyzed based on their building data and floor plans which were drawn to the same scale. Since there were no significant differences in the building structure and materials used among the sampling units, this information was excluded in the classification. The outcome of the classification is presented in Table 4 and Figure 1. Table 4 summarizes the range and most common building data from the sample. Figure 1 shows the classification of the sample according to its floor plans in an XY plot of total floor area per house unit (x-axis) and internal layout type (y-axis). The layout diagram on the y-axis represents the arrangement of bedrooms as well as living, dining and kitchen areas in the house, as derived from the floor plan analysis of all sampling units. From the sample, five types of internal layout could be distinguished for double-storey terraced houses (Figure 1). In parallel, three types of internal layout were identified for single-storey terraced houses. The sampling units have total floor areas between 40 m^2 and 220 m^2 each (Figure 1).

Table 3 Profile of terraced house sample by development year and house type.

Development Year	Sampling Units
1960s	2 (2%)
1970s	13 (14%)
1980s	18 (19%)
1990s	38 (41%)
2000s	22 (24%)
Total	93 (100%)

House Type	Sampling Units
Single-storey	34 (37%)
Double-storey	59 (63%)
Total	93 (100%)

Table 4. Building data of the terraced house sample

Building Data	Range	Most Common (Mode)
Lot area	72 to 204m^2 (770 to 2200 ft^2)	143m^2 (1540 ft^2)
Lot width	4.3 to 7.9m (14 to 26 ft)	6.7m (22 ft)
Lot length	15.8 to 30.5m (52 to 100 ft)	21.3m (70 ft)
Total floor area	46 to 221m^2	120-130m^2
Building width/depth ratio	0.38 to 0.81	0.4-0.6
No. of bedrooms	2 to 4 (single-storey) 2 to 6 (double-storey)	3 (single-storey) 4 (double-storey)
Ceiling height	2.7 to 3.2m	3.0m

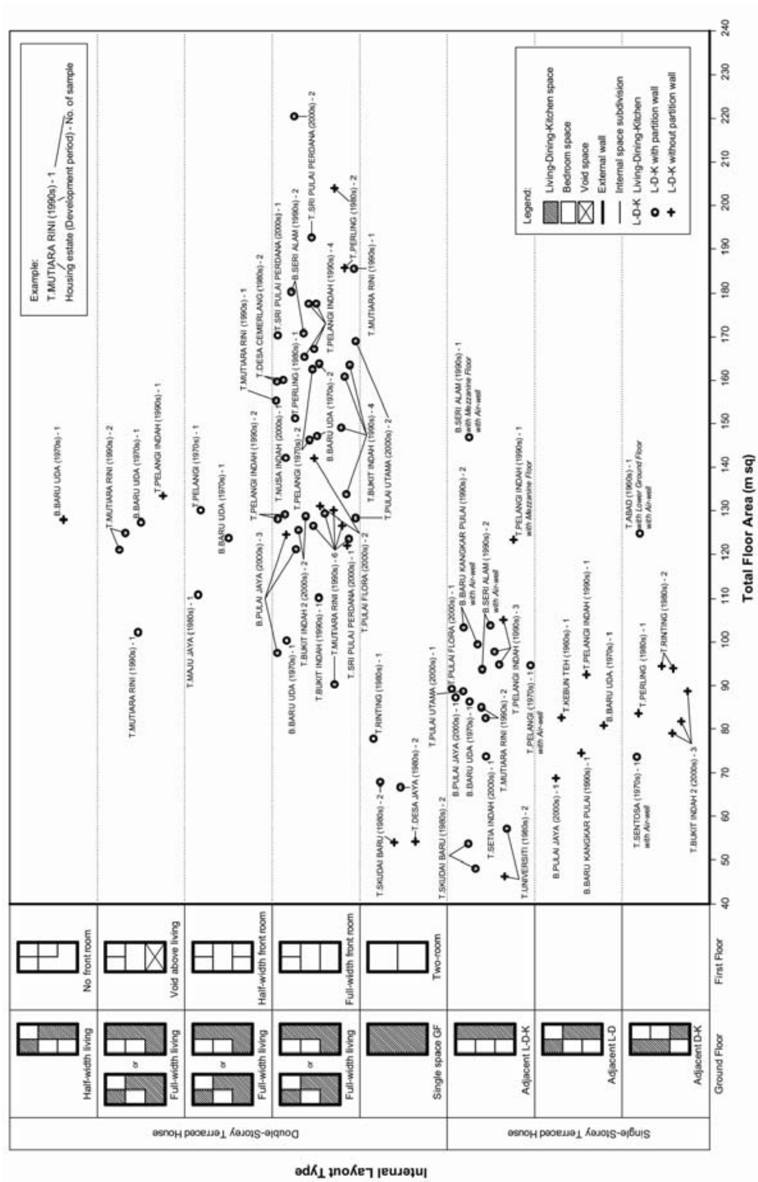

Figure 1. Plot of the terraced house sample by internal layout type and total floor area per house unit.

DETAILS OF THE CASE STUDY HOUSES

Based on the classification, two adjacent units of double-storey terraced house were selected as the case study houses. They are located in Taman Mutiara Rini, which is a major housing estate in the suburb of Johor Bahru city. The houses were constructed in 1996. The case study houses fall within the typical layout group for double-storey terraced house. The total floor area of the case study houses, which is 155 m^2 each, is also close to the averaged floor area (148 m^2) among the sampling units. In addition, the case study houses share some of the most common building data as outlined in Table 5 (cf. Table 4). The two houses are named House 1 and House 2, respectively.

Figure 2 shows the front view of the case study houses while Figures 3 shows the floor plans. Both houses are identical in terms of design, size, building orientation, construction and materials, despite being symmetrical in layout. The building structure is reinforced concrete with plastered brick walls of 240mm thick for party walls and 140mm thick for other walls. The roof is constructed of concrete tiles and laid with a thin layer of double-sided aluminum foil underneath the tiles as radiant barrier. The ceiling for the first floor is 4mm thick asbestos-free cement boards without insulation. The floors are reinforced concrete slab, and finished with ceramic tiles on the ground floor and timber strips on the first floor. All windows are either casement or sliding type and constructed of 5mm thick single-glazed clear glass with aluminum frames. The heights of the window head and window sill in the living rooms and master bedrooms are 2.1m and 0.5m above floor, respectively. A clerestory window of fixed glass louvers is available above the family area on the first floor for natural ventilation. Such construction represents common practice in terraced housing in Malaysia.

Table 5. Building data of the case study houses.

Building Data	Case Study Houses 1 and 2
Lot area	$143m^2$ ($1540\ ft^2$)
Lot width	6.7m (22 ft)
Lot length	21.3m (70 ft)
Total floor area	$155m^2$
Building width/depth ratio	0.51
No. of bedrooms	4
Ceiling height	3.0m

During the site visit, it was observed that windows were not adequately shaded. Both master bedrooms and living rooms therefore received direct solar radiation through the glazed windows on the afternoon of hot days. It was observed that direct solar radiation could enter the living rooms from approximately 2 p.m. to 6 p.m. and the master bedrooms from approximately 2.30 p.m. until 6.45 p.m. All exterior and interior walls were painted light colors. It was also found that an additional boundary wall was constructed next to the turfing area of House 1. Other than that, the compound and surroundings of both houses were similar. The only means to naturally ventilate the houses was through window openings. Ceiling fans were available in the living rooms and master bedrooms. No attic ventilation was available.

Figure 2. Front view of the case study houses.

EXPERIMENTAL CONDITIONS

Johor Bahru, and Malaysia as a whole, is located close to the equator and largely surrounded by seas. Due to this condition, there are little variations in most of the major climatic elements in a year except for rainfall (Lim and Abu Samah, 2004). Most towns in Peninsular Malaysia including Johor Bahru experience high temperature and high humidity throughout the year. Meanwhile, significant changes in rainfall are strongly influenced by the monsoons (Lim and Abu Samah, 2004).

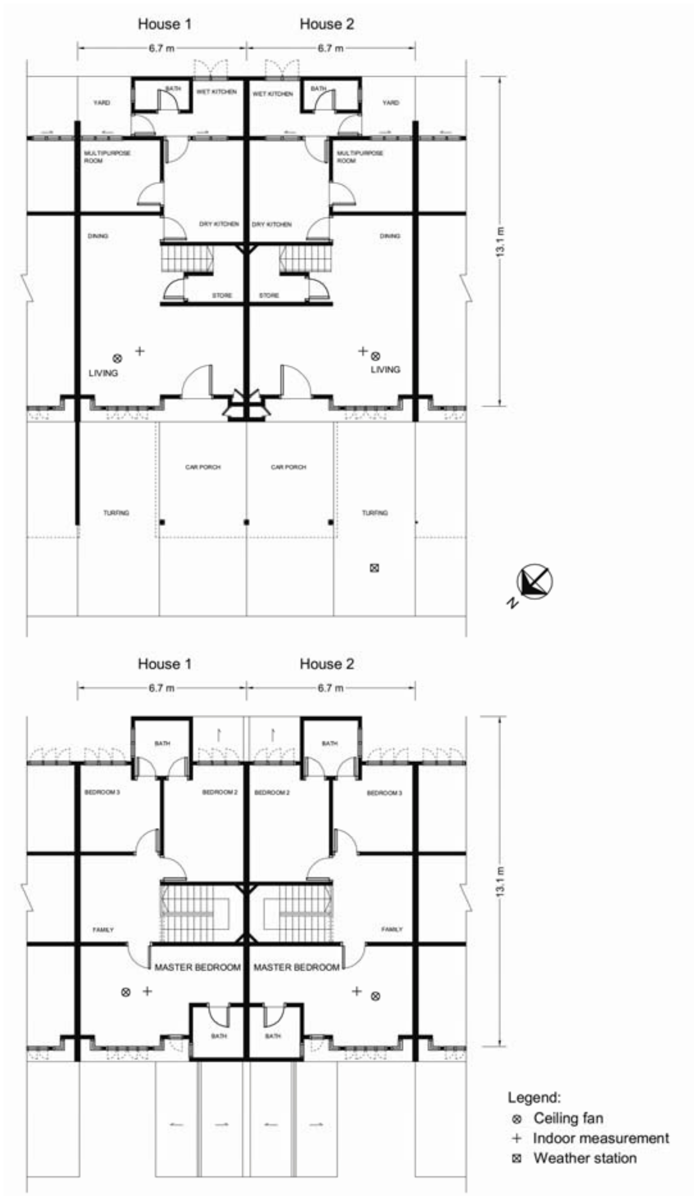

Figure 3 Ground floor plan (*top*) and first floor plan (*bottom*) of the case study houses.

The monsoon seasons can be divided into the northeast monsoon period (November to March), the southwest monsoon period (May to September) and the inter monsoon period (April and October) (Kubota and Ahmad, 2006). It should be noted that the monsoons also influence the prevailing wind condition and direction. In the southern part of Peninsular Malaysia which is the case study area, the southwest monsoon season, particularly from June to August, brings less rainfall compared to the northeast monsoon and two inter monsoon seasons (Sani, 1998). It was determined from here that the field experiment period would be selected to avoid the rainy monsoon seasons.

A field experiment was performed from 19 June to 30 August of 2007 in the two case study houses. The main objective of the field experiment was to measure and compare the thermal environment in a night-ventilated house with the other house under daytime ventilation, full-day ventilation and no ventilation conditions. For this purpose, the field experiment consists of six cases as outlined in Table 6.

House 2 was set to be night-ventilated for all cases while House 1 was applied with a different ventilation condition for each case (Table 6). In Case 1, daytime ventilation was achieved by opening the windows of House 1 from 8 a.m. to 8 p.m. in order to emulate the most common household behavior as reported in Kubota and Ahmad (2005). Windows were closed at night from 8 p.m. to 8 a.m. In contrast, House 2 was night-ventilated by opening windows from 8 p.m. to 8 a.m. and keeping windows closed from 8 a.m. to 8 p.m. During Case 2, windows of House 1 were kept closed 24-hours so that the indoor of the house was totally unventilated. During Case 3, windows in House 1 were kept open 24-hours to obtain full-day ventilation. In all cases, natural ventilation was applied by manually opening all windows of the entire house to their maximum opening areas according to the time period specified. When the house was not ventilated, all windows were closed and fastened. Both houses were visited twice daily by the researchers at ten minutes before 8 a.m. and 8 p.m. to perform these tasks.

In Cases 4-6, the above ventilation conditions were repeated accordingly. In addition, night ventilation, daytime ventilation and full-day ventilation were further assisted with ceiling fans in the living room and master bedroom (Table 6). The positions of ceiling fan are shown in Figure 3. The ceiling fans were operated at a moderately high speed for 24 hours during Cases 4 and 6 in House 1 and Cases 4, 5 and 6 in House 2. All bedroom doors of both houses were opened during all cases.

Table 6. Ventilation conditions for Cases 1-6.

Case	House 1	House 2
1	Daytime ventilation	Night ventilation
2	No ventilation	Night ventilation
3	Full-day ventilation	Night ventilation
4	Daytime ventilation (fan-assisted)	Night ventilation (fan-assisted)
5	No ventilation	Night ventilation (fan-assisted)
6	Full-day ventilation (fan-assisted)	Night ventilation (fan-assisted)

Each case was conducted for six continuous days to ascertain longer-term cooling effect and to obtain adequate number of days of typical sunny outdoor condition. On the pre-experiment day of each case (8 a.m.-8 a.m.), all windows in Houses 1 and 2 were opened equally in order to naturally ventilate both houses so that their indoor thermal conditions would be similar at the starting stage of the experiment.

Throughout the field experiment, both houses were unoccupied and empty except for the daily short visits and also the field measuring instruments in the living rooms and master bedrooms. No artificial lighting was used in the houses during the experiment. Therefore, internal heat gain from occupants and appliances was not taken into account in the data analysis.

MEASUREMENTS OF THERMAL ENVIRONMENT

In general, two types of measurement were recorded during the field experiment. They are: i) measurement of indoor thermal environment in Houses 1 and 2, and ii) outdoor weather data. Three main references used as guide for the field measurements are: i) ASHRAE (2004; 2005) and ISO 7726 contained in BSI (2001), ii) other literatures by Benton et al. (1990), Schiller et al. (1988), Parsons (2003), McIntyre (1980) and Chrenko (1974), and iii) manuals, specifications and calibration certificates of the instruments used. Details of the indoor and outdoor measurements, instrumentation and calibration procedures are explained in the following two sections accordingly.

Instrumentation and Calibration for Indoor Measurement

Measurements of indoor thermal environment were taken on the ground floor in the living rooms and on the first floor in the master bedrooms of Houses 1 and 2. These two rooms can be considered to be the main area where occupants spend the most time in. Besides, the master bedroom recorded the highest frequency of air-conditioner installation in a previous survey by Kubota and Ahmad (2005). According to ASHRAE (2004), measurements should be made in occupied zones away from the boundaries of the occupied zone and from any surfaces to allow proper air circulation around measurement sensors. In this research, the indoor measurements were carried out in the center of the expected occupied zone after considering the positions of walls, windows and the ceiling fan. The measurement positions are shown on the floor plans in Figure 3.

Table 7 outlines the measurement heights above floor and the physical quantity measured at each point. Room floor-to-ceiling height is 3.0m. At 1.5m height above floor, more than one basic quantity was measured. These include air temperature and relative humidity in the living rooms, and air temperature, relative humidity, air velocity and globe temperature in the master bedrooms. The objective of the measurements at 1.5m height, especially in the master bedrooms, was to assess their respective comfort condition using thermal indices which combine all or some of the quantities. Other measurement points recorded air temperature or surface temperature. These measurements were designed to provide a vertical distribution of indoor temperatures from the floor surface to the ceiling surface of the ground and first floors, respectively. In addition, air temperatures in the attic space above the master bedroom were taken at a height of 0.8m above the ceiling during Cases 4, 5 and 6. Attic air temperature was considered an ancillary parameter that might be useful in future research.

Table 7 Indoor measurements in the case study houses.

Measurement Point	**Measured Quantity**	
(Height Above Floor, m)	**Living Rooms**	**Master Bedrooms**
3.0 (ceiling height)	Ceiling surface temperature	Ceiling surface temperature
2.9	Not measured	Air temperature
2.4	Air temperature	Air temperature
1.5	Air temperature, Relative humidity	Air temperature, Relative humidity, Air velocity (House 2 only), Globe temperature
0.6	Air temperature	Air temperature
0.0 (floor level)	Floor surface temperature	Floor surface temperature

The following step was instrumentation. ASHRAE Standard 55 and ISO 7726 specify the required and desirable measurement accuracy and response time of sensors for each of the basic quantity (Benton et al., 1990; BSI, 2001) (Table 3.8). Other than that, ISO 7726 and ASHRAE *Handbook – Fundamentals* 2005 provide useful information on the types of sensors that can be used and their principles of measurement (BSI, 2001; ASHRAE, 2005). These were used as a guide for selecting suitable instruments for this research. Instruments for this field experiment were sourced from the Building Science Laboratory at the Faculty of Built Environment in *Universiti Teknologi Malaysia*. Tables 9 and 10 list the models and details of all measuring instruments used during the field experiment. As shown, most of the instruments used are within the required accuracy recommended by the standards (cf. Table 8).

Some of the important points regarding the instrumentation and measurement procedures are noted next. For air temperature measurement, the accuracy at 1.5m height was maintained at ± 0.3°C in all rooms for standardization and accordance with ISO 7726's required accuracy (Tables 9 and 10). Also, as advised by ISO 7726 and ASHRAE, all air temperature sensors were installed with open cylindrical aluminum shading devices to reduce the effect of radiation while allowing sufficient air movement around the sensors (BSI, 2001; ASHRAE, 2005).

Table 8 Requirements of measuring instruments given in ASHRAE Standard 55-1981 and ISO 7726. Source: Benton et al. (1990); BSI (2001).

	ASHRAE 55-1981	ISO 7726		
Quantity	Accuracy	Accuracy	Measuring Range	Response Time (90%)
Air temperature	± 0.2°C	Required: ± 0.5°C Desirable: ± 0.2°C	10°C to 40°C	The shortest possible
Mean radiant temperature	Desirable: ± 0.2°C	Required: ± 2°C Desirable: ± 0.2°C	10°C to 40°C	The shortest possible
Air velocity	± 0.05 m/s over range 0.05 m/s to 0.5 m/s	Required: ± 5% ± 0.05 m/s Desirable: ± 2% ± 0.07 m/s	0.05 m/s to 1 m/s	Required: 0.5s Desirable: 0.2s
Humidity	± 0.6°C (for dew point temperature)	± 0.15 kPa (for partial pressure of water vapour)	0.5 kPa to 3.0 kPa	The shortest possible
Surface temperature	N/A	Required: ± 1°C Desirable: ± 0.5°C	0°C to 50°C	The shortest possible

Regarding relative humidity measurement, three of the instruments used were temperature/humidity data loggers (TR-72U, T&D Corporation) (Tables 9 and 10). Although these humidity sensors have lower accuracy (± 5% RH), they were used due to their affordable cost, small size and ability to record both air temperature and relative humidity. The other relative humidity sensor was a capacitance hygrometer (HP472AC, Delta Ohm) (Table 9). Since it has a higher accuracy (± 2% RH), it was used as the standard instrument for calibration and data correction of the TR-72U humidity sensors.

In determining mean radiant temperature, the black globe thermometer was used due to its simplicity and wide acceptance. The internal temperature of the black globe is an equilibrium temperature caused by heat loss and gain from radiation and convection (ASHRAE, 2005). In this method, measurements of air temperature and air velocity are required to calculate the mean radiant temperature. The size of the black globes used in both case study houses were 150mm in diameter, which is the recommended standard globe size (BSI, 2001). The globe thermometer in House 1 was constructed by inserting a type-T copper-constantan thermocouple into a hollow black sphere. A bamboo chopstick was used to position the thermocouple in the center of the globe without contact with the thermo-junction. The SICRAM module for the said thermocouple was TP471D for use with DO9847 multifunction data logger (Delta Ohm) (Table 3.9). The black globe thermometer used in House 2 was the WBGT transducer manufactured for Brüel & Kjær Innova Thermal Comfort Data Logger Type 1221 (MM0030, Innova AirTech Instruments A/S) (Table 10). This instrument complies with ISO 7726. Since the former globe thermometer was self-built, it was tested against the latter in typical indoor environment before use.

Table 9. Instrumentation description and accuracy for House 1.

Quantity	HOUSE 1				
	Sensor Location*	**Instrument Model****	**Sensor Type**	**Accuracy**	**Measuring Range**
Air temperature	L: 2.4m	TP120 [1]	Digital temperature sensor	± 1°C over range -10°C to 80°C	-40°C to 80°C
	L: 1.5m	TR-72U [2]	Thermistor	± 0.3°C	0°C to 50°C
	L: 0.6m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	M: 2.9m	D200 [4]	Thermistor	± 0.28°C at 25°C	-20°C to 70°C
	M: 2.4m	TR-72U [2]	Thermistor	± 0.3°C	0°C to 50°C
	M: 1.5m	HP472AC [5]	Platinum resistor (Pt100)	± 0.30°C	-20°C to 80°C
	L: 0.6m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	Attic space	TP120 [1]	Digital temperature sensor	± 1°C over range -10°C to 80°C	-40°C to 80°C
Relative humidity	L: 1.5m	TR-72U [2]	Macromolecular humidity sensor	± 5% RH at 25°C 50% RH	10% to 95% RH
	M: 1.5m	HP472AC [5]	Capacitance hygrometer (Mk-33)	± 2% RH	5% to 98% RH
Globe temperature	M: 1.5m	TP471D [5]	Type T thermocouple inside 150mm diameter black globe	± 0.1°C	-200°C to 400°C
Surface temperature	L: 3.0m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	L: 0.0m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	M: 3.0m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	M:0.0m	TR-52 [3]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C

* L: living room; M: master bedroom
** Source:
[1] Dickson (2006)
[2] T&D Corporation (2004a)
[3] T&D Corporation (2004b)
[4] Dickson (1998)
[5] Delta Ohm (2005)

Table 10. Instrumentation description and accuracy for House 2.

	HOUSE 2				
Quantity	**Sensor Location***	**Instrument Model****	**Sensor Type**	**Accuracy**	**Measuring Range**
Air temperature	L: 2.4m	TP120 [1]	Digital temperature sensor	± 1°C over range -10°C to 80°C	-40°C to 80°C
	L: 1.5m	TR-72U [2]	Thermistor	± 0.3°C	0°C to 50°C
	L: 0.6m	D200 [3]	Thermistor	± 0.28°C at 25°C	-20°C to 70°C
	M: 2.9m	D200 [3]	Thermistor	± 0.28°C at 25°C	-20°C to 70°C
	M: 2.4m	TR-72U [2]	Thermistor	± 0.3°C	0°C to 50°C
	M: 1.5m	TR-72U [2]	Thermistor	± 0.3°C	0°C to 50°C
	L: 0.6m	MM0034 [4]	Shielded platinum resistor (Pt100)	± 0.2°C over range 5°C to 40°C	-20°C to 50°C
	Attic space	TP120 [1]	Digital temperature sensor	± 1°C over range -10°C to 80°C	-40°C to 80°C
Relative humidity	L: 1.5m	TR-72U [2]	Macromolecular humidity sensor	± 5% RH at 25°C 50% RH	10% to 95% RH
	M: 1.5m	TR-72U [2]	Macromolecular humidity sensor	± 5% RH at 25°C 50% RH	10% to 95% RH
Globe temperature	M: 1.5m	MM0030 [4]	Platinum resistor (Pt100) inside 150 mm diameter black copper globe with 0.98 emissivity	± 0.5°C over range 5°C to 50°C	5°C to 100°C
Air velocity	M: 1.5m	MM0038 [4]	Elliptical omnidirectional constant temperature anemometer	± 5% ± 0.05 m/s for v < 1m/s; ± 10% over range 1m/s to 10m/s	0m/s to 10m/s
Surface temperature	L: 3.0m	TR-52 [5]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	L: 0.0m	TR-52 [5]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	M: 3.0m	TR-52 [5]	Teflon-shielded thermistor	± 0.3°C over range -20°C to 80°C	-60°C to 155°C
	M:0.0m	MM0035 [4]	Spring-loaded platinum resistor (Pt100)	± 0.5°C over range 5°C to 40°C	-20°C to 100°C

* L: living room; M: master bedroom
** Source:
[1] Dickson (2006)
[2] T&D Corporation (2004a)
[3] Dickson (1998)
[4] Innova (2004)
[5] T&D Corporation (2004b)

Air velocity measurement was taken in the master bedroom of House 2 using an omnidirectional constant temperature anemometer (MM0038, Innova AirTech Instruments A/S) (Table 10). This device complies with ISO 7726. Air velocity was not measured in House 1. Due to the fluctuating nature of air movement, the mean value over a measuring period of 100s at 0.05s sampling time was measured.

In addition to air temperature measurements, surface temperature measurements on the floor and ceiling were also important for vertical thermal analysis. This is because the ceiling and roof of the case study houses (and most Malaysian terraced houses) were not insulated. As such, heat may be radiated from the roof/ceiling into the room during the day. It should be noted that minimizing contact with surrounding air is important for surface temperature measurement. Air and surface temperature sensors were calibrated against a type-T thermocouple or a platinum resistor (Pt100) sensor before use and no correction was needed except for the D200 model.

All indoor measurements were recorded at 10-minute intervals using portable, automatic data loggers. The recording method was instantaneous reading except for air velocity measurement described above. Figures 4a & b are photos of the sensor placements in the living rooms and master bedrooms of the case study houses. As shown, full-height poles were used to position the temperature and relative humidity sensors at their respective measuring heights. Globe thermometers and the air velocity sensor were placed next to the temperature and relative humidity sensors at 1.5m height on a separate frame.

Data of the indoor measurements were retrieved serially on-site to a laptop computer. This data acquisition was performed twice, i.e. upon the completion of Cases 1, 2 and 3, and upon the completion of Cases 4, 5 and 6. Since the Innova Thermal Comfort Data Logger Type 1221 (Innova AirTech Instruments A/S) was run on electrical power supply with short battery backup, data were transmitted daily (during the morning site visit) to the same laptop computer in order to minimize data loss in case of power supply failure. However, data from the said logger, which was placed in the master bedroom of House 2, were lost on 26th August due to power supply failure in the house.

Figure 4 Indoor measurements in the case study houses. Master bedroom (first floor) and Living room (ground floor) of House 1

Outdoor Weather Data Measurement

Outdoor weather data during the field experiment period were obtained on-site using a mini-weather station. The climatic parameters recorded are: i) air temperature, ii) relative humidity, iii) wind speed, iv) wind direction, v) global horizontal solar radiation, vi) rainfall, and vii) barometric pressure at the station level. All measured data were logged automatically at 15-minute intervals. Each data was averaged, or totaled in case of solar radiation and rainfall data, over the whole 15 minutes at one minute sampling period. The 1-minute sampling was also not single snapshot reading. Similar to indoor data, these outdoor data were transmitted serially to the laptop computer, on a weekly basis.

The model of the weather station used was EASIDATA Mark 4 (Environdata, 2003). Table 11 lists the sensor type, measuring range and sensor accuracy for each climatic parameter. The air temperature sensor was a semi- conductor integrated circuit which translates the output voltage into ambient air temperature. Its accuracy over the measuring range is ± 0.3°C. The relative humidity sensor was an electronic sensor based on capacitance and has an accuracy of ± 2% RH. Wind measurement sensors consist of a three-cup anemometer for measuring the wind speed and a vane to determine the wind direction. The minimum measurable wind speed is 0.3 m/s. Regarding solar radiation measurement, the sensor used was a silicon photovoltaic cell pyranometer which detects global incoming solar radiation equivalent to that falling on a non-reflective, flat surface. In this research, the solar radiation sensor read the total incident solar energy over a period. The error of reading is ± 5% or less. Total rainfall was ascertained by a tipping bucket rain gauge where one tip is equivalent to 0.2 mm of rainfall. The barometric pressure sensor used a solid state silicon strain gauge to measure actual atmospheric pressure between 750 and 1050 hPa. (Normal atmospheric pressure at sea level is 1013.25 hPa.) Before being deployed at the site, all sensors were sent for calibration by the weather station manufacturer, Environdata Australia Proprietary Limited. The factory calibration results compared satisfactorily with the specified accuracy.

Table 3.11. Characteristics of the weather station used for outdoor measurement.

Quantity	**Sensor Height Above Ground**	**Sensor Type**	**Accuracy**	**Measuring Range**
Air temperature	1.75m	Semi-conductor integrated circuit	± 0.3°C	-20°C to 60°C
Relative humidity	1.75m	Monolithic integrated circuit (capacitance using a thin film polymer)	± 2% RH	0% to 100% RH
Wind speed	2.45m	Three-cup anemometer	± 0.2 m/s or ± 1% of reading whichever is greater	0 to 60 m/s
Wind direction	2.45m	Vane	± 5°	0° to 360°
Global solar radiation	Approx 7.8m	Pyranometer (silicon photovoltaic cell with ± 3% cosine correction)	± 5% of reading	0 to 1500 W/m^2
Rainfall	0.95m (top) 0.6m (bottom)	Tipping bucket rain gauge with syphon mechanism	± 0.2mm or ± 2% of reading whichever is greater at low rainfall rates; ± 5% at rainfall rates above 300mm/hr	0 to 350 mm
Barometric pressure	1.75m	Solid state silicon strain gauge	± 3 hPa	750 to 1050 hPa

The weather station was placed in the immediate outdoor of House 2 on turf ground. The air temperature, relative humidity and barometric pressure sensors were protected by a ventilated sensor screen at 1.75m height above ground. The wind speed and wind direction sensors were positioned at 2.45m above ground while the rainfall sensor was fixed on a separate stand at 0.6m above ground.

Figure 5 The weather station placed in the immediate outdoor of House 2 for outdoor weather data collection. This photo shows the instrument stand *(right)* and the rainfall sensor on a separate stand *(left)*. Mounted on the instrument stand are wind direction and wind speed sensors, a solar panel, and housing for the data logger, air temperature, relative humidity and barometric pressure sensors.

This chapter has described the overall methodology of conducting a field experiment in two Malaysian terraced houses. It included the selection of the case study houses, an outline of the experimental conditions, and the details of measurement of indoor and outdoor thermal environments. The main steps of the methodology are summarized as follows:

1) A primary survey of Malaysian terraced houses was carried out in Johor Bahru city and its conurbation from January to February 2007. Subsequently, two typical and adjacent terraced houses were selected for the field experiment.

2) The typology of Malaysian terraced houses beginning 1960s until 2000s was analyzed. It was found that double-storey terraced houses are more common than single-storey terraced houses at present. From the survey, five types of internal layout were distinguished for double-storey terraced houses while another three

types of internal layout were identified for single-storey terraced houses. The typical layout group of double-storey terraced houses was found to have total floor areas of 90-220 m^2 per unit, with a mean value of 148 m^2. In addition, the most common building data from all terraced house sampling units were determined as follows: 143 m^2 lot area, 6.7m lot width, 21.3m lot length, 0.4-0.6 building width-to-depth ratio, 3 and 4 bedrooms for single-storey and double-storey terraced houses respectively, and 3.0m ceiling height. It was also found that the air-well, operable louver window and ventilation blocks were commonly used in early terraced houses but much less used after mid-1980s. Single-glazed casement windows are quite common at present.

3) The details of the selected case study houses were explained. They are two adjacent units of double-storey terraced houses constructed in 1996. Both houses are symmetrical in layout, but identical in terms of design, size and orientation. The two houses represent the typical terraced house in terms of internal layout type and building data outlined above. Total floor area of each house is 155 m^2. Both houses were found to be high mass buildings constructed of reinforced concrete structures and plastered brick walls. Only a thin layer of double-sided aluminum foil was applied underneath the concrete roof tiles as radiant barrier while the first floor ceiling was not insulated.

4) Six experiment cases were set to include daytime ventilation, night ventilation, full-day ventilation, no ventilation and ceiling fans. As found from the review of Kubota and Ahmad (2005b), daytime ventilation represents the current pattern of opening windows in Malaysian terraced houses while the use of ceiling fans is common throughout the day and night.

5) The calibration for measuring instruments was performed in typical indoor conditions in the university laboratory prior to the field experiment. Equations to correct indoor relative humidity,

globe temperature and some of the air temperature data were obtained from the calibration results.

6) The measurement method of indoor and outdoor thermal environments was explained in above sections. Details of the models, sensor types and measurement accuracy of calibrated instruments were described. All basic quantities were included for measurement at 1.5m height above floor in the master bedrooms for the analysis of general thermal comfort. Other measurement points were located in the living rooms and master bedrooms for the analysis of vertical distribution of indoor temperatures.

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7

THE SCIENCE OF FIRE AND FIRE SPREADING IN BUILDING

Yahya Bin Mohamad Yatim

INTRODUCTION

In the event of fire, people died are mostly caused by smoke or smoke inhalation related instead of direct burning. Smoke and heat become a major threat in building fire, therefore understanding the characteristic of smoke and heat are crucially important in building fire for the sake of life safety. With the knowledge and understanding of the behavioural of smoke and heat, ones can be expected to be able to make a wise decision once in a critical situation i.e. dealing with the building fires. Life safety would be increased if occupants of the high-rise residential buildings know at what limit that the risks can safely to be taken. By understanding the science of fire and fire spreading in the building, evacuation process would be eased because occupants in high-rise buildings know what to do in the event of fire.

The size of a fire is related to the heat release rate. To determine a design fire, a database on heat release rate should thus be developed (Peacock et al, 1994). The size of the fire and its heat release rate is the first and most important element among the following list of parameters commonly used to characterize an unwanted fire (FPEH, 2002, Huggett, 1980). However, the threat to the occupants may be minimized and the damage to the fabric and structure of the building could be reduced to an acceptable level by increasing knowledge of fire science and the principles of fire safety engineering (Bishop & Drysdale, 1998).

A fire tragedy will not only be involved the damage on the property but also could be lost of life. Undeniable that every body needs for fire but uncontrolled fire is very dangerous and can be devastated. Therefore we must be very careful when dealing with the elements which are having a high risk of fire ignition. Another importance factor that needs to be considered is the *fire load*[1] stored in the building. According to Clark (1988), even buildings constructed of non-combustible materials will almost without exception contain materials that burn under certain circumstances. On the other hand, materials that are designated as a combustible material, according to tests, may be of negligible significantly in fires. Wood is a good example of a common material for which fire performance is difficult to predict. It ignites if its surface reaches about 300°C in the presence of a flame or perhaps 400-500°C in its absence. It may also ignite, however, at much lower temperatures if the time of exposure to heat is longer. Charring, a process related to ignition, has been recorded when the temperature was not much above 100°C. Before we go further about science of fire, let we look at the definition of fire and fire safety related attributes.

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[1] Fire Load – Every thing inside the building which is form a part or not a part of the building structure such as people, furniture, finishing etc….

DEFINITION FOUND IN VARIOUS REFERENCES.

Definition of fire and fire safety attributes given in this chapter are gathered from various sources. Hopefully it will help in fully understanding the meaning of terms' used in later on chapter fire safety study. The basic principle and the terms' used in fire safety engineering field are.

a) Combustion

Oxford Dictionary (OD) and International Encyclopaedia (IE) gave the definition of combustion as follows:

> *"A state of combustion in which the substances combine chemically with oxygen from the air and usually give out bright light and heat" (OD)*

> *"A rapid combustion characterized by high temperatures and flame. In order to produce fire, a combustible material and oxygen must be present and in contact at sufficiently high temperatures to initiate combustion" (IE)*

Meanwhile, the The American Heritage Dictionary of the English Language (TAHDEL, 2004), gives the definition of combustion as the process of burning or a chemical changes, especially oxidation, accompanied by the production of heat and light. The word combustion was believed originated from the late Latin that *combustiō, combustiōn* or from Latin *combustus* that the past participle of *combūrere* which is giving a meaning of to burn up or blend of combustion or to burn around.

The Columbia Electronic Encyclopaedia (CEE, 2003) defines combustion as a rapid chemical reaction of two or more substances with a characteristic liberation of heat and light; it is commonly called burning. The burning of a fuel (e.g., wood, coal, oil, or natural gas) in air is a familiar example of combustion. Combustion reactions involve oxidation and reduction. Before a substance will burn, it must be heated to its ignition point, or kindling temperature. Although the ignition point of a substance is essentially constant, the time needed for burning to begin depends on factors such as the form of the substance and the amount of oxygen in the air (CEE, 2003). However, combustion sometime may not involve oxygen to the process for the ignition to start e.g. hydrogen burns in chlorine to form hydrogen chloride with the discharge of heat and light that a characteristic of combustion too.

Vikipedia (2004) defined combustion or burning is an exothermic reaction[2] between substances and gases to release heat. Combustion normally occurs in oxygen (often in the form of gaseous O_2) to form oxides, However, combustion can also take place in other gases like chlorine. The products of such reaction usually include water (H_2O) as well as carbon monoxide (CO) or carbon dioxide (CO_2), or both which is high in toxicity. Other by products, such as partially reacted fuel and elemental carbon (C), may generate visible smoke and soot. Generally, the chemical equation for combusting a hydrocarbon, e.g. octane, in oxygen is as follow: $C_xH_y + (x + y/4)O_2 \rightarrow xCO_2 + (y/2)H_2O$. For example, the burning of Propane is: $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$.

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[2] In chemistry, an **exothermic reaction** is one that releases heat. It is the opposite of an endothermic reaction. Expressed in a chemical equation: Reactants → Products + Energy. When using a calorimeter, the change in heat of the calorimeter is equal to the opposite of the change in heat of the system. This means that when the solution in which the reaction is taking place gains heat, the reaction is exothermic. In an exothermic reaction the total energy absorbed in bond breaking is less than the total energy released in bond making (Vikipedia.org).

b) Rapid Combustion

Rapid combustion is a form of combustion in which large amounts of heat and light energy are released. Example of rapid combustion is burning of fuel i.e. petrol or diesel in internal combustion engine, burning of highly combustible material in open burning, etc.

c) Slow Combustion

Slow combustion is a form of combustion which taken place at a low temperature. Example of slow combustion is what we see in everyday life e.g. gas cooker used to cook food, burning of candle, etc.

d) Fire

A rapid, persistent chemical change that releases heat and light and is accompanied by flame, especially the exothermic oxidation of a combustible substance.

The American Heritage Dictionary of the English Language (TAHDEL, 2004), further explains the meaning of fire i.e. the word of fire was inherited directly from Germanic, the other borrowed from Latin. The word *fire* goes back to the neuter member of the pair. In Old English "fire" was *f[ymacr]r,* from Germanic **fūr.* The Indo-European form behind **fūr* is **pūr,* whence also the Greek neuter noun *pūr,* the source of the prefix *pyro–.* The other Indo-European word for fire appears in *ignite,* which is derived from the Latin word for fire, *ignis,* from Indo-European **egnis.* The Russian word for fire, *ogon'* (stem form *ogn–*), and the Sanskrit *agni–,* "fire" (deified as Agni, the god of fire), also come from **egnis,* the active, animate, and personified word for fire.

The word fire is used to refer to the combination of the brilliant glow and large amount of heat released during a rapid, self-sustaining exothermic oxidation process of combustible gases ejected from a fuel. The fire itself is a body of gas that releases heat and light. It starts by subjecting the fuel to heat or another energy source, e.g. a match or lighter, and is sustained by the further release of heat energy i.e. change reaction. The word fire by itself is used more often to refer to uncontrolled fires than to refer to controlled fires (Wikipedia, 2004).

According to Jerome (1994), fire is the manifestation of a chemical reaction called combustion. This reaction takes place between a fuel and oxygen but requires heat to initiate the reaction. When the reaction has started it generates its own heat and this reaction will continue until all available fuel finished. This reaction called *chain reaction*[3] which means that fire spread by it owns heat.

According to CEE (2003), chain reaction is self-sustaining reaction that, once started, continues without further outside influence. Proper conditions for a chain reaction depend not only on various external factors, such as temperature, but also on the quantity and shape of the substance undergoing the reaction. A chain reaction can be of various types, but nuclear chain reactions are the best known. A line of dominoes falling after the first one has been pushed is an example of a mechanical chain reaction; a pile of wood burning after it has been kindled is an example of a chemical chain reaction. In the latter case each piece of wood, as it burns, must release enough heat to raise nearby pieces to the kindling point. The wood, therefore, must be piled close enough together so that not too much heat is lost to the surrounding air. The conditions for a nuclear

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[3] According to the Encyclopedia Britannica **Chain reaction** is a series of reactions in which the product of each step is a reagent for the next. Many polymerization reactions are chain reactions. A simpler example, however, is found in the synthesis of hydrogen bromide. The overall synthesis equation is H_2 + Br_2 ® 2HBr.

chain reaction can be understood by analogy. In the case of the fission of a nucleus, the reaction is begun by the absorption of a slow neutron. Each of fission produces two or three fast neutrons. In order to sustain a chain reaction, a sample must be large enough to slow the neutrons so that one can be captured by another nucleus and produce a second fission. The sample must also be compact to prevent neutrons from escaping. The minimum quantity of a fissionable material necessary to sustain a nuclear chain reaction is called the critical mass.

e) Pyrolysis:

Pyrolysis is a process of decomposition or transformation of a compound caused by heat. (TAHDEL, 2004) It is a chemical decomposition of organic materials by heating in the absence of oxygen and water. When water is present *hydrous pyrolysis*[4] takes place. The term pyrolysis generally refers to *anhydrous pyrolysis*, without water. Anhydrous pyrolysis has been assumed to take place during *catagenesis*[5], the conversion of *kerogen*[6] to fossil fuels. One use of industrial pyrolysis is to extract usable fuels from a wide variety of organic products. The production of charcoal through the pyrolysis of wood has been widely used. In many industrial

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[4] **Hydrous pyrolysis** refers to the chemical processes which take place when material is heated to high temperatures in the presence of water.

[5] **Catagenesis** is a term used in petroleum geology to describe the cracking process which results in the conversion of organic kerogens into hydrocarbons.

[6] **Kerogens** are chemical compounds formed by the low-grade metamorphism (i.e. diagenesis) of organic molecules derived from decaying plant and animal matter. These are long-chain polymers which do not dissolve in several specific solvents.(Vikipedia,2004)

applications the process is done under pressure and at operating temperatures above 430°C (800°F) (Vikipedia, 2004).

It also can be used to degrade wastes, as a form of incineration. Pyrolysis is also a common technique to produce liquids from solid biomass. The most common technique uses very low residence times (<2 seconds) and high heating rates using a temperature between 350-500°C and is called either fast or flash pyrolysis.

f) Fire Safety

Fire safety is a generic term normally used in component of building fire safety which including some elements as follow:

- Maximum occupancy or occupancy load that the number of peoples permitted to occupy any building at one particular time. This is to ensure that they all can evacuate the building as quick as possible in an emergency situation.
- There are sufficient of fire exits and proper signage which workable even if power failure occurred. The exit signage should be able to direct the occupiers to the designated safe assembly area.
- Fire extinguishers or fire suppression system and fire alarms are placed in an easily accessible location. The system regularly being inspected and maintained.
- All flammable materials are banned from being stored in building in a certain huge amount unless permission has been given by the relevant authority. The place to store that material should be built with fire retardant materials and has passed the fire test.
- Regular inspecting to public buildings being carried out to check for violations of fire safety policy or fire precaution act and if necessary closing order issued until the violation is corrected or condemn it in extreme cases.

g) Fire Exit

Fire exit is a fire escape route that forming a part of the building component which is used by the people to evacuate from the building in a case of an emergency such as a fire. It is usually a strategically located (e.g. in a stairwell, hallway, or other likely place) outward opening door with a crash bar on it and with exit signage leading to it. The name is an obvious reference to when they are frequently used, however a fire exit can also be a main doorway in or out. A fire escape is a special kind of fire exit, mounted to the outside of a building.

THE PRINCIPLE OF FIRE

Fire is a manifestation of a chemical reaction called combustion. The principle of fire is categorised as a rapid chemical reaction of two or more substances with a characteristic of heat and light. It is commonly called burning. However fire is categorist according to the types of fuel it consumes and named various classes of fires i.e. A to F or E (for United State). In Europe and Australia, classes of fire are grouped into six groups as follows:

- Class A: Fires that involve flammable solids such as wood, cloth, rubber, paper, and some types of plastics.
- Class B: Fires that involve flammable liquids or liquefiable solids such as petrol/gasoline, oil, paint, some waxes & plastics, but NOT cooking fats or oils.
- Class C: Fires that involve flammable gases, such as natural gas, hydrogen, propane, butane.
- Class D: Fires that involve combustible metals, such as sodium, magnesium, and potassium.
- Shock Risk Fire (formerly known as Class E): Fires that involve any of the materials found in Class A and B fires, but with the introduction of an electrical appliances, wiring, or other electrically energized objects in the vicinity of the fire,

with a resultant electrical shock risk if a conductive agent is used.

- Class F: Fires involving cooking fats and oils. The high temperature of the oils when on fire far exceeds that of other flammable liquids making normal extinguishing agents ineffective

In the U.S., fires are generally classified into four groups: A, B, C, and D.

- Class A: Fires that involve wood, cloth, rubber, paper, and some types of plastics.
- Class B: Fires that involve gasoline, oil, paint, natural and propane gases, and flammable liquids, gases, and greases.
- Class C: Fires that involve any of the materials found in Class A and B fires, but with the introduction of an electrical appliances, wiring, or other electrically energized objects in the vicinity of the fire.
- Class D: Fires that involve combustible metals, such as sodium, magnesium, and potassium.

THE COMBUSTION THEORY

Combustion is a process of chemical reaction between the substances with the present of oxygen which will give out the bright light and heat. In general, when combustion process happened, it will usually involve the rapid process of oxidation[7] which usually produced bright light, heat, flame and smoke. What actually happen was a process called pyrolysis which is the process of vaporising the

[7] According to The New Dictionary of Cultural Literacy, Third Edition Edited by E.D. Hirsch et al, oxidation is any chemical reaction in which a material gives up electrons, as when the material combines with oxygen. Burning is an example of rapid oxidation; rusting is an example of slow oxidation.

substances chemical compound especially the carbonise compound which left char after the process has completed.

FIRE CHARACTERISTICS

a) Heat

Heat is evolved in exothermic processes and absorbed in endothermic processes; such processes include chemical reactions, transitions between the states of matter, and the mixing of two substances to form a solution. Heat is a non-mechanical energy in transit, associated with differences in temperature between a system and its surroundings or between parts of the same system. According to AHD, (2004), heat is a form of energy associated with the motion of atoms or molecules and capable of being transmitted through solid and fluid media by conduction, through fluid media by convection, and through empty space by radiation. The following information about the heat characteristics are taken from The Columbia Electronic Encyclopaedia, 2003, at the website www.cc.columbia.edu/cu/cup/.

Measurement of Heat

Heat measured base on the energy release during combustion process. A number of different units are used in heat measurement, e.g., the calorie, the British thermal unit (Btu), and the joule. The apparatus used in heat measurement is called a calorimeter. Temperature is a measure of the average transactional kinetic energy of the molecules of a system.

Specific Heat

As heat is added to substances in the solid state, the molecules of the substances gain kinetic energy and the temperature of the substances rise. The amount of heat needed to raise a unit of mass of the substance one degree of temperature is called the specific heat of the substance. For example, the specific heat of water is 1 calorie per gram per degree Celsius; i.e., 1 calorie of heat is needed to raise the temperature of 1 gram of water by 1 degree Celsius; it is also 1 Btu per pound per degree Fahrenheit.

Heat of Fusion

When a solid reaches a certain temperature, it changes to a liquid. This temperature is a particular property of the substance and is called its melting point. While the solid-liquid transition is taking place, there is no change in temperature. All of the heat being added is being converted to the internal potential energy associated with the liquid state. The amount of heat needed to convert one unit of mass of a substance from a solid to liquid is called the heat of fusion, or latent heat of fusion, of the substance. Like specific heat, latent heat is also a property of the particular substance. The latent heat of fusion for the ice-to-water transition is 80 calories per gram.

Heat of Vaporization

After a substance is completely changed from a solid to a liquid, further addition of heat again causes the temperature to rise until it reaches the boiling point, the particular temperature at which the given substance changes from a liquid to a gas. During the liquid-gas transition, the temperature remains constant until the change is completed. The heat of vaporization, or latent heat of vaporization, is the heat that must be added to convert one unit of mass of the substance from a liquid to a gas.

Transfer of Heat

Heat may be transferred from one substance to another by three means that conduction, convection, and radiation. Conduction involves the transfer of energy from one molecule to adjacent molecules without the substance as a whole moving. Convection involves the movement of warmer parts of a substance away from the source of heat and takes place only in fluids, i.e., liquids and gases. Radiation is the transfer of heat energy in the form of electromagnetic radiation, principally in the infrared radiation portion of the spectrum.

Study and Analysis of Heat

The study of heat and its relationship to useful work is called thermodynamics and involves macroscopic quantities such as pressure, temperature, and volume without regard for the molecular basis of these quantities. Low-temperature physics is concerned with phenomena that occur at extremely low temperatures. The analysis of heat on the basis of the structure of matter is considered in the kinetic-molecular theory of gases and provides an explanation for the various gas laws. The gas laws in turn serve to define an absolute temperature scale based on theoretical considerations.

b) Flame

Flame is a phenomenon associated with the chemical reaction of gases that have been heated above its kindling temperature with some other gas, usually atmospheric oxygen. The heat and light given off are characteristic of the specific chemical reaction (or reactions) going on; the luminosity of the flame is usually caused by solid particles of foreign matter present (naturally or artificially) in the burning gas and heated to incandescence; and the shape of the flame is commonly that of a hollow cone. Further information about the flame can be getting from CEE (2003).

Flame colour

Flame colour is varies and dependant on the chemical composition of the burning elements or fuel it consume and intermediate reaction products. In many cases such as burning organic matter like wood or incomplete combustion of gas, incandescent solid particles produce the familiar red-orange 'fire' colour light. This light has a continuous spectrum. Complete combustion of gas has a dim blue colour due to the emission of single wavelength radiations from various electron transitions in the excited molecules formed in the flame.

c) Smoke

Smoke is a visible gaseous product of incomplete combustion made up of small particles of carbonaceous matter in the air, usually comprises hot gas and suspended particles of carbon and tarry substances, fine solid or liquid particles in a gaseous medium, or soot and forming a cloud of fine particles resulting mainly from the burning of organic material, such as wood or coal. Smoke varies with its source, but it wood gives little smoke if burned when dry and if the fire is given a good supply of air.

UNDERSTANDING THE BASIC OF CHEMICAL AND PHYSICAL NATURE OF FIRE

In spite of knowing the definition of fire and fire related terms, the basic chemical and physical nature of fire needs to be studied for better understanding of fire and how it can be controlled during initial growth and development. In fire science, the well known theory of fire is ‘Triangle of Fire’ model. Figure 1 illustrates the triangle of fire which having three components links together to form a triangle. Those components are fuel, oxygen and heat which chemically bonding together to form fire characteristics that flame, smoke and heat.

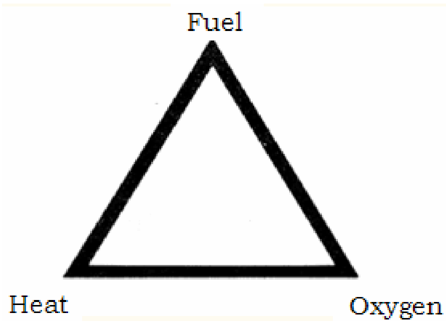

Figure 1: The triangle of fire concept model (Mehaffey, 1987)

This triangle of fire can be understood that if we want to extinguish the fire, it can be done by isolating one of the three components from the combination. Fire can be suppressed by removing either heat, which commonly use water spray to cool the heat, or by removing the fuel, which normally by limiting or turning off the flow of gas in a gas stove or by removing the oxygen that by smothering the fire with a fire blanket for example. However, we should not forget about the fact that ‘Chemical Reactions’ are also needed to keep the fire spreading. This reaction known as ‘Chain Reaction’ which is heated molecules will freely and rapidly moving in all directions. These molecules on flame are very active moving around and hitting the other molecule to set fire on other molecule. Fire will be continued due to chain reaction process which the heated molecules will touch the others until the temperature reached the state of auto combustion where hydrogen gas and oxygen gas from the air actively taking part in burning process. Figure 2 illustrated the process of chain reaction in burning materials.

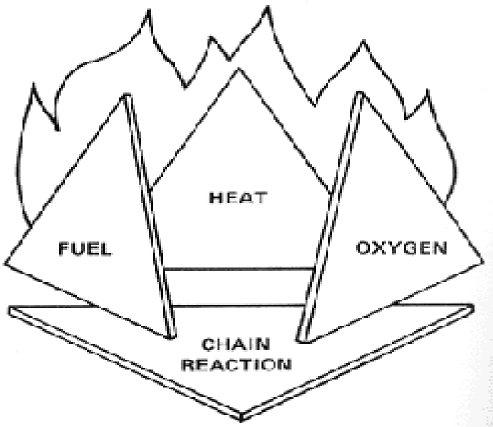

Figure 2: The chain reaction process in burning material, (Mehaffey, 1987)

How rapid of the chain reaction will taken place is depend on the how fast of the pyrolisis process is done on the fuel. For example, polymer's products of building materials e.g. synthetic polymers or plastic products have a very rapid chain reaction compare to organic carbonise construction materials e.g. woods. By breaking the chain reaction, fire can be suppressed and this allows for the possibility of a fourth extinguishment technique that building component coated with the fire retardant chemicals to react while being heated to break the chain reaction. Gypsum is one of among material which acted in this fashion. It is a mineral composed of calcium sulfate (calcium, sulfur, and oxygen) with two molecules of water. Chemical formula for calcium sulfate is $CaSO_4 \cdot 2H_2O$. When it heated approximately 150°C (302°F) partially dehydrates the mineral by driving off exactly 75% of the water contained in its chemical structure rather than increasing the temperature of the mineral. The temperature will rise slowly until the water is gone as steam and delaying the burning process by slowing the chain reaction. The chemical formula for this process as follow:

$CaSO_4 \cdot 2H_2O$ + heat → $CaSO_4 \cdot ½H_2O$ + $1½H_2O$ (steam) (Answers.com, Sept. 27, 2005).

Products of combustion rise above the flame are in the form of smoke and heat. Smoke consists of airborne solids (soot), liquid droplets, and gases, some of which may be toxic. Among the toxic gases produced, carbon monoxide is certainly the most lethal gas. However, Carbon Dioxide, Hydrogen Cyanide, Hydrogen Chloride, Nitrogen Dioxide and may others also be produced when relevant material set on fire. Carbon monoxide is the main toxic gas produced from the combustion of polyethylene and other organic materials that are made up of carbon and hydrogen atoms. It is produced as a result of incomplete combustion when the oxygen supply is limited. When it is inhaled causes asphyxiation by combining with haemoglobin in a reversible reaction to form *carboxyhaemoglobin*. Its formation at the expense of *oxyhaemoglobin* reduces the availability of oxygen for the cellular systems of the body (Sumi & Tsuchiya, 1971).

THE STAGES OF A FIRE

Fire behaviour within an enclosed space is behaved differently and with different rate of burning from those in the open (Stollard & Abrahams, 1995). The growth period lasts from the moment of ignition to the time when all combustible materials within the enclosure area are burned.

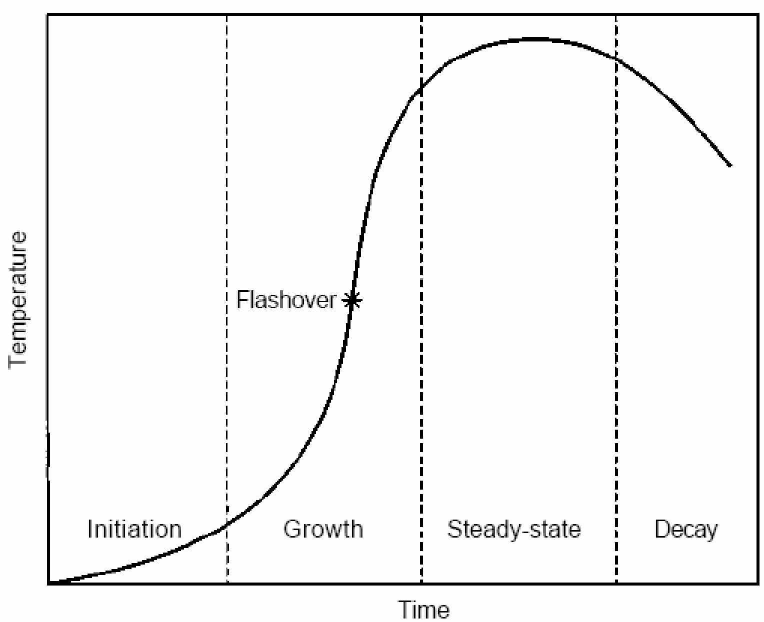

Figure: 3: A standard fire curve in enclosed spaces (CIBSE, 2003)

Figure 3 shows standard fire curve in compartment fire. The Time – Temperature curve in this figure 3 is not according to the scale and the time taken in each stage can not be directly measured to get an empirical reading but rather than a conceptual graph to show the behaviour of fire in building. The purpose of this graph is to show a graphical explanation about the stages of normal fire behaviour in compartment fire. There are four stages all together i.e. initial stage, growth, steady Combustion and decay. In initial stage, fire behaviour is largely depends on the types of fuel available in the building. If the fuel is in gases form, the ignition will be very rapid and if the fuel is in a solid material like timber, it will be a slow combustion or smouldering fire. On the other hand, fire behaves largely influent by how fast pyrolisis processes are taken place. At the initial stage only smoke and heat will be released. Once smoke has detected, i.e. fire alarm goes off, people in the affected buildings should start to make their way out to the escape stairs as soon as possible. They should not wait until the fire emerged and become serious or uncontrollable before begin to evacuate. A better chance to safe life is greater if immediate action is taken to evacuate the building soon after the fire has detected.

The rate of development of fire and it durations are influenced by the nature of the content of the building and materials of the room surfaces (Marchant, 1972). The phase of fire growth is started when ignition has begun and continues until all combustible materials are lighted. At this point flashover began and fire started to full growth and begins to enter the steady state combustion phase where most of the combustible materials are burning and the heat releases is maximum. For building fires the temperature at this stage is ranging from 900^0 C – 1200 ^{0} C and the duration of fires are determine by the amount of air supplied and the amount of quantity of combustible material available. After all the material has been consumed, it then started to enter the next stage that decay phase.

In decay phase, fire is started to decay until it put off if there are no more combustible materials available. The heat releases will gradually reduced to leave charcoal and dust at the end of the combustion process. Even though fire is in a decaying process, it is still dangerous and still fatal if extremely exposed because there is still smoke at the fire vicinity and posed a danger to the people if they breathe this smoky air. It can possibly chock the respiration system and lethal. Furthermore if there are toxic gases produced during combustion process. This can possibly happen if the materials involved are classified as toxicity materials such as materials contain high chlorinate or nitrite compounds.

FIRE SPREADING IN BUILDING

When fire starts to burn in a compartment, i.e. after ignition, it burns just like in open space. After a short period of time, smoke produced by the burning processes starts to form a hot layer below the ceiling, heating the ceiling and upper walls of the room. Thermal radiation from the hot layer, ceiling, and upper walls begins to heat all objects in the lower part of the room and may augment both the rate of burning of the original object and the rate of flame spread over its surface as illustrated in figure 4.

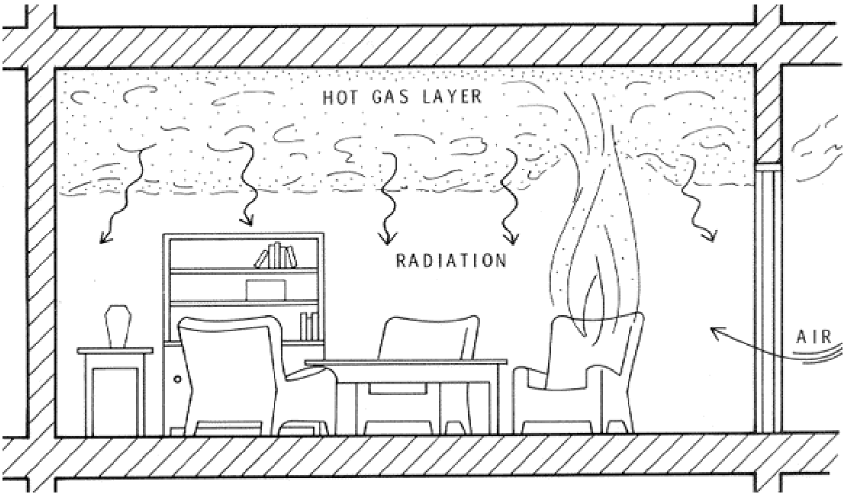

Figure 4: Fire behaviour in compartment (Mehaffey, 1987)

To reduce the risk to persons if there is a fire, it is necessary to consider how to control or restrict the spread of fire and smoke in building because the majority of people who die in fires are overcome by the smoke and gases. Thick and black smoke can obscure vision, choke breathing, and block the escape routes. Fire can spread by three methods i.e.

- Convection,
- Conduction, and
- Radiation

Convection is the most dangerous and causes the majority of injuries and fatalities. Heat and smoke spreads by convection, once fire starts in an enclosed space, when heat and smokes rises from the burning material and is trapped by the ceiling and walls. Heat and smoke will pass through any holes or gaps in the ceiling, walls, or floor into other parts of the building. The heat from the fire trapped in the building will increase the temperature of other combustibles until they reach their ignition temperature and ignite more or less simultaneously to cause flashover.

Conduction occurs when heat absorb by metal and transmit it to other room where it can set fire to combustible materials that are in contact with the heated metal.

Radiation transfers heat in the air in the same way that electric bar heater heats the room. Any combustible materials close to a fire will absorb the heat until they reach their ignition temperature and start to burn.

There are many reasons for the fires to start. The most common reasons are faulty of electrical equipments, poor maintenance of home appliances, over loaded of the electrical power usage, intentional fires, negligence and etc. The issue here is not what has started the fire but what occupants of high-rise residential buildings should do after fire ignited.

Fully understanding the science of fire and fire spreading in building could be able to reduce the risk of fire casualties in building fire. Building occupants are expected to be able to take an appropriate action once they are facing with fire tragedy in their building.

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8

MEASURING INDOOR THERMAL ENVIRONMENT IN TRADITIONAL BANGLADESHI HOUSE

Rumana Rashid
Mohd Hamdan Ahmad

INTRODUCTION

This chapter describes field study deals with the thermal performance of traditional Bangladesh house roof section with the special reference to Dhaka. A field study was essential to evaluate the relationship between upper space and indoor comfort. It presents the methodology of the fieldwork employed to study the effectiveness of the traditional upper space and its influence on the overall thermal performance of the selected traditional house.

THE IMPORTANT OF FIELD STUDY

It is a common practice in Bangladesh particularly among architects and environmental engineers to use data recorded at the meteorological station for the design purposes. It is evident from the field study performed in Dhaka that indiscriminate use of meteorological data in the context of Dhaka city, of a considerable size and diverse texture, is inherently inaccurate (Sabbir Ahmed, 1995; Bijon Behari Sharma, 2002; Abu Mukim Mirdha, 2002).

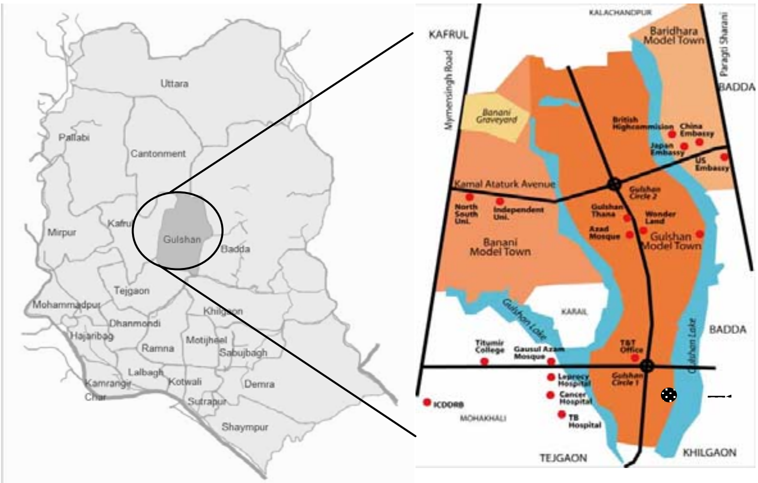

Figure 1: Location of Test house area (Gulshan) in Dhaka city Map

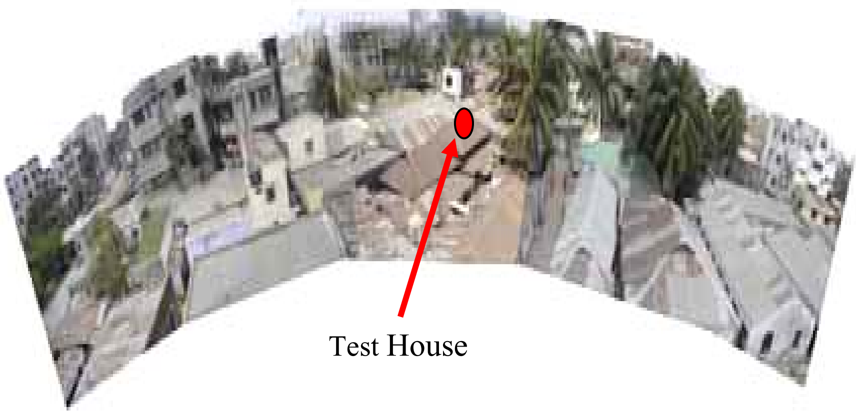

Figure 2: Physical condition of Test house area (Gulshan) in Dhaka city

The environmental data recorded at the meteorological station are affected by characteristics of that particular observation site. Such measurement does not always account for the various characteristics of the different urban sites, often leading to distinct micro-climates.

Hence their applicability for design purposes can be considerably limited although environmental factors, such as relative humidity, radiant temperature and air flows are indicative of these variations in the urban climate. Site air temperature has been found to be the most notable indicator. For this reasons the research's field study are done on site for physical measurements of both indoor and outdoor conditions.

SELECTION OF CASE STUDY HOUSE

Historical Background of the Test House

The test house was first built at the rural area of Maowa in Bangladesh in 1955. In rural area it was arranged in a courtyard arrangement with other four units within one boundary. It had open planning which provided cross ventilation. The selected room was the master bed room with two doors, one was towards a courtyard and another was towards kitchen units and toilet. But when the owner migrated to Dhaka city, he then brought one unit of the house and rebuilt it in the Gulshan area. In the new location, the surrounding situations changed in term of density, lack of privacy, lack of safety and security. Due to their continuous demand for space, they extended the living space after ten years of rebuilding.

Selection of the Particular Test House

The primary criteria for the selection of the test house are as follows,

- Traditional house is effectively designed to establish approach towards sustainability of worst urban environment. So the test house which is selected for this research is situated in the urban context in Dhaka city at highly dense Gulshan area.

- To justify the performance of the traditional house in an extreme surroundings conditions within an urban micro climate.

- 53 years ago this house was built in rural area (Maowa, in Bangladesh since 1955). In 1975, when the owner migrated to Dhaka city, he brought this one unit house and rebuilt it at Gulshan area. So there is no doubt that this particular test house is the most appropriate as an example of traditional house, which have all features of the traditional houses in Bangladesh.

Figure 3: Traditional house (selected as test house) in dense Gulshan area.

Figure 4: The same type of traditional house in rural area of Maowa

Description of the Test House

The test house is surrounded by similar type of traditional house on the north and south side within 0.6m and 1.5m gap at respective orientations. The west and east sides are facing a 1.5m road.

Figure 5: Birds eye view of the surroundings Test House

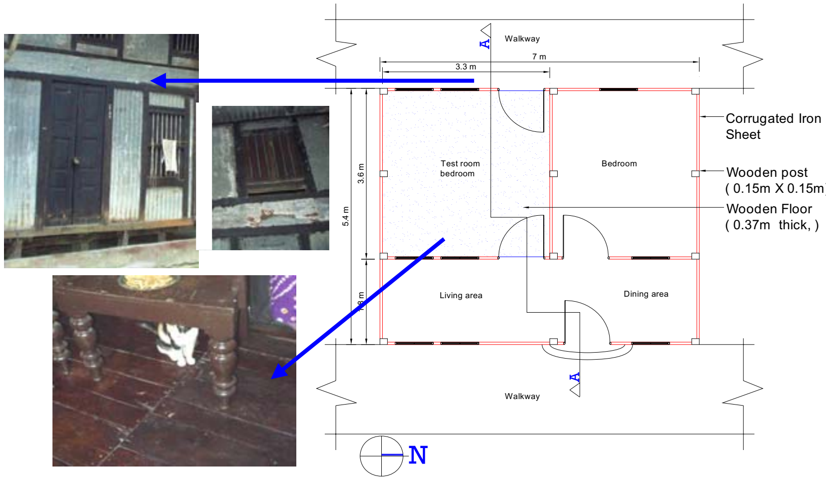

Figure 6: Plan and construction material of the Test House

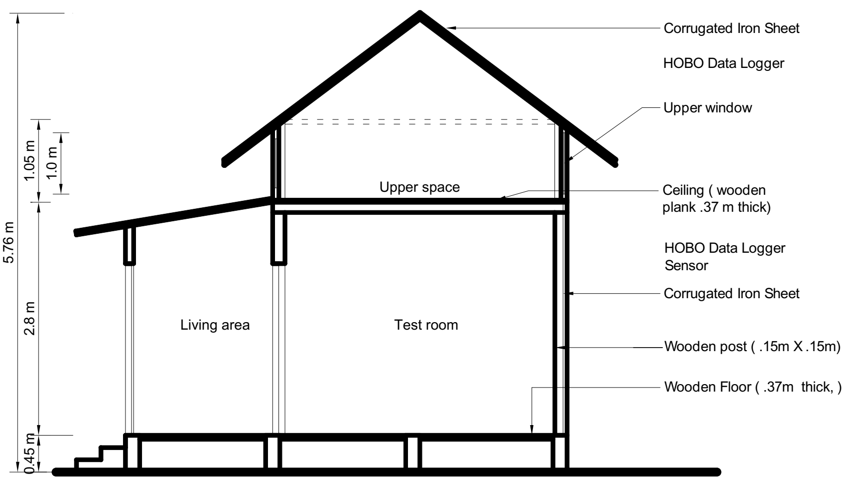

Figure 7: Section AA of the Test House

For collecting the indoor data, the bedroom was selected which is occupying the southwest corner of the house. The room height is 2.8m. The size of the bedroom is 3.3m wide by 3.6m length. This room has two windows of 1m wide on west and east side periphery and two doors. This room is connected to living area through a door. Walls are made with 150mm by 150mm wooden post and corrugated sheets. The ceiling is made of 37.5mm thick wooden planks with 125mm by 75mm wooden beams. Furniture of the room consists of a wooden double bed, wooden wardrobe, wooden cabinet and a wooden study table with chair. The floor is raised from the ground and made by wooden planks. There are two 60 watt florescent lights (one is regularly used and the other is occasionally used) and one ceiling fan in the test room.

Figure 8: Interior of the Test House

There is another consideration in the selection of the test room. In the house there are another two rooms, which are small bedroom and small living room that can be selected. The bedroom is at the north side of the house and the living area is at the east side. The selected test room is located at the southwest corner, which is the hottest corner of the house according to user experience. The selected room receives solar radiation for a longer period compared to other two rooms and also from a study of Sharma (2002), she found that the relation between hot category rooms and cardinal locations, the west side room took the highest position and southwest room took the 2nd highest position in Bangladesh. This research selects the worst corner of the test house to justify the thermal performance of the traditional house in Bangladesh.

The outer surface of the upper space is made of corrugated iron sheets. It is directly exposed to the sun. The extended roof protects the windows of upper space from sun and rain. The upper space has four windows on west and east wall, which are 1.25m by 1m wide. The window of north and south side of the upper space is closed. The floor of the upper space is of wooden planks. In this area there is an incandescent light, which is used occasionally. Generally upper space is used as a store.

INSTRUMENTATION AND EXPERIMENTAL PROCEDURE

Data loggers were installed in the test house for collection of air temperature and relative humidity data. The remote data loggers recorded indoor air temperature and relative humidity with the help of external sensor.

Thermal Data Logger and sensor   External sensor of thermal Data Logger

Figure 9: Thermal Data Logger position in upper space (left) and placement of external sensor under shade of extended roof of the house (right)

Outdoor air temperature, humidity and upper air temperature and humidity are also taken using the sensor of data loggers. Data were recorded at interval of five minutes. The controlling software assigns range of the logger interval. The loggers are initiated by software Box Car Pro 4.0. The software is required for the downloading of data from the data loggers and in making the graph; and exporting data to excel file. Excel software also used for data analyses.

Figure 10: Thermal Data Logger position in upper space (right); Entry from indoor space to upper space (left); Wooden ladder for entering to the upper space (middle).

The instruments used in this field study were as follows

Thermal Data Logger (HOBO H08-007-02)	2 Nos.
External Sensor TM C6-HA	3 Nos.
USB cable	1 No.

The sensitivity of the manufacturer's calibration of the data loggers were compared with the meteorological recording (under similar condition) in Agargaon Meteorological Office and found to be satisfactory.

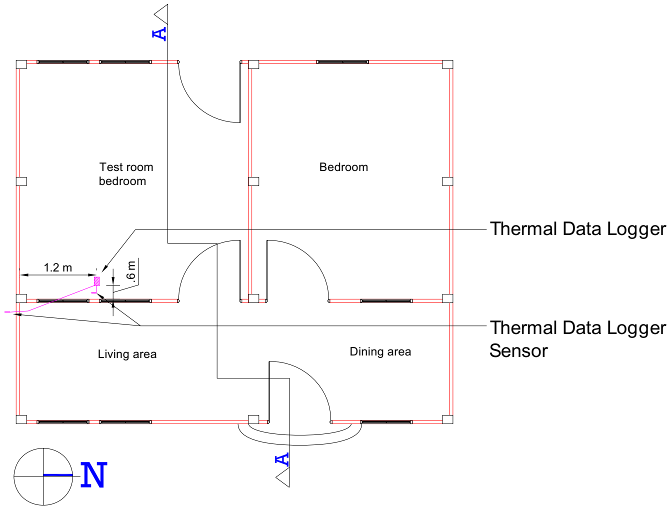

Figure 11: Thermal Data Logger position in indoor and outdoor of the test house

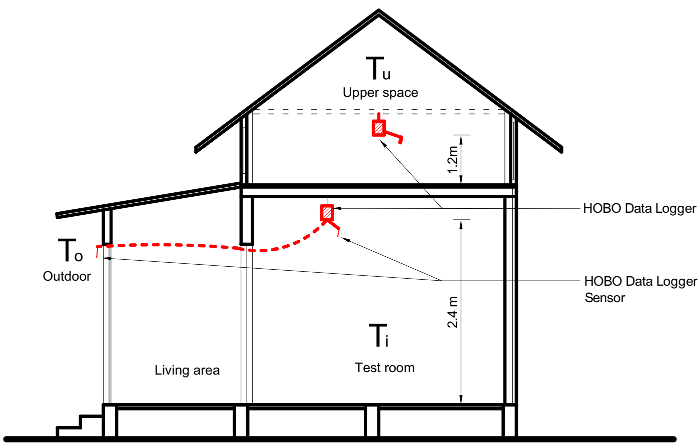

Figure 12: Thermal Data Logger position in indoor, outdoor and upper space in section of the test house

Installation of the Thermal Data Loggers

The thermal data loggers and sensors were installed in the test house in three areas. One data logger with two sensors was used for indoor and outdoor data collection. Another data logger with one sensor was placed in the upper space. The external sensor was hanged to avoid any contact of the wall surface and placed under shaded area for the protection from direct weather effect during the data collection period. So for the outdoor only one data collection point was used.

Position of one data logger and sensor in the upper space is at 1.2m from the wooden ceiling level (figure 12). Thermal data loggers were mounted to the wooden post with the help of hook, nails and steel net.

In the indoor, the data logger was hooked at 2.4 m from the floor level to record immediate changes of air temperature occurring between the upper space and indoor space (figure 12).

Methodology of Data Collection

The data of the field work was taken during the most persistent and dominant seasons; winter and summer. At the same time the most extreme climatic value are also registered during these periods. General climatic condition of the observation period is described in table 1.

Table 1: The seasons and months of Bangladesh and climatic condition

Dominant Season	Gregorian Calendar Months	Meteorological Seasons	Climatic Condition
Summer	March	Pre-monsoon	hot-dry
	April	Pre-monsoon	hot-dry
	May	Pre-monsoon	hot-dry
	June	Monsoon	hot-wet
Winter			
	January	Winter	cool-dry
	February	Winter	cool-dry

From previous study it was identified that January is the coolest month and April is the hottest month for Bangladesh. The mean maximum temperature over Dhaka has its lowest value in January and progresses as the season progresses. It becomes maximum temperature in April with a decreasing tendency up to August. The mean temperature increases from January to April, then remains almost constant up to September, and decreases up to January. The mean minimum temperature is the lowest in January, increases up to June and remains fairly constant up to September and decreases after that (Karmokar et. al, 1993). Winter period in Bangladesh is from December to February but only for three months. For this reason, in this research the field study was carried out in winter in the month of January and February. For the long summer season the selected month was March to June because April to September remained almost constant.

Climatic data were collected using HOBO thermal data loggers and sensors for a duration of six months. To verify the air temperature of Dhaka city, five days data was taken per minutes and was found that within eight to ten minutes air temperature had not changed significantly. For this reason data logger has been programmed to collect data for every five minutes interval. With this interval, the loggers set for seven days and 2030 temperature and humidity data. The data was downloaded after six or seven day's intervals. Data collection started from 10 January 2007 and it was continued up to 20 June, 2007.

Concurrently, the following details were obtained from the occupants of the traditional house.

- The upper space is used normally as store. During winter season (January and February) the weather is cold and dry, all the windows of the upper space are closed for the protection from cold wind flow. From the practical use it was found that if windows remain close in the winter season, indoor becomes warmer than the outdoor air temperature.

- In summer period (March to June) the weather is hot and dry and hot and wet. According to user, during this time, all the windows of the upper space will remain open for cross ventilation and for that reason the temperature of the upper space and indoor living space remain less or lower than the outdoor temperature. In this research, the field study of this phenomenon will justify the thermal performance of Bangladesh traditional house's upper space during winter and summer seasons.

Further, in order to analyze the thermal performance the following methods were used for data collections.

The percentage of opening of the upper space is different in different months. Observation on environmental factors relate directly to thermal behavior of indoor environment, air temperature and relative humidity.

Table 5.2: Tabular output method of Climatic data for the test room of the traditional house

Season	Month	Date	Collected Data (Air Temperature)			Indoor Relative Humidity	Opening of window in Attic
			Indoor (Ti)	Upper (attic) (Tu)	Outdoor (To)		
Winter	January	10th to 31st	Ti	Tu	To	Rhi	0%
	February	1st to 28th	Ti	Tu	To	Rhi	0%
Summer	March	1st to 31st	Ti	Tu	To	Rhi	0%
	April	1st to 30th	Ti	Tu	To	Rhi	25%
	May	1st to 31st	Ti	Tu	To	Rhi	75%
	June	1st to 20th	Ti	Tu	To	Rhi	75%

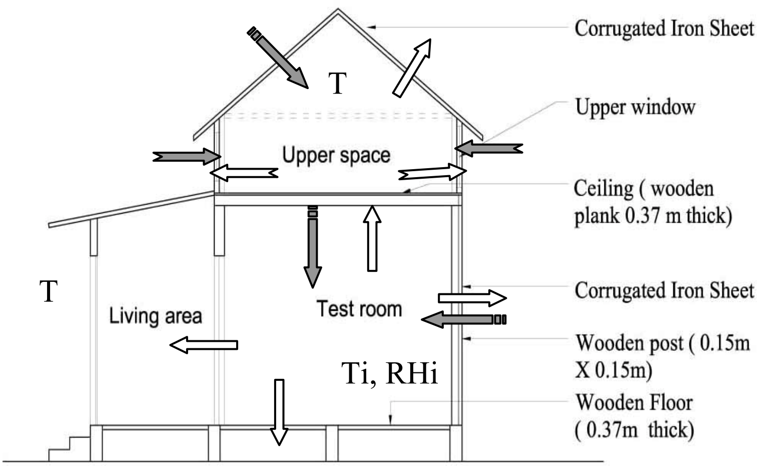

Figure 13: Position of the Data loggers Ti = Temp indoor, To= Temp outdoor, Tu = Temp upper space

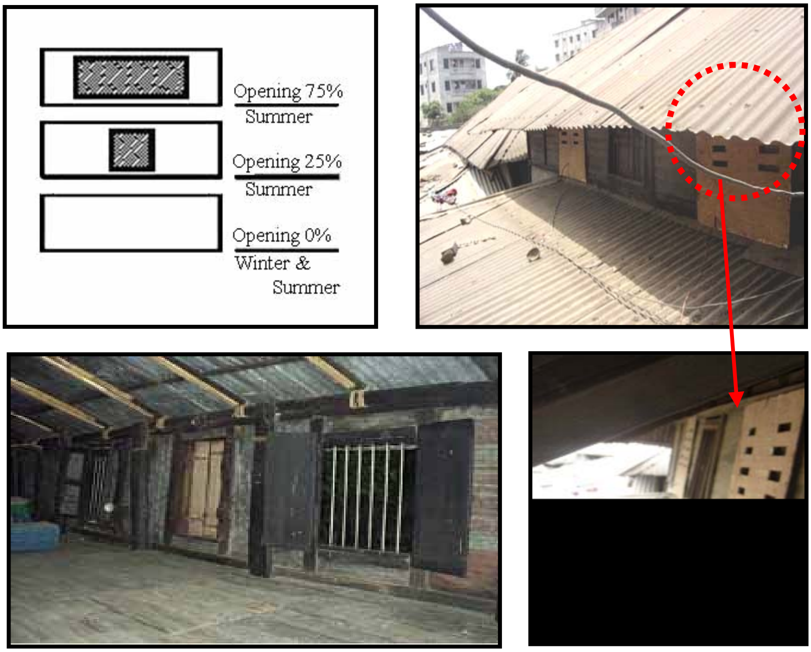

Figure 14: Window opening 25% of the upper space during construction (right top) and 75% window opening (left bottom).

Impact of the surrounding

The test house is densely surrounded by other traditional houses. The distance between other surrounding houses are East-West side 1.5m and North-South side 0.6m. Air temperature, air humidity and wind velocity varies depending on the density of the surroundings built forms (Ahmed, 1995). Wind velocity does not affect the indoor air temperature because of high density of the built forms. Highest wind speed occurred in April 2.9m/s while lowest was November 1.3 m/s. The prevailing wind direction was the same as for last thirty years. Urban, suburban and rural relative humidity exhibits a marked diurnal variation and generally decreases towards city center. During the afternoon in the dry seasons the difference may be as high as 12% (Ogunloyinbo, 1984) and night temperature difference can be as high as 13% in the same seasons.

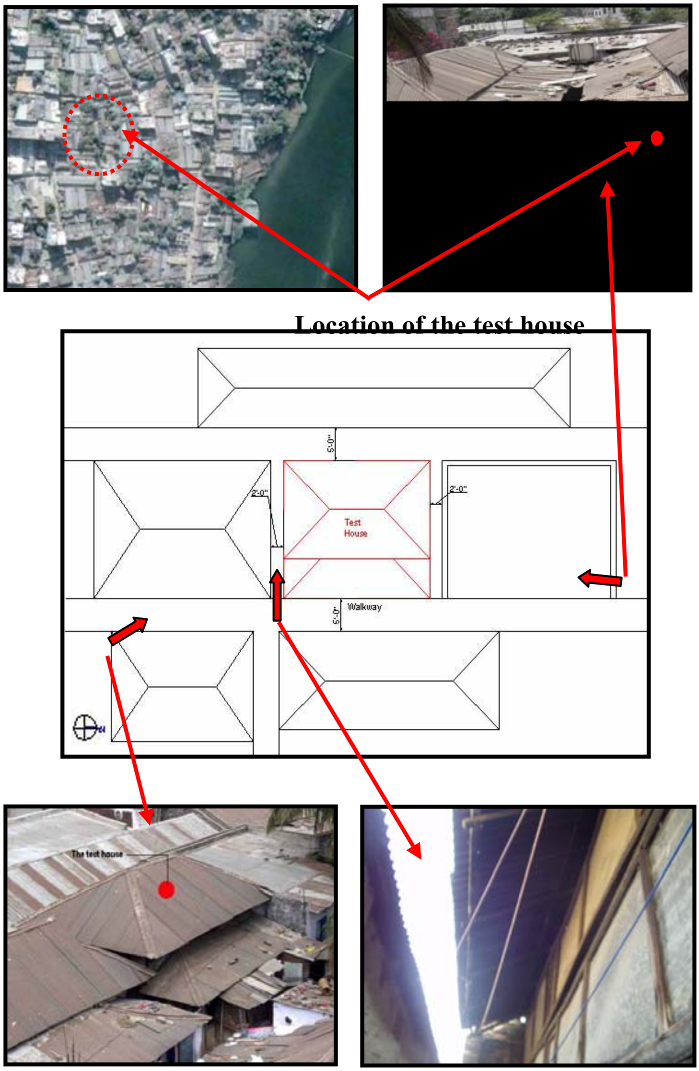

Figure 15: The site and surroundings of the test house and distance from other houses

Rapid urbanization after 1980 plays a vital role in the reduction of wind speed in Dhaka city (Sabbir, 1995). According to the above consideration, it is identified that the wind speed does not affect the thermal performance of the traditional house in this dense surroundings. Indoor cross ventilation does not work successfully.

Therefore, the wind velocity was not measured for this research. The reading of the BMD data has shown variation in temperature data (1.47ºC to 3.09ºC) difference from the field study temperature data. Furthermore, observation made by Karmakar and Khatun (1993) and Hossain and Nooruddin (1993) indicates that because of inexorable urban growth in Dhaka a noticeable variation is observed in temperature in different part of the city. Sharma (2002) indicates the existence of further micro-climate variation in the same locality.

CONCLUSION

The topics discussed in this chapter include methodology and the field study procedure. It also includes how the various readings were taken and recorded, how the data and information were transformed into tables and graphs to present comprehensive picture of conducting research using field study.

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9

A MULTI DISCIPLINARY APPROACH IN UNDERSTANDING THE SYMBOLIC MEANING OF BUILT FORM: CASE STUDY OF STATE MOSQUE

Alice Sabrina Ismail

INTRODUCTION

The purpose of this paper is to position a multi-disciplinary logic of inquiry which combines the interpretive and structuralist paradigms in qualitative research as well as reviewing a methodological framework that incorporates both semiotics and hermeneutics as a 'pluralist' approach to interpret the social world. This proposed methodological framework is considered as an important contribution as it introduces new ways of looking at buildings in particular to mosque's architectural attributes as a system of 'sign' as well as proposing various indicators in order to investigate this matter in depth. This study builds upon the theories and concepts outlined by Saussure on sign relations, Barthes on levels of signification and Gottdiener on reading the material culture as reliable ways for analysing and understanding the religious building. Furthermore, this paper also introduces a new approach in comprehending the meaning of the built form that depends on the building patron's situation. This research builds upon concepts outlined by Wallace and Barber in their model of leadership to develop a new methodological framework in order to understand the patron's ideological intentions.

This framework of inquiry is beneficial namely for architectural researchers and social scientists as it enables the analysis of the built environment from three aspects of concern. Firstly, reveals the symbolic meaning embedded in the design of the built form and their mundane settings. Second, elucidates on the structural relationship that exists between the built form and the human culture. Thirdly, uncovers the patron's intentions and associated actions during the creation of the built form.

As a result, specific interpretations of meaning of the social-physical phenomenon were developed in narrative form and holistic fashion. As a sample of discussion, states mosque were used as a case study to show how its symbolic and representational meaning are portrayed in denotative and connotative manner. This includes descriptions on all possible influencing codes and conventions that reveal the rules explaining how the Muslim cultures and societies organise their ideologies, to give meaning and make sense of the state mosque design.

This paper offers new insights which not only add to knowledge by widening and strengthening the understanding of new methodological approach to understand the meaning of built form and their attributes, but also is valuable for range of associated fields including architectural semiotics and non verbal communication. This is because this paper reveals deep understandings of the built form and material environment - (state mosque) operating as a 'sign' in the Muslim cultural and social context.

ARCHITECTURE AS A 'SIGN' AND AS A FORM OF COMMUNICATION

The assumption that architecture is invested with meaning and is a means of conveying meaning is not a new one. Throughout history, architects and writers in the architectural field have argued and discussed this subject. Many contend that architecture is more than utilitarian since architecture is the evidence of social life. Architecture is capable of conveying social and intellectual meaning including expressing the religious belief and political practice of society through its physical and visual form (Rappoport 1990; Vitruvius 1991; Morris 1998). Preziosi (1979) adds that architecture may also be understood from another aspect, which involves the structured relationship that exists between the building with its immediate and wider surrounding environment: both at the time it was built and thereafter.

Since architecture by itself is a self contained sign system, with its own grammar and syntax, most scholars in the field of architecture have attempted to import structuralist methodology to understand architecture, as they believe that architecture can be read as ‘text’ (Whyte 2006). This structuralist approach to understanding architecture was based upon the assumption that architecture was a ‘sign system,’ a means of communication that was analogous to verbal or written language. Examples of this approach are seen in the work by Broadbent (1980), Eco (1997), Hersbeger (1988), Jencks (1997) and Whyte (2006) where they state that architecture can be understood by analogy to language; as a ‘code’ capable of being used to communicate the intentions of the patron to the building user. The physical manifestations of architectural ‘form’ and ‘space’ can be read through a recognised code, to be interpreted by the user (Jencks 1997; Eco 1980). In Boffrand’s words (1972:2), “ ‘form’ including ‘spatial layout’ through their disposition, their structure, and the manner in which they are decorated, announce their purpose to the spectator”. ‘This is because the dynamic qualities of ‘form’ and ‘spatial layout’ help translate the building function into a non verbal coding system which makes communication with the user possible’ (Arnheim 1977:263). As described by Jencks (1980:20-21):

> When I look at the architectural form - windows on the façade of the building, my attention may be turned to a window as an opening for viewing the outside world - meaning that is based on function, but in which the function has receded to the extent that I may even forget it, for the moment concentrating on relationships through which the windows become elements of

architectural rhythm - Windows in their form, their number, their disposition on a façade (portholes, loopholes ,curtain walls, etc) - may, besides denoting function , refer to a certain inhabitation and use; they may connote an overall ideology that has informed the architect's operation.

Since the works of Jencks, Eco, Boffrand and Arnheim have shown that architecture can be described as a communication system, capable of communicating its function when the user decodes the building's physical attributes of 'form' and 'space, therefore it can be said that architecture - which includes religious building (state mosques) are commonly being organised by the creators to potentially transmit meaning and acts as a symbol.

THE BUILT FORM – 'STATE MOSQUE' AS CASE STUDY

The state mosque traditionally has played an important role in Muslim societies by organising not only space but also society. The state mosque acts as a landmark or becomes a point of reference for Muslims. Most mosques in Muslim countries have common architectural elements as a 'sign' for a place of prayer. These elements include the minaret (tower used to call for prayer or the azan), dome, entrance, mihrab (niche in the middle of the qiblah wall for the imam), mimbar (pulpit where the imam gives the sermon), and qiblah wall (wall orientated to the Ka'ba in Mecca) (Serageldin 1990; Holod & Khan 1997; Frishman & Khan 1994).There are also additional features such as the sahn (courtyard), hypostyle around the courtyard, pointed or semi-circular arches and classical Islamic decorations in the form of geometric patterns, Quranic verses in calligraphic writings and repetitive floral motifs (Brend 1991). However, its potential role as a 'sign' of prayer does not delimit itself as a religious structure but its role, function and symbolic meaning extends beyond that.

According to Holod and Khan (1997:21), "mosques express a collective identity, and glimpses of that identity can be discerned in the client's word of intent, the shapes of design, the pragmatism of realization, in the theater of their inauguration, and in the realities of the everyday use of this special building. Through them the process of the creation of state identities can be charted. Through them the dynamics of regional politics can be discerned".

They state that this is because of the mosque's role and function since it is closely affiliated with Muslim life and society so that it represents the unity of Islam in spiritual and worldly matters. This includes the patrons' ideas and philosophies. In this regard, the selected state mosques are analysed from their architectural aspect in order to show how meanings (creator's ideas) are embedded in these religious built form and how to unpack the symbolic meaning anchored in the studied object that is state mosques in the Muslim social and cultural setting.

This process is done by referring to the established research design framework, which involves the research paradigm and methodology and how these two- formed a framework that capable of analyzing both of the above aspects.

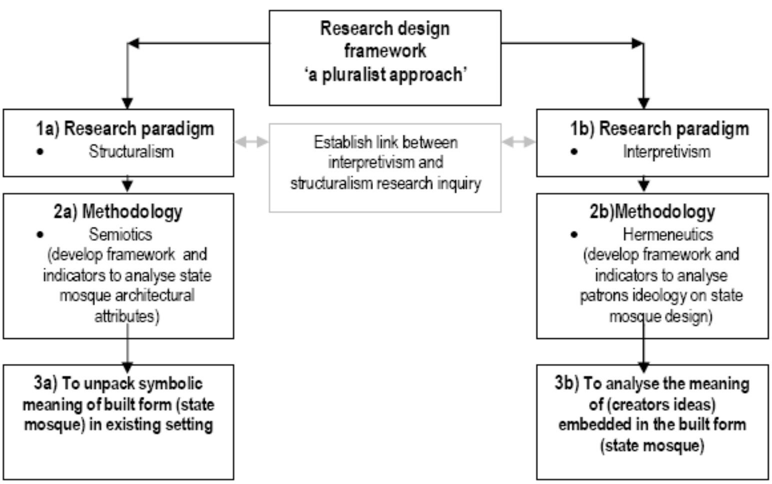

Figure 1 Research design framework

RESEARCH PROCEDURE

Since this current study involves the investigation on how patrons' ideology informed the design of the state mosque, identification as well as collection of evidence concerning the social phenomena involving data on state mosque and its patrons is required. This also includes the need to understand the structural relationship that exists between the state mosques and social culture, which contributes to the production of meaning. In this case, structuralism and interpretivism are the two paradigms best suited to this task (Figure 1). A research paradigm is used for three main reasons: to help establish appropriate facts, to match facts and theory and to help articulate the theory. Bogdan and Biklin (1998:22) defined a paradigm as "a loose collection of logically related assumptions, concepts, or propositions that orient thinking and research; or the philosophical intent or motivation for undertaking a study." However, there are tensions between these two paradigms as each has a different foundation to the logic of inquiry and world view; and thus differ in their approach to conducting research as follows.

THE TENSIONS BETWEEN TWO METHODOLOGICAL FRAMEWORKS (STRUCTURALISM AND INTERPRETIVISM)

Structuralism is different from interpretivism because structuralism rejects the notion that the knowledge of ourselves and the world of lived reality is interpreted through the human mind or grows out of individual consciousness (Hawkes 2003). "For structuralism, the knowledge of the world arises within the structures such as language, imagery or genre and argues that these structures determine how people interpret them" (Hughes 2001:358). Therefore, structuralism focuses on the relationships that exist between concepts or signs, within language, and the way that language structures society and culture. In other words, structuralism holds that the true nature of things lies not within the things themselves, but within the relationships we construct between things (Hawkes 2003).

"Interpretivism, on the other hand, requires the consciousness of the human act of inquiry and recognises its position within a specific context" (Patton 1990:114-115). Interpretive researchers hold the belief that reality is bound by the interpretation of an object or situation according to the context and from the vantage point taken by the interpreter (Patton 1990). "The 'context' including the structures embedded in our society not only influences how we think about others and ourselves – and in consequence, how we act –but will influence opportunities for potential thought and action. The 'context' includes not only the cultural and social aspects, but also the material world" (Smith 2001: 36). Although these two paradigms reflect different ways of knowing about and valuing the social world, each is recognised to reveal us a differing aspect of the research problem. By studying an instances in culture (such as the design of a state mosque) we gain insights into the systems that structure it and the ways people devise and live within that system (Fiske 1994 in Smith 2001) That is, "understanding comes through the juxtaposition of the different viewpoints and the insights gained from these provide a richer analysis and knowledge"(Smith 2001: 33).

THE INTEGRATION OF TWO METHODOLOGICAL FRAMEWORKS (STRUCTURALISM AND INTERPRETIVISM)

Interpretivism is appropriate for this study as the aim of the research is to read and interpret the meaningful nature and concepts that are embodied in the built environment through the creation process which is bound to a specific context and setting. Furthermore, interpretivism also helps to question the actual condition and context to elucidate the constructed meaning that shapes the studied object which, in this case, is the state mosque.

For that reason, interpretivism enables the researcher to understand what the creator of the state mosque intended to convey. This is because interpretivism accepts that the investigator and the investigated object are interactively dynamically linked (Guba & Lincoln 1998). In addition, "interpretivism also allows the researcher to make explicit her theoretical position by participating in the social world to understand more effectively the emergent properties and features"(Denzin 2001 : 25).

Although interpretivism may be seen as an appropriate way of inquiry for the present study to reveal the meaningful nature of the state mosque in its particular situation, there are also some limitations. Interpretivism does not deal with the conditions or potentially causal factors that give rise to the interpretation of meanings of the state mosque. In other words, the interpretive paradigm does not acknowledge or elucidate emergent structures or relationships which may contribute to the production of meaning of the state mosque. Therefore, it is vital to integrate interpretivism with other paradigms in order to succesfully deal with the overall research situation even though there may be contradictory ideas and contested arguments that arise in using multiple paradigms.

In realising the limitations of the interpretivism paradigm, structuralism is seen as another way of inquiry to support the interpretive framework in order to provide a sophisticated understanding about the studied phenomena and to answer the problem under study (Figure 2). This is because by adopting structuralism to support interpretivism framework the researcher is able to identify and understand in depth the reciprocal relationship between state mosques with events in a specific context.

Furthermore, it will help the researcher to uncover the conceptual codes and conventions that govern and exist in relation to the observed object. Comprehending possible influencing codes and conventions will reveal any rules explaining how various cultures or societies organise their ideologies, to give meaning and make sense of the built environment. In addition, it also enables the identification of codes, customs, habitual laws, and conventions that may suggest sets of interpretative possibilities, in order to give a more in-depth understanding on the existing structural relationship between the state mosques with the human culture (Figure 1).

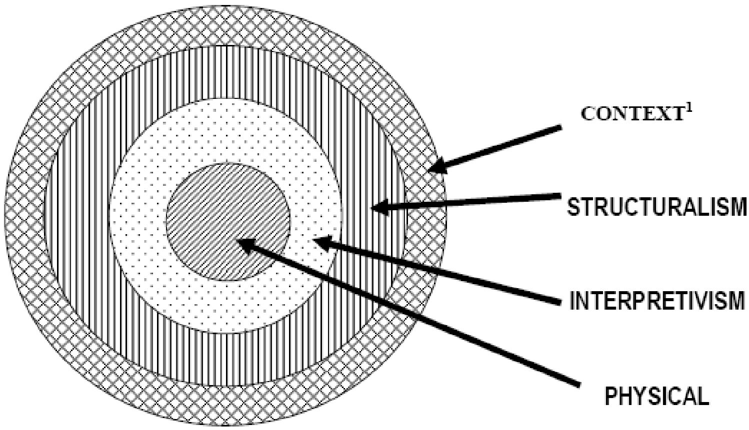

Figure 2 Integration of structuralism and interpretive paradigm as way of inquiry

RESEARCH METHODOLOGY ON SEMIOTICS AND HERMENEUTICS

Since structuralism holds a view that our knowledge of 'reality' is not only coded but also conventional, that is, structured by and through conventions, made up of signs and signifying practices, structuralism forms the basis for semiotics, a science that studies the life of signs within society (Hawkes 2003). As the present research seeks to understand the structure or reciprocal relationship that may contribute to the production of meaning, semiotics seems best suited to this study, to determine how meanings are embedded in an object. In other words, semiotics is applied to unpack the symbolic meaning anchored in the studied object that is three Western Malaysian state mosques in their social and cultural setting.

Interpretivism seeks understanding of the world of lived reality which involves subjective interpretation. In this case, hermeneutics is the appropriate approach to make this understanding possible as it enables a researcher to interpret or inquire into the meaning of social phenomena that includes written texts, human behavior and symbolic artefacts (such as art, sculpture or architecture) and imports these phenomena, through understanding the point of view and 'inner life' of an insider, or the first-person perspective of an engaged participant in these phenomena. In the present study, hermeneutics is the key approach to understanding the concept of human intention and the associated actions, and their consequences involved in the creation of the state mosques. In particular, the level of involvement of the patron in the making of the state mosques and the political climate during the construction period of the built form will be identified by referring to documents available such as political archives and texts.

Semiotics and hermeneutics will be discussed in detail in turn to explain how they have been applied to the study theoretically. This is important, as by understanding semiotic and hermeneutic theories, a systematic framework for analysing architectural elements of the state mosque and patrons' ideology embedded in the state mosque design will be developed.

SEMIOTICS

Semiotics, or semiology, is the study of signs and symbols and how meaning is constructed and understood (Fiske 1990:40). Semiotics covers three main areas of study. These are the study of sign itself, the codes and systems into which signs are organised and the culture within which these codes or signs operate (Leeuwen 2005). A 'sign' is defined as a display of structure - an act, gesture or something physical perceivable by human senses that conveys an idea, desire, information or command. However, things only become a sign when meaning is invested in them (Leeuwen 2005). Since the study of a sign may not be divorced from the concrete form of social intercourse, and cannot exist, as such, without it, the theory of semiotics therefore is commonly applied to the fields of art, literature, anthropology, and architecture. Semiotics is also widely applied in architecture to investigate how people project meanings onto the built form (Hawkes 2003). There are two dominant models in the study of semiotics. The founders of these two schools were C.S Pierce and linguist, Ferdinand Saussure. As Saussure's work will benefit this present study, his ideas on 'sign' relations, how a 'sign' operates and the way it conveys meaning will be discussed in detail.

SEMIOTICS: THE STATE MOSQUE AS A 'SIGN' – FERDINAND SAUSSURE

Ferdinand Saussure founded the structuralism school of thought, proposing a dualistic notion of signs. According to Saussure (1966:78), a sign "doesn't exist in reality and it is formed by the associative link between the signifier and the signified". In his linguist theory, the signifier is the sound and the signified is the thought. As put forth by Saussure (1966:66), "a sign is not a link between a thing and a name, but between a concept (signified) and a sound pattern (signifier)" - to form a meaning-imbued 'sign'. Saussure (1966:128) also states that "signs too can exist only in opposition to other signs.

That is, signs are created by their value relationships with other signs. The contrasts that form between signs of the same nature in a network of relationships is how signs derive their meaning". Since the meaning of a sign is also determined by how a sign is differentiated from other signs, therefore it involves the mental concept (signified) to categorise meaning to help understand the sign better. For Saussure, this mental concept (signified) is constructed by people and is influenced by the culture or subculture to which they belong (Fiske 1990:45). Saussure's model of signs is of value for this study, as there is a need to understand how three Western Malaysian state mosques operate as a meaningful sign. To clarify this, the example of the sign MOSQUE can be used (Figure 3). As a sign, it is composed of the signifier - the word or sound pattern 'mosque', and the signified - mental concept of 'mosque', which one has of this particular type of building. The relationship between the mental concept of (mosque) - signified and the word or sound pattern (signifier) - 'mosque' is known as signification. Referring to the Saussure model, the mental concept (signified) is also a product of a particular culture. Therefore the mental concept (mosque) may be articulated differently by each individual or reader, who is influenced by the culture they come from and belong to.

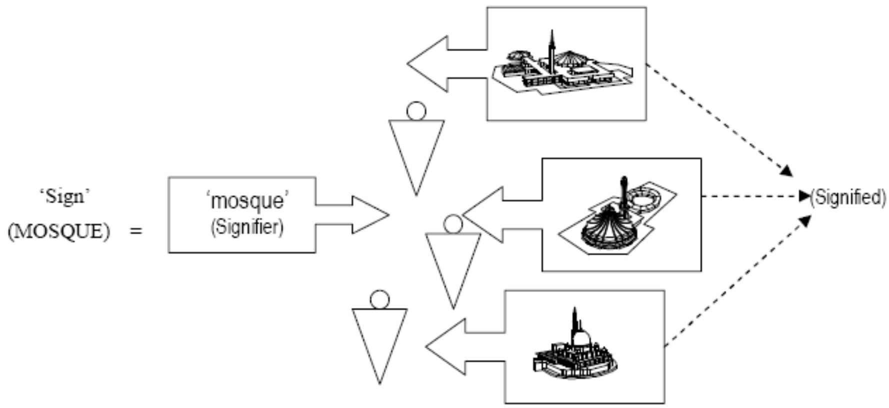

Figure 3 Signifier ---- Signified relationship

Since the mental concept which we articulate will be different for every one of us, Saussure also stresses the arbitrariness of the sign (Saussure 1966). On this matter, he states that the relationship between the signifier and signified is determined by conventions, rule and agreements among users (Holdcraft 1991;Fiske 1990).There are formal conventions that fix the meaning and enable one to experience similar signs and communicate with each other. For example there is a formal convention which is agreeable to all within our culture that the sign MOSQUE refers to a building and not a platter of food. Because the relation that exists between the signifier and the signified is arbitrary, codes are also developed and used to help us learn what some signs mean (MacGregor 2005). In addition, codes which are defined as, "sets of signs and rules for their use by semioticians also help to simplify phenomena in order to make it easier to communicate experiences" (Hurwitz 1993:53).

Meanings, therefore, are activated within the repertoire which the code offers us (Fiske 1990). Saussure (1966:72) also states that "signs can be organized into codes in two ways. First is by paradigm and second is syntagm". A paradigm can be defined as a set of signs from which the one to be used is chosen. It is a set of associated signs which are all members of the same category. A syntagm is the messages with which the chosen sign is combined (Fiske 1990; Hurwitz 1993). For example, the contents of one's wardrobe = paradigm; what one is actually wearing = syntagm.

Although Saussure's work is best suited for the paper, as his model of signs forms the basis of understanding how signs work, nevertheless there are limitations to his study. He did not describe in detail the social cultural experience, expression and conventions when dealing with the understanding of signs. This is because Saussure's model of the sign only focused on denotation rather than at the expense of connotation (Fiske 1990). As also argued by Smith (2001:9), "one limitation of Saussure's approach was his understanding of a sign that an object x comes to have a meaning y within a certain structure. The process of meaning making thus, resembles 'pattern matching".

Due to this limitation, Roland Barthes' work is referred to next, as he elaborates on Saussure's model of signs in a more extensive way. Barthes stated that the bond between the signifier and signified (mental concept) is also dependent on social and cultural conventions. Furthermore, Barthes analysed the meaning of signs based on orders of signification. These are denotation, connotation and myth. His application in the material culture is known as socio semiotics (Hawkes 2003).

SEMIOTICS: THE STATE MOSQUE AS AN 'INTEGRATIVE SIGN' – ROLAND BARTHES

Socio-semiotics articulates the material context of daily life and the signifying practice within a social context, where all meanings arise from a more articulated codified dimension. Here, the systems of signification (relationship between the signifier and signified) are multileveled structures which not only contain denotative signs but also connotative signs when particular cultural codes are ascribed to these signs (Barthes 1988:182).

The first order of signification is that of denotation: at this level there is a sign consisting of a signifier and a signified. Connotation is a second-order of signification which uses the denotative sign (signifier and signified) as its signifier and attaches to it an additional signified. In this framework, a connotation is a sign which derives from the signifier of a denotative sign (so denotation leads to a chain of connotations) (Barthes 1988:183) (Figure 4).

SIGN			
Denotation (1st level of signification)	Signifier	Signified (mental concept)	
Connotation (2nd level of signification)	Signifier		Signified (mental concept)

Figure 4 Denotation and connotation (1st and 2nd level of signification)

In other words, denotation, or first order of meaning can be described as the relationship between signifier and signified within the sign. This refers to the definitional, literal meaning of a sign. This relationship can extend further as a sign may also have additional values. Here, the sign can also become a signifier of another sign (connotation) or second order of meaning, which signifies cultural values such as status structure in society. The level of connotation may also develop further when it combines with denotation to produce ideology. The sign becomes its own referent as a third order of meaning (myth), where it becomes a hypostatization that condenses an entire ideology in a single word or image (Barthes 1967). In other words, the function of myths is to help us to make sense of our experiences within a culture. Myth also expresses and serves to organise shared ways of conceptualising something within a culture (Barthes 1988). An example is a daily use object such as a 'pen'. At the denotative level, this object is generally associated with its daily function as a writing tool. The 'pen' however may also be susceptible to other meaning when it is linked or being connoted by ideology of high status. At a connotative level the pen may parade a certain sense of wealth, status or position. This meaning could also include other associations through condensation and hypostatization at the mythic level such as progress, technology or intellectuality (Barthes 1988:182).

The first (denotative) order (or level) of signification, therefore is seen as primarily representational and relatively self-contained. The second (connotative) order of signification reflects 'expressive' values which are attached to a sign. In the third (mythological or ideological) order of signification, the sign reflects major culturally-variable concepts underpinning a particular worldview, such as masculinity, femininity, freedom, individualism, objectivism, Englishness and so on (Chandler 2002). To understand how Barthes' theory of orders of signification relates to the present study, the diagram below can be referred to as an example (Figure 5).

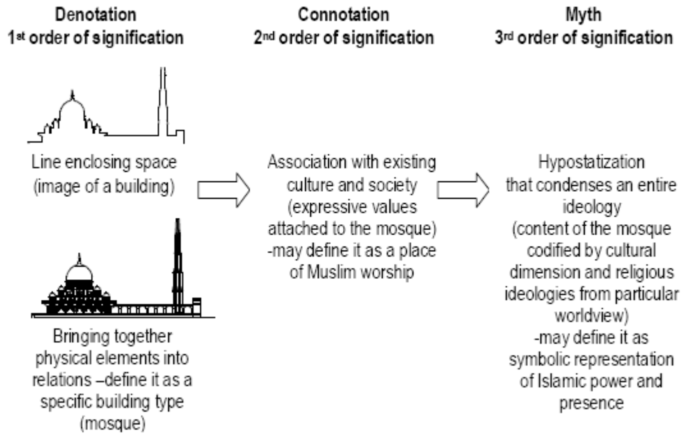

Figure 5 Example of denotation, connotation, myth (1st, 2nd and 3rd level of signification)

At the denotative level, the above is a diagram of an image of a building, and by bringing together all its physical architectural elements such as dome, minaret, arches, entrance portal, into relations, we then identify it as a mosque. At a connotative level, we then associate mosque with the existing culture and society. The mosque therefore is viewed as a place of Muslim worship, a religious learning center for the Muslim, a Muslim communal place and a spiritual place. At a mythic level, we understand the mosque as a sign, activating the myth of Islamic religion, status, identity, power and glory. In this case, the mosque may be a statement of Islamic ruling, ideological symbol for the propagation of Islamist thinking, symbolic representation of Islamic power and presence, dominion of Islamic government and so forth.

Barthes' work, therefore, is of greater value for this paper, as the aim of this paper is to read and interpret the meaningful nature and concepts that are embodied in the state mosque as a sign which is bound to a particular social context and cultural setting. In this regards, Barthes' interactive idea of meaning is relevant for this work because he clearly defined that signs work in order of signification, and, during the process of signification, interaction occurs between the sign with the user's experience and his or her social cultural position. As a result, diversity of interpretations is obtained, instead of one defined or literal meaning.

In order to understand further how socio-semiotics is applied in analysing the built environment, the work by Mark Gottdiener will be referred to next, as the main reference for this paper. This is because he explicitly focuses on the subject of socio-semiotics and its application to analyse the phenomena of material culture. Gottdiener uses the organisation of signs for this paper to understand how ideology articulates with material forms or, in other words, how material forms are encoded through ideological meanings which are engineered into form. By understanding this, one will be able to decode and 'read' the meaning of the material culture. Although his research focuses on Las Vegas as an environmental setting, his study provides methodological insights for the study of other settings such as state mosques which are also products of social and political contexts.

SOCIO-SEMIOTICS : WORK OF GOTTDIENER – THE RELATION BETWEEN SOCIO-SEMIOTICS AND THE MATERIAL CULTURE

Gottdiener (1995) introduces the socio-semiotic model of the sign to describe the way ideology articulates with material forms. According to him, socio-semiotics accounts for a two way process to present symbolic interaction in daily life: first, is the articulation of ideology and second, is the material form. The term 'ideology' here is defined as the value system of a social group. A value system is correlated to the content of a sign, whereas materiality is correlated to the expression of sign (Gottdiener 1995:27) (Figure 6)

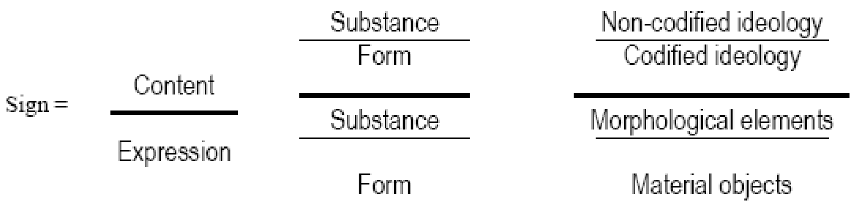

Figure 6 Decomposition of sign (socio-semiotic model of sign) Gottdiener (1995:28)

The 'content' then can be divided further to 'substance' and 'form'. The contents of form and substance are determined by the ideological culture of the society. This ideology, which belongs to a particular cultural practice, may be codified or non-codified ideology (Gottdiener 1995). The 'expression' is also divided further by substance and form. Both of these, however, refer to the object. In the case of the object, it may refer to the specific morphological elements or material existence of the object (Gottdiener 1995). In order to understand the way ideology relates to the built environment, Gottdiener also produces another type of socio-semiotic model using the same format as the above (Gottdiener 1995:84) (Figure 7).

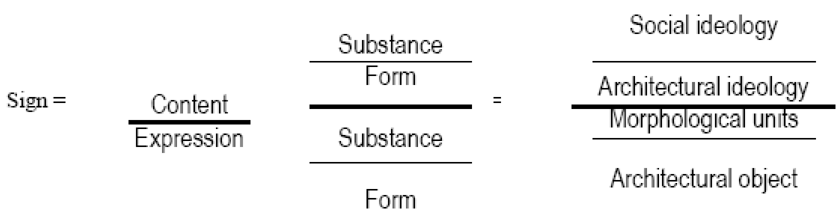

Figure 7 Decomposition of architectural sign (socio-semiotic model for architectural sign) Gottdiener (1995:87)

To explain how this socio-semiotic model works for the built environment, Gottdiener carried out an analysis of the mall as his case study (Figure 8). In the study of the mall, Gottdiener (1995:84) outlined that the mall as a built form is best understood as the intersecting site of two distinct structural principles (see Gottdiener 1995). These two principles are the mall ‘content’ and its ‘expression’. Since every sign is also a part of system of signification, which is structured by the paradigmatic and syntagmatic axes, these two separate orders of meaning are also important in reading the sign system which can be found at the mall. Gottdiener (1995:84) also states that the paradigmatic axes of the mall can also be referred to as the ‘content’ of the mall which involves the mall design motif, while the syntagmatic axis is referred to as the ’expression’ of the mall. This second axis consists of the way the separate elements within the mall produce meaning through metonymy[1] and contiguity[2] (Gottdiener 1995:84).

$$\text{Mall (sign)} = \frac{\text{Content}}{\text{Expression}} \qquad \frac{\text{Paradigmatic (design motif of the mall)}}{\text{Syntagmatic (elements within the mall)}}$$

Figure 8 Reading of sign systems for the mall as a built form (Gottdiener 1995:84)

Since the mall ‘content’ also involves the design motif of the mall which is to sell consumer goods, the codified ideology of the building hence articulates an ideology which is driven by the culture of the society that relates to consumption and consumerism (Gottdiener 2003:131). The mall ’expression’, on the other hand, refers to the morphological elements of the mall that can stimulate consumer fantasies and at the same time attract shoppers, to promote

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[1] A metonym is a figure of speech involving using one signified to stand for another signified which is directly related to it or closely associated with it in some way, notably the substitution of effect for cause.

[2] Contiguity refers to something which touches or adjoins something else; some semioticians use it to refer to something which is in some sense part of (or part of the same domain as) something else. Contiguity may be causal, cultural, spatial, temporal, physical, conceptual, formal or structural.

purchasing. In this case, the 'expression' or syntagmatic axes of the mall involve the articulation of design elements within the built form such as the built form interior façade, its spatial layout and decorative features (Gottdiener 2003:132).

For the purpose of this paper, the decomposition of architectural signs proposed by Gottdiener seems suitable in describing the case study to elucidate the state mosque as an object of social culture. This is because by looking at the content and expression of the state mosque it is possible to describe the way cultural and political codes are articulated within the built form. This also includes an explanation of how the codified ideology of the state mosque articulates a particular ideology belonging to a society and culture.

INDICATORS TO READ THE BUILT FORM OF STATE MOSQUE AS A 'SIGN'

Since the present paper involves the reading of the state mosque as a sign, there is a need to identify the architectural elements within the state mosque. This is because Gottdiener's work focuses on describing the mall as a social product. Therefore, only two elements within the mall were identified by him. These are the spatial layout, and the facades and decorative elements of the mall.

However, since the study is about the state mosque as a symbol of patron's ideology and belief system, the selection of elements within the state mosque should be more specific and appropriate. For that reason, the work by Holod and Khan, Hammoda and Mahrok on mosques is referenced as they generated the appropriate elements for reading state mosques found in Muslim countries as a symbol of patron's ideology (see Holod and Khan 1987; Hammoda 1990; Mahrok 2000). They identified four main elements. These are size, spatial organization and treatment, setting, and structural form and material expression. Therefore by combining principles from both Gottdeiner's research and Holod and Khan's, Mahrok's and Hammoda's study, a suitable framework for the current study was generated. These new indicators to read the state mosque as a sign are set out in the model below (Figure 9). Based on this model (Figure 9), the reading of the state mosque 'sign' system is possible by recognising that signification that occurs with reference to two separate orders of meaning, - the paradigmatic and syntagmatic axes. During the process of investigating the state mosques, the design motif and elements within the (built form)-state mosque can be read, to unpack their symbolic meaning in a systematic and comprehensive manner.

State mosque (sign) = Content / Expression = Paradigmatic (design motif of the state mosque) / Syntagmatic (elements within the state mosque): scale, setting, access, spatial organisation, facades and structural arrangement

Figure 9 Reading of sign systems for the state mosque as a case study

HERMENEUTICS

Hermeneutics is a "particular approach used in the study and interpretation of texts" (Johnson 2000:142). The term 'text' here "applies to anything which can be seen as signifying something or refers to anything that can be read. Texts (be they written discourse, oral narratives, aesthetic object, architectural buildings and others) are understood as 'conventionalized expressions of the experiences of their authors" (Johnson 2000:142).

Although the term 'text' can be defined in many ways, for this study the term specifically refers to the documentation on state mosque and archival records on the Islamic policy and political agenda of patrons who are involved in the establishment of the state mosque. Texts attempt to communicate and transmit the experiences, ideas, beliefs and values of the author and his or her community to intended audiences and their communities. A text acts as a messenger, from someone to someone. The messages contained in the text are framed within cultural, historical, and intellectual contexts. Therefore, an interpretation of a text not only will reveal the meaning of the words of the text, but includes the cultural and intellectual contexts in which it was formed. This provides a better understanding of the original experiences and ideas of the author of the text. There are four forms of hermeneutics to help refine understanding of the interpretative approach as introduced by previous scholars and philosophers (Fischer & Arnold 1994). These are hermeneutical theory, hermeneutical philosophy (the work of Heidegger and Gadamer), critical hermeneutics (the work of Habermas) and phenomological hermeneutics (the work of Ricouer) (Fischer & Arnold 1994).

However, since the purpose of this paper is to uncover the patron's intentions and associated actions during the creation of the built form (state mosque) from documented text, hermeneutical theory influenced by Friedrich Schleiermacher is adopted. His theories of interpretation and translation rest on two main principles: the hermeneutic circle followed by two sides of interpretation, one linguistic, the other psychological (Schleiermacher 1998).

HERMENEUTICS: INETRPRETATION OF DOCUMENTED TEXT RELATING TO STATE MOSQUE – FRIEDRICH SCHLEIERMACHER

According to Schleiermacher, hermeneutics cannot be approached using a pre-determined set of criteria because of its interpretive nature. Therefore, an approach known as the 'hermeneutic circle' is introduced. The hermeneutic circle involves a logical contradiction; for we must grasp the whole before we can understand the parts. Yet the part derives its meaning from the whole (Schleiermacher 1998; Bernofsky 2004). In this case, the analysis process occurs in a circular way until the entire text is interpreted. In this sense, the interpretation does not only involve making sense of the wordings or sentences in the text, but also the need to interweave all passages and integrate a comprehensive account of specific elements in the text into a coherent interpretation - to form an understanding which is free from any contradictions (Schleiermacher 1998).

The next step is to complement the linguistic interpretation with psychological interpretation. Schleiermacher implies that linguistic interpretation is mainly concerned with what is common or shared in a language, whereas, psychological interpretation mainly deals with what is distinctive to a particular author (Schleiermacher 1998; Bernofsky 2004). In other words, the linguistic interpretation refers to interpretation of evidence, by looking at particular actual uses of words to the rules that are governing them, in examples of their usages and thus to their meanings (Schleiermacher 1998; Bernofsky 2004). Psychological interpretation, on the other hand, focuses on the author's psychology which is the conceptual-intellectual distinctiveness of individuals and the context that he or she is situated in (Schleiermacher 1998; Bernofsky 2004).

In this hermeneutic inquiry, the interpretation and construction of reality greatly depends on the researcher's awareness of the text, and its position in specific context. In this sense, "the epistemological position for hermeneutics become a 'transactional and subjectivist' one, in which the investigator and investigated object are linked interactively" (Guba & Lincoln 1998:205). In other words, hermeneutical interpretation is a dialectic process as the synthesis of the text and the extrapolated cultural and intellectual contexts of the author are juxtaposed alongside with the researcher's own cultural and intellectual contexts. Hermeneutics, therefore, rests on the discussion of human sciences that involves the interpretation of the human phenomena and refers to the human world, not through introspection, but through the understanding of expressions of life (Schleiermacher 1998; Bernofsky 2004).

Schleiermacher's concepts are useful in two main ways as technique of analysis, to investigate the state mosque's patron ideology. First, referring to his concept of linguistic interpretation and hermeneutic circle, will guide the reading and interpreting of the political text and archival documents. Second, his concept on psychological interpretation is useful during the process of interpreting patrons' ideology and the climate that they are situated in. This is because Schleiermacher's hermeneutical theory took the position that understanding is the objective recognition of the author's intended meaning -in which there is a need to see the world from the author's perspective *(verstehen)* and recognise what the author originally felt or thought. In brief, Schleiermacher's hermeneutics approach is appropriate for interpreting written text that relates to the state mosque historical development and ideological agenda of state mosque patrons'. This is important to achieve the objective of this study, which is to understand how the patrons' ideology affected state mosque design development. Next step is to determine the indicators for analysing the documents and archival records.

INDICATORS FOR INTERPRETING DOCUMENTED TEXT ON THE IDEOLOGY OF STATE MOSQUE PATRONS

Before conducting hermeneutical analysis on the text, there is also a need to determine the indicators that relate to patrons' ideology and their agendas. This is vital, as by defining these indicators a thorough and systematic analysis on the documents and archival records can be conducted. These indicators are important, because they will give a clue to define what kind of leadership style was employed by the state mosque patrons as country's political leaders, and what agendas were evident during the course of their administration in the country.

To determine the indicators, work by Barber (1972) and Wallace (1992) are considered, due to three main reasons. First, Barber's and Wallace's leadership theories have been widely applied by many scholars in the field of politics to analyse influential leaders' political styles and their personality throughout history, in different contexts and settings. These include studies done by Schreiber (1982), Kaarbo and Hermann (1998), Tamir

Sheafer (2001), Palmer (2003) and Rahman Azly (2004). Second, Barber's and Wallace's studies adopt the interpretive method of inquiry, where the focus was to interpret and reconstruct meaning from biographies of prominent political leaders and influential figures in history. Third, their work offers a typology which will be useful in providing the framework for this paper to critically analyse the leadership style of the state mosque patrons' as well as their role as the country's political leaders.

Barber (1972) carried out a study on United States' presidential characters based on biographical data, while Wallace (1992) wrote on the meaning of creative development based on influential personalities in history. In Barber's study (1972), he outlined that there are five main elements that make up a political leader's personality. These are character, worldview, style, climate of expectations, and power situation.

The term 'character' here relates to how a leader positioned his own self to face confronting issues. Character is "the way the (leader) orients himself toward life - not for the moment, but enduringly. Character is the person's stance as he confronts experience". (Barber 1972:8). 'Worldview', on the other hand, is much related to the leader's political agenda and his strategies to overcome the conflicts affecting his administration. A leader's worldview consists of :

"…his primary, politically relevant beliefs, particularly his conceptions of social causality, human nature, and the central moral conflicts of the time. This is how he sees the world and his lasting opinions about what he sees. (A leader's)……world view affects what he pays attention to, and great deal of politics is about paying attention". (Barber 1972:7-8)

'Style', however, is much about the leader's habitual pattern and his personalities. It is "the leader's "habitual way of performing his three political roles: rhetoric, personal relations, and homework. No (leader) can escape doing at least some of each. However …..the balance among the three styles elements varies" (Barber 1972:8-9).

'Climate of expectations' deals with the situation the leader faced and interacts during the time he serves as an administrator"

(Barber 1972:9). "Power situation' is defined as the political situation that influences his decision making as the leader of the nation" (Barber 1972:9).

If Barber's work outlines a model of leadership typology, Wallace on the other hand, looks upon the subject's internal system of thinking. Wallace concluded that there are six concepts of personalities to interpret an influential person. These are: his outlook in life; his achievements (epitome); his central conflict in life; the range of activities his involved in; his skills; his development ideas; and his successful interpretive work. Although Barber's (1972) and Wallace's (1992) concepts are pertinent to form the framework for the present research one difference is important. To analyse the political leaders' character and their leadership type, Barber and Wallace's research included personality tests on the leaders' psychological traits and were therefore very specific.

The scope of the paper is to understand of the state mosque patrons' ideologies, their achievements and contribution to the social context and built environment from interpreting the political text and archival documents. Therefore, it is important to carefully select the most appropriate concepts of personality proposed by Barber (1972) and Wallace (1992); and then synthesise these concepts, to develop a typology to suit the need of this study. These typologies will act as indicators to help in the analysis of the documents and archival records in relation to the state mosques patrons'. The indicators are: Individual personal character ; political climate and context ; individual intention; strategy; action (with a general focus on their overall contribution for the country's development, politics, society and economy); individual Islamic approach, practice and ideas ;individual intention; strategy; action (with a specific focus on their contribution towards Islamic development in the country including mosque development). All of these five indicators are important to help reveal if the built form (state mosque) may be shaped by the patron's system of thinking including individual character values, as well as the political–economic context.

CONCLUSION

This paper elaborated in detail how structuralism and interpretive research paradigms were adopted as a way of inquiry, using semiotic and hermeneutic methodology as approaches for the study of built form - Muslim religious building typology. By establishing a methodical design framework that involves the integration of multiple methods- the state mosque architectural features and the patrons' ideologies on Islam manifested in the design of the state mosque were able to be investigated and identified in comprehensive manner. In addition, this systematic research process not only for ascertain why is the Islamic ideology promoted by the Muslim patrons played a dominant role in shaping the state mosque design but also help to elucidate how such an interrelationship may have existed.

In the field of design and communication, this paper therefore, is significant as it provides clear understanding on non-verbal communication by proposing a multi-dimensional approach to investigate the complex level of meanings invested in built form connecting to a specific cultural context by referring to the concept of Saussurean semiology, semiotics and socio-semiotics. This paper thus is essential for designers, social theorists and researchers, who require a means of analysing the profusion of 'sign' and the built environment, as it provides an understanding of how architecture as a cultural object is capable of conveying multi layered messages, as well as describing how society invests meaning in the built environment.

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10
INVESTIGATING THE STRUCTURE AND BEHAVIOUR OF DESIGN CONVERSATIONS

Khairul Anwar Mohamed Khaidzir

INTRODUCTION

The topic expounds the methodology for using design conversations as means for comprehending the nature and implications of design expertise in studio activities. Comparing strands of conversation in design studio tutorials is useful in establishing potential discernable patterns of cognitive behaviour between participating tutors and students who may possess different backgrounds, levels of skill and experience. Such approach was instrumental in the observation and subsequent analysis of 12 unmitigated tutorial conversations recorded between tutors and second year architectural students at University of Sheffield (United Kingdom) (Khaidzir 2007). Each tutorial session consisted of direct conversation between a tutor and a student. The study looked into the utility of verbal protocols as a rich source for understanding the nature of designers' cognitive and perceptual activities during a conceptual phase of design like studio tutorial. The approach described here does not specify means for soliciting data of situated acts of 'designing', but rather it is a 'reflection-on-action' of activities by designers. By this, it means that designers first 'step back' from emerging situations revealed through design interactions, followed by the instigation of certain cognitive actions that may affect the development of 'projects', ideas, propositions or schemes at hand or alleviate problems encountered during those interactions. The study proposes a *cognitive* basis for investigating the substance of tutor-student interactions during tutorials. This could be undertaken by clarifying the nature of differences in cognitive actions, skills and strategies that might transpire from design tutorial conversations observed.

STUDIO 'CONVERSATIONS' AS A MEDIUM FOR STUDYING EXPERTISE IN DESIGN

Donald Schon (1983) famously characterised the design studio as the archetypal setting for educating 'reflective' practitioners like architects. Design conversations that occur between tutors and students during studio tutorials could reveal the characteristics of the conceptual phase of design activities. By studying them we could gain insight into the differences in cognitive interactions between groups of designers who might possess disparate levels of expertise. Generally, they could disclose how designers deal with 'problematic' (Dorst 2006) and 'opportunistic' (Guindon 1990; Visser 1990) situations that emerge through these conversations. We now know that designers solve problems with solutions in mind and that design problems co-evolve with design solutions (Lawson 1979; Dorst and Cross 2001). In the design process, the designer's cognitive input is necessary in providing a meaningful structure to the problems he or she is dealing with. Thus, designing is largely the psychological initiative of the designer in that such an input is strongly linked to the use of personal and episodic knowledge (Polanyi 1974; Visser 1995; Lawson 2004). In addition, design problems are more symptomatic of the designer's psychological abilities rather than the predetermined circumstances of a design task (Dorst 2006).

Some consider designing as a kind of intelligent behaviour due to the growing evidence of expert-novice differences (Gardener 1983; Cross 1990). A more recent definition of intelligence describes this as the ability to 'learn from experience', use 'meta-cognitive processes to enhance learning' and adapt to the environment (Sternberg 2006). The fact that designers are able to address to the contingent nature of design (Goel 1995) appears to support the notion of designing as an intelligent activity. By this, the designer can move arbitrarily to work on another part of a design problem while keeping 'hold' of existing ones, only to return to deal with the outstanding issues at a later stage of designing. It appears that expert designers are better at 'incubating' aspects of design problems than novice designers, thereby resulting in more creative solutions for a particular designed product (Kim, Kim et al. 2007). As opportunities arose, designers could undertake actions that appear to deviate from the original 'plan' at various stages of problem solving activities (Suchman 1987; Guindon 1990; Visser 1990). In fact, the designer would only adhere to a plan as long as it was 'cognitively' economical (Guindon 1990). The designer is also at liberty to 'stop and turn a round' along the trajectory of an ongoing design activity, as well as possessing substantial flexibility in modifying original problem conditions as seen fit in terms of acquired expertise and experience (Goel 1995). These highlight the presence of meta-cognitive mechanisms at work when handling design problems as opposed to dealing with well-defined problems that required transformation between problem states (Chi and Glaser 1985).

One of the most well known approach to structuring problematic situations is by '*framing'* (Schon 1983). This is necessary in delineating the scope of potential problems to be solved and solutions that could be solicited from memory and experience. The basic notion of 'framing' was expanded further to suggest that designers elicit *metaphors* in dealing with conflicting 'frames' during design activities (Schon 1993). Metaphors are means for restructuring outmoded existing 'frames' and fostering new ways of 'seeing' underlying problems in existing design tasks. Essentially, 'frames' and 'generative metaphors' are useful for coordinating and realigning active but incoherent concepts in designing (Clancey 1997). More crucially, they lay a framework for studying interactive and discursive activities like studio tutorials, where two or more designers with different levels of expertise engage in a dialectical development and transaction of perception and ideas (Dorst and Cross 2001). These activities are further differentiated by the fact that each designer could perform different cognitive 'roles' to suit the various cognitive 'streams' in a conversation (Lawson and Loke 1997). Such factors add to the multifaceted challenges in studying situated 'conversations' in comparison to other research in expertise. In particular, it has implications on the methodology for eliciting and analysing patterns of behaviour in a conceptual activity of design, that is the studio tutorial. These patterns would enable us to determine the differences between designers in terms of underlying strategies, skills and cognitive actions involved in interacting with emerging design 'situations'. Significant research on these situations had focused on the subject of visual emergence, in which the ability in perceive rich visual imagery is linked with expertise. Expert designers draw on a richer representation of images from the visual field than novices do (Goldschmidt 1991; Liu 1995; Suwa, Purcell et al. 1998; Athavankar and Mukherjee 2003; Bilda, Gero et al. 2006; Menezes and Lawson 2006)

BACKGROUND STUDY OF DESIGN 'CONVERSATION': THE TWO MODES OF DESIGNING

We can at least identify two cognitive modes of design: cognitive actions that occur in 'doing' design, and cognitive actions that transpire as we converse or are in discourse about design (Lloyd, Lawson et al. 1995). Both modes involve situated acts of cognition since humans are ever receptive to perceiving and knowing about their environment. This follows Gibson (1986), who suggested that perception is like a perceptual 'stream'. However, the nature of knowledge, representation and behavioural effects between the two modes cognition are fundamentally different. Knowledge related to 'doing' design is tacit and difficult to elicit from concurrent verbalisation (Lloyd, Lawson et al. 1995). In contrast, knowledge involved in conversation, talk or discourse on design is verbally explicit. This will be the focus of the current study on studio tutorials, where tutors and students discuss specific states of design the latter has attained at the point of interaction.

During studio conversations, verbal expression runs parallel to the process imagery in experts (tutors) and novices (students). To a greater or lesser degree, we see both tutors and students at ease in handling both verbal and visual expressions during studio interactions. This is not surprising due to the complementary and interdependent nature of imagery and verbal activities (Fish and Scrivener 1990). These interactions often involve mental 'simulations' based on the descriptions and depictions of design artefacts at the centre of tutorial discussion. Table 1 provides segment examples showing these mental 'simulations', the following obtained from verbal protocols in tutorial session 1 (tutor T1 and student S1).

Such mental simulation reflects at least the first two of the processes that we find in imagery, which are image generation, inspection, maintenance and transformation (Kosslyn 1999). It indicates that designers are capable of verbally describing what they are *learning* about their task environment and their *adaptation* to emerging situations during tutorial interactions. This is typical of the early or conceptual phase of design, which we often refer to as the problem structuring or conceptualisation stage.

In the early phase of design, both tutors and students attend to specific issues, restructure problematic situations and seek meaningful patterns as part of the effort to grasp the essence of a particular situation of design. These occur at different levels for corresponding tutors and students. It is at this stage of learning that we find a reasonable correspondence between design cognition and the process of concurrent verbalisation (Lloyd, Lawson et al. 1995). This justifies the use of verbal protocol analysis method in studying and comparing designers' cognitive activities during tutorial conversations. However, such an effort faces several challenges:

- Segmenting interactive protocols like tutorial conversations, which contain two sequences of cognitive activities (one from tutor and the other student) that interweave with each other.

- Encoding segments with attributes that would enable us to answer certain assumptions and hypothesis often stipulated earlier prior to any study of verbal protocols.

Table 1: Examples of protocol segments in Tutorial session 1 (Tutor T1, Student S1)

Segment	Contributor	Protocol Segments
3	S1	Because what I did was, I did this with the first floor plan because I was really happy with myself. Later I'm was going to see how it looks like 3D. And then I thought, okay it looks fine. So, I've got to think of what's happening at the ground floor now [Reference to image inspection]
4	S1	And then I looked at that (model). And then ok, I think like I could need something else here because it seems like a bit towering over the other one [Reference to image inspection]
15	T1	So if we have a six metre shaft in a space that's say 3 metres wide, that's going to be like *sitting in a bottom of a chimney* [Reference to image generation]

OUTLINE OF TUTORIAL OBSERVATION

The case study involved 12 verbal protocols taken from direct tutorial interactions between an architectural tutor and a second year architectural student at the School of Architecture, University of Sheffield during the 2003-2004 second year academic studio session. A total of four tutors and 11 second-year students were involved. The former consist of a permanent staff of the school and three practising architects who worked as part time tutors for the department. All tutors have at least 5 years in practice. At the time of audio-visual recording, the second year students were midway through their first and second semester design projects.

Audio-visual recording of these tutorials used Hi-8 and Mini DV camcorders on tripods and microphone. Recording was made under the condition that it should be as inconspicuous as possibly could. As such, the researcher only conducted intermittent checks on these apparatus during recording to ensure that this occurred smoothly. The initial objective was to select at least 20 direct or one-to-one audio-visual recordings of tutorial sessions. However, this did not materialise due to the unpredictability surrounding the progress of these tutorials. For the purpose of the current study, any tutorial session that involved active engagement by students other than the one whom the tutor of the group is directly addressing were 'discarded'. This was necessary in view of cutting back on the potential influence of external issues a third party might introduce to a tutorial session and the effect this might have on the cognitive activities of the tutor and student involved in the original conversation. Table 2 shows the tutorial sessions considered for the study.

For the current study of 12 tutorial conversations, the effect of conversation was different from the conventional protocol analysis methods used for previous studies of designers' interactions. The main difference here is that the current researcher did not deliberately intervene in order to obtain a desired outcome from tutorial conversations. This differs from other forms of observation that involved deliberate probing or introduction of cues such as those in simulated or focus groups methods.

Table 2 Tutor-student interactions in tutorial conversations

Session	Tutor	Student	Total Duration (min)
1	T1	S1	23.34
2	T2	S2	27.15
3	T3	S3	17.90
4	T4	S4	23.21
5	T4	S5	29.98
6	T1	S6	22.03
7	T1	S4	16.55
8	T3	S7	11.28
9	T2	S8	10.67
10	T2	S9	24.07
11	T4	S10	20.38
12	T4	S11	24.78

SEGMENTING THE VERBAL PROTOCOLS

A segment is a basic unit for protocol analysis. Generally, a segment here is akin to Goldschmidt's (1991) 'design move', which is regarded as 'an act of reasoning which presents a coherent proposition pertaining to an entity that is being design' (p.125). Similarly, Suwa and Tversky (1997) defined segment as a 'coherent statement about a single item/space/topic', even if there could be one or many sentences in such statement. Furthermore, it could also be defined as 'a set of thoughts and /or actions that are interpreted as having occurred simultaneously' (Suwa, Tversky et al. 2001). It is also possible to differentiate subsequent segments by observing the 'change in the subject's intention or the contents of their thoughts' (Gero and McNeill 1998). We could also identify a segment through pauses in conversation (Ericsson and Simon 1993) and, particularly in the current study, conversational 'turns' between tutor and student. We find all these definitions useful in directing the processes of segmentation and coding in the current study.

COGNITIVE ACTION SEGMENTS FROM 'PERFORMATIVE' UTTERANCES

One of the most convenient ways in identifying explicit segments in tutorial conversations is by inferring a correspondence between the designer's verbal utterances and cognitive activities. Designers' utterances are productive in a sense that they could bring about certain kind of effect or action during conversations. They reflect designers' intention and are appropriate for advancing cognitive propositions in design activities. In essence, these utterances move design activities forward. In a seminal study on communicative action, Austin (1976) suggested that we often use words and utterances to perform 'speech acts' rather than simply describe meanings and facts. Calling these verbal activities 'performatives', he suggested that words and utterances could either be 'locutionary', 'illocutionary' or 'perlocutionary' acts (Austin 1976). 'Locutionary' utterances are descriptions or references of things. 'Illocutionary' utterances directly motivate certain kinds of action. For example, these might denote verbal acts of 'informing', 'ordering' and 'warning'. 'Perlocutionary' utterances are 'what we bring about or achieve by saying something' (Austin, 1976, p.109). These could be affective words produced in processes like 'convincing', 'persuading', 'deterring' or even 'misleading'.

Designers' conversations are more than just about communicating intention. They are cognitive responses to a variety of circumstances that emerges from the perception of design situations. In the context of tutorials, these conversations translate into tutors and students experiencing various transformations in cognitive 'roles' in dealing with specific situations and problems of design. Such phenomenon relates to an assumption stipulated earlier, that designers who possess distinct levels of expertise perceive problematic design situations differently. Verifying such assumption requires us to examine tutors and students' cognitive activities in tutorial conversations obtained for the current study.

PARALLEL VISUAL AND VERBAL ACTIONS

Words and utterances provide a useful reflection of cognitive activities that occur in studio tutorial conversations. They serve as memory 'indices' that gather and represent various types of information. Tulving (1983) emphasised the ability of words to function as a 'focal element' in describing the collective experiences of the likes of things, events and spaces that occur in specific situations. With this characteristic, tutorial conversation serves as an important conduit for imparting descriptive or propositional knowledge. Tulving (1983) described the propositional nature of verbal activities:

> Words can be grouped in a variety of systematically describable ways; conceptual categories, acoustic or orthographic similarity groups, semantically associated associated pair, as well as phrases, sentences, and larger linguistically meaningful units. (Tulving, 1983, p.147)

Like sketches, verbal utterances could represent 'objects, scenes or events' that are not 'physically present' (Fish and Scrivener, 1990, p.117). In the study of emergence of visual forms, Liu's (1995) postulated that designers are capable of encoding images both in visual and verbal memory. For example, it would be easy to for them to attend, firstly, to the 'named' underlying pattern like 'triangle', 'parallelogram', 'diamond' and 'hour-glass', before proceeding to recognise sub-variant patterns (Liu 1995). This suggests that at abstract or conceptual stage, cognitive activities that transpire through the visual dimension (perception and imagery) achieve parallel expression in the verbal dimension. Schon (1983) suggested that 'drawing' and 'talking' form parallel elements in the 'language of designing' (p.80). Tulving (1983) supported this parallel modality of visual-verbal representation:

> Words have useful properties: they have meanings and semantic senses; they can be presented either visually or

> auditorily, or both; their mode of presentation within a given modality can also be varied, by using different typescripts, speakers' voices, spatial locations, and the like. (Tulving, 1983, p.147)

The notion that there exists a parallel expression of cognitive activities in visual and verbal dimension provides us with a theoretical basis for coding tutorial conversations.

ENCODING COGNITIVE ACTION SEGMENT

Encoding segments enables us to undertake a purposeful analysis, evaluation and management of data on design conversations. The related study deals with the interactive nature of studio design conversations rather than individual utterances. The latter were evident from the studies by Suwa and Tversky (1997), Goldschmidt and Weil (1998) and Suwa, Purcell et al. (1998). The former consist of rich cognitive interactions between tutors and students. There is a need to acquire a coding framework for protocols that express such interactions. This would allow us to encode segments, which is the process of applying 'a code to a single segment' (Maher and Tang, 2003, p.51). As in the study of Suwa, Purcell et al. (1998), a segment may also possess several coding categories and subcategories. The current study adopts this approach in order to express information-rich and interactive activities in tutors and students' conversation protocols.

Accordingly, a segment is marked by the following coding categories: *Cognitive action, Cognitive organisation, Knowledge doain* and *Transformation type*. In the following sections, we discuss the basis for such a coding scheme for conversation protocols. This then leads to subsequent section 4.8, which describes and discusses the format for tabulating data of cognitive attributes denoted through the prescribed coding scheme.

a) Cognitive action

Based on the parallel or 'co-evolving' development of problems and solutions in design cognition (Schon 1993; Clancey 1997; Suwa, Gero et al. 2000; Dorst and Cross 2001; Maher and Tang 2003; Lawson 2006), we derive a category of Cognitive action consisting of (1) problem *formulation*, (2) *evaluative* function and (3) solution *moves*. Through this category, we acknowledge that designers mutually redefine problems and solutions until a firm problem-solution 'coupling' (Clancey 1997) or 'bridge' (Dorst and Cross 2001) emerges as a fitting proposition for specific design tasks. It is reasonable to suggest that an experienced designer would have access to a substantial repository of problem-solution 'indices'. Perceptually, this would allow him or her to make an automatic link between a particular problem formula and a move for a corresponding solution. If there is disparity between tutors and students in terms of *formulate*, *evaluate* and *move* actions, then this would point to different capability in 'bridging' problem-solution between the groups.

We made inferences as to what these Cognitive actions are in the current tutorial protocols. Based on work of Austin (1976), these actions are clearly identifiable by the role they 'intend' to perform (i.e. 'performative') in a coherent segment. We further outline the three types of Cognitive action as follows:

i) Formulate action

It is useful to designate *framing* activities within a general category of problem *formulation* that also include *ways of understanding* and *identifying* problems (Lawson 2006). This avoids the potential confusion in definition (Valkenburg 2003; Lawson 2006) that might arise through the use of Schon's archetypical 'frame' activity as the overarching category. Nevertheless, the current study accepts framing as a 'selective window' to formulate and structure problems. Some of the examples of Formulate actions are as follows:

Tutor T1 prescribing the feel for space in a design (Tutorial Session 1)

Segment	Contributor	Protocol Segments
47	T1	And I think, you know, *once things start to find a place*, and I think things are really, you know, they're beginning to look as though they've *got some life*, you know, which is exciting

Tutor T2 makes framing enquiry on configuration of scheme (Tutorial Session 2)

Segment	Contributor	Protocol Segment
45	T2	Is there another *framework that holds the whole building* together then. You know, in terms of where you arrive and where you leave, how does the circulation in a way gives some sense of order to these various programmes that are beginning to come together. Have you begun to develop that?

Tutor T4 asks for relationship between spaces (Tutorial Session 4)

Segment	Contributor	Protocol Segment
23	T4	And how are these spaces *connected?*

ii) Evaluative action

According to Lawson (2006), skilled designers cannot avoid making both objective and subjective evaluations in design. Being evaluative incorporates various abilities in making specific judgements about the value of certain object of attention or subject matter. For the current study, we postulate that the *Evaluative* function groups together iterative activities like analysis, synthesis and evaluation. These activities form an effective 'processing' environment between problem and solution 'spaces' illustrated by the 'co-evolving' model of design (Dorst and Cross 2001). Some examples of Evaluate action are as follows.

Tutor T2 enquires whether building program fits site (Tutorial Session 2)

Segment	Contributor	Protocol Segment
20	T2	I mean, is the site *big enough to do all* that?

Tutor T3 expresses his judgement on a feature of building (Tutorial Session 3)

Segment	Contributor	Protocol Segment
40	T3	That seems *too physical*, really, it's not actually part of the building, is it? *It's just a screen*, really (reference to sketch)

Tutor T4 compares sketches to model (Tutorial Session 4)

Segment	Contributor	Protocol Segment
46	T4	Although interestingly these *sketches don't relate that closely to this model*

iii) Move action

Designers prescribe solutions through a variety of *move* actions. We regard this as parallel to the idea of Goldschmidt (p.195), who equates a design move to a move in chess: 'a design move is a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move' (Goldschmidt 1995). In the same light, a segment of utterance from a designer is comparable to the conventional idea of a 'design move'. The following segments reflect this type of action.

Tutor T2 asks student to configure a framework for space planning (Tutorial Session 2)

Segment	Contributor	Protocol Segment
58	T2	Now, what you need to do is to start looking at *organising kind of a framework* that allows the users to move around these various spaces, and also the quality of the spaces, the quality of light that you envisage in these various areas

Tutor T3 prescribes an 'atmospheric' solution to a spatial problem (Tutorial Session 3)

Segment	Contributor	Protocol Segment
52	T3	I just perhaps being a bit more subtle somehow, so you keep the enclosure of the space in the darkness and sombre light and just see (sketch)….

Tutor T4 suggests an intervention in a tower building (Tutor Session 5)

Segment	Contributor	Protocol Segment
91	T4	You know, I wonder whether that tower, if you could open up the top part of it…… to make the café in there (starts sketching)

b) Cognitive Organisation

Design activities draw considerably from visual cognitive activities. At abstract or conceptual level, there is parallel expression between visual and verbal dimension of cognition (Fish and Scrivener 1990). Since tutorial conversations are discourses on design rather than about designing itself, we consider it appropriate to infer visual activities from verbal expressions as well as explicit physical gestures that transpire during tutorial conversation. We then categorise these inferred visual activities in relation to basic processing functions of human vision. In the current study, basic visual functions pertain to the organisation of 'percepts' and imagery that emerge at the forefront of attention during tutorials. Based mainly on the work of Ullman (1996), the human visual processing addresses the following three kinds of organisational activities and their respective examples in the tutorial conversation protocols:

i) Low level vision (Componential)

This activity relates to process of extracting primitive physical properties from objects in the visible environment. This includes 'depth', 'three-dimensional (3-D) shape', 'boundaries' and 'surface material properties' (Ullman 1996). This is the 'bottom up' approach that we find in perception. It is also called early or local vision (Subirana-Vilanova 1993). For the current study, we can call it *componential* organisation due to its early identification of components or parts of objects that emerge in the visual field. The following are some examples componentially organised segments.

Student S1 reflecting on the size of her plans (Tutorial session 1):

Segment	Contributor	Protocol Segments
44	S1	I think I might have made the plans a bit small. I think the rooms are a bit small because every time I start doing it I get smaller and smaller

Tutor T1 commenting on the scale of student's plans (Tutorial session 1):

Segment	Contributor	Protocol Segments
46	T1	I think that you're working on a small scale in any case. I mean, what is it, 1:200? It's tiny

Tutor T1 recognising a familiar shape in plan (Tutorial session 6)

Segment	Contributor	Protocol Segment
32	T1	What's that….what's that 'kink' in the plan here? (sketch plan)

ii) Intermediate level vision (Structural)

Unlike 'high level vision', this process does not depend on specific knowledge about objects or domain knowledge (Ullman 1996). It relies on its own 'gestalt' dynamics that work on ambiguous, embedded or occluded visual objects so that the latter become more explicit and amenable for subsequent 'top down' visual processes like symbolic or high level cognition to occur. It is also called *global* vision (Subirana-Vilanova 1993). This level concerns the more organisational aspect of vision like segmenting, grouping, linking, differentiating, combining and restructuring of visual elements. The following segments are good examples of this kind of organisation.

Tutor T1 describes conceptual link between several elements of design (Tutorial session 6):

Segment	Contributor	Protocol Segment
107	T1	And this is a central sort of zone or a pin that's holding the two cubes together. It could be expressed more distinctly. Yeah, I mean, it might push up both the roof at this point (reference to section sketch)

Tutor T3 seeks clarification on the arrangement of building elements (Tutorial session 8):

Segment	Contributor	Protocol Text
17	T3	I mean is that trying to enclose not just the theatre but the proper foyer and the other things around it?

iii) High level vision (Symbolic)

This kind of organisation concerns the interpretation and use of information in the image, rather than direct recovery of physical properties (Ullman 1996). It is also called symbolic or late vision (Subirana-Vilanova 1993). Kosslyn (1999) further described that high level visual processing does not only involve perception but also mental imagery. In addition, it also relates to the faculty of 'reasoning' (Oxman 2002). Two examples of 'Symbolically' organised segments are as follows.

Tutor T1 suggests some ideas on student's space planning (Tutorial session 7):

Segment	Contributor	Protocol Segment
71	T1	You could do what you are proposing here and glaze each floors and say, well okay, this is a kind of a continuation of the space out into something semi-public that can happen here (points to centre of atrium)

Student S5 describes design scheme (Tutorial session 5):

Segment	Contributor	Protocol Segment
64	S5	So that's like the main place for learning and studying, exhibition, and then the more communal, well, the more recreational thing is the word

c) Domain of Knowledge

This category reflects on the kind of knowledge designers employ in cognitive activities as reflected from their protocol conversations. It concerns the distinction between content-based and process-based taxonomies in the analysis of design activities. According to Dorst and Dijkhuis (1995), reflective practice like design inherently preserves a link between the two types of knowledge. This implies that designers do not only work with knowledge at the stimulus level but also make use of higher order knowledge that will enable them to comprehend the world that they are dealing with. However, the current study is only concerned with obtaining exact differences in tutors and students' production of content-based and process-based segments rather than assessing the extent of preservation in process-content links that exist in tutors and students' segments. We differentiate between process and content domains of knowledge as follows.

i) Process domain of knowledge

The process domain of knowledge relates to problem solving 'processes' and issues concerning *problem-states*, *operators*, *plans*, *goals* and *strategies* (Suwa, Purcell et al. 1998). Process-based segments in protocols suggest the presence of *executive* function that brings about 'active monitoring and consequent regulation and orchestration' of cognitive activities (Flavell 1976). This implies that a 'different' kind of knowledge is involved, particularly when utterances communicate 'meta-cognitive' notions of *concepts* and *skills*, rather than just *basic information* of the 'world'. One study that dealt with process-content classification is the experts' and novices' categorisation and representation of physics problems (Chi, Feltovich et al. 1981). The study revealed that experts' descriptions of task problems mainly involved 'underlying principles' while novices simply expressed objects and other 'surface characteristics' to those problems. In the current study, process-based cognitive action segments alludes to *concepts, precedence, analogies, regulations, scale, model, brief and programme, strategies, frameworks* and *plans*. These examples are indicative of 'what people know about their knowledge' (Vos 2001; Vos and De Graaff 2004). The following are two of the many examples of process-based cognitive action segments in the tutorial session protocols.

Tutor T2 advises student to devise overall strategy in space planning (Tutorial session 2):

Segment	Contributor	Protocol Segment
58	T2	Now, what you need to do is to start looking at *organising kind of a framework* that allows the users to move around these various spaces, and also the quality of the spaces, the quality of light that you envisage in these various areas

Student S3 agrees on the need for planning (Tutorial session 3):

Segment	Contributor	Protocol Segment
69	S3	Yeah, I've definitely got to start *thinking about plans*

ii) Content domain of knowledge

This category of domain knowledge relates to 'what designers see, attend to, think of and retrieve from memory' (Suwa, Purcell et al., 1998, p.457). Often, content-based knowledge refers directly to issues and elements about the actual product of design. They bear supporting information, descriptions, explanations and clarifications (Vos 2001) on products or artefacts at the centre of tutorial design conversations. The following are two examples of content-based cognitive action segments.

Tutor T3 suggest an idea on planning to student (Tutorial session 3):

Segment	Contributor	Protocol Segment
77	T3	Yeah, so maybe, maybe this has the sort of the things like the library and the external galleries in, which has it linked with the cathedral where, you know…

Student S5 enquires on planning aspect of scheme (Tutorial session 5):

Segment	Contributor	Protocol Segment
96	S5	Do you think that that position of the tower should be at this end (lower end of site) or should it be elevated (upper end of site)?

d) Transformation

We can establish the relationship between successive segments by identifying the type of transformation a current segment makes in relation to a previous one. Goel (1995) used the term 'transformation' in describing the movements of ideas: a 'lateral transformation' indicates a shift from one idea to a different idea, while 'vertical transformation' suggests a detailed development of the same idea. Similarly, Suwa and Tversky (1997) used 'focus-shift' and 'continuing' segments respectively. Using transformation to differentiate between segments enables us to investigate tutors and students' overall strategies as they experience emerging 'situations' in tutorial conversations.

There are many interpretations to these transformations. For example, 'lateral' transformation might indicate that the designer has seen a new 'opportunities' due to purposeful or unintended reorganisation of perception. In contrast, 'vertical' transformation could reflect 'deepening' deliberation on existing ideas. Both types of transformation show that tutors and students experience cognitive 'learning' during studio tutorial. The extent of these experiences is a subject of comparison in the current study. Studying studio tutorial 'conversations' as an environment of contesting 'universes' (Schon 1988) and 'discourses' (Dorst 2006) might reveal a measured level of disparity between experts (tutors) and novices (students) in cognitive actions.

TABULATED FORMAT FOR SEGMENTATION

This section proposes a unique method for tabulating conversational activities like studio tutorials. It follows earlier suggestion that each complete segment is encoded with relevant attributes (in bracket) under the following four categories: (1) *Cognitive action* (Formulate, Evaluate or Move), (2) *Cognitive organisation* (Structural, Symbolic or Componential), (3) *Domain of Knowledge* (Process or Content), and (4) *Transformation* type (Lateral or Vertical). These attributes then populate a table referred to as the *Matrix of Cognitive Interaction* as shown in example Table 4. Each attribute is an interpretation of a corresponding protocol segment illustrated in Table 3. The tables were created using Microsoft Excel application. The following sections highlight the basis for the current tabulation format.

a) Systematic and Coherent Description of Cognitive Actions in Conversation

The proposed tabulation scheme forms an effort to represent and capture protocol data from a series of live tutorials performed between two groups of designers (i.e. tutor and student) who possess disparate levels of expertise. These tutorials are *interactive* and *dynamic* in nature. Therefore, extracting information from two interacting subjects through a common framework of analysis and evaluation is by no means easy and forthright. This differs substantially from many previous studies on design expertise and cognitive activities, which often analysed and compared protocol data obtained from discrete 'talk-aloud' method applied to individual or team designers (e.g. Goldschmidt (1995), Suwa and Tversky (1997) and Suwa, Purcell et al. (1998)).

In the proposed method of tabulation in Table 4, *Cognitive actions*, *Cognition organisation* and *Domain of knowledge* are categories that provide *exact* qualities of a segment. The *Transformation* category (i.e. lateral or vertical) reveals the nature of relationship between successive segments. It denotes the *directional* quality of a segment.

Table 3: Selected Protocol segments 45-57 of Session 2 (Tutor T2, Student S2)

Segment	Contributor	Protocol Segment
45	T2	Is there another *framework that holds the whole building* together then. You know, in terms of where you arrive and where you leave, how does the circulation in a way gives some sense of order to these various programmes that are beginning to come together. Have you begun to develop that?
46	S2	Yeah, the main entrance will be here and will kind of allow you to walk almost all the way through. You have a door here door there (model)
47	T2	Have you kind of develop that *idea in terms of plans* anywhere yet?
48	S2	Of course, I've got some ideas. This was just a quick sketch of what I imagined this ground floor to be. You've got most access running up this side of Brown Lane side so from there you'll be able to, I'm trying to find.........anyway, basically this side where most of the circulation (model)
49	T2	So you've got circulation around that edge, which is this one here (models)
50	S2	You can go down, that's going to be a (shoved) close to that wall. There'll be like that cube where you can go along into this. . ..(model)
51	T2	I think that this is a good model, yeah. What I think you need to do is to in a way *develop a large scale model* for this, you know, that explains the whole scheme
52	T2	Because at the moment what we have is lots of information everywhere, but I think in a way symptomatic of how the project is developing as well. I think it's *developing in a piecemeal*, right. I kind of sensed that because you were searching when we're having our discussion. Basically is, you've got lots of ideas but it seems to be, in a rather chaotic manner
53	S2	Yeah, I just *need to organise* it
54	T2	Yeah, and I think in a way *that reflects* i*n the way you present* your architecture across
55	T2	I think that you should do for next week in our next tutorial, *establish a very clear set of drawings* that determine what's happening at what level, what type of spaces that you envisage at the lower ground floor
56	S2	Do you reckon that this is *too much going on* in the building?
57	T2	No, that's irrelevant. It doesn't matter whether how much, I think. That's not the question, *the question is what is your brief right? W*hich is a series of basically three, starting with the studio......you've got main studio, you've got rentable space and private accommodation on the ground floor as well, with the display gallery space

Table 4: Matrix of Cognitive interaction for Tutorial session 2 (Segments 45 to 57)

Seg. No	Contributor		Cognitive Action		Cognitive Organisation		Domain of Knowledge		Transformation		T (min)
	Precede	Current	Precede	Current	Precede	Current	Precede	Current	Precede	Current	
45	T2	T2	F	F	ST	SY	PRO	PRO	L	L	0.333
46	T2	S2	F	F	SY	SY	PRO	CON	L	V	0.167
47	S2	T2	F	F	SY	SY	CON	PRO	V	V	0.100
48	T2	S2	F	F	SY	CO	PRO	CON	V	V	0.983
49	S2	T2	F	F	CO	SY	CON	CON	V	V	0.083
50	T2	S2	F	F	SY	SY	CON	CON	V	V	0.117
51	S2	T2	F	M	SY	SY	CON	PRO	V	V	0.150
52	T2	T2	M	F	SY	SY	PRO	PRO	V	L	0.333
53	T2	S2	F	M	SY	SY	PRO	PRO	L	L	0.017
54	S2	T2	M	F	SY	SY	PRO	PRO	L	V	0.100
55	T2	T2	F	M	SY	SY	PRO	PRO	V	V	0.283
56	T2	S2	M	E	SY	SY	PRO	CON	V	L	0.067
57	S2	T2	E	F	SY	SY	CON	PRO	L	L	0.350

Contributor	T2	Tutor	Cognitive Organisation	CO	Componential
	S2	Student		ST	Structural
Cognitive Action	F	Formulate		SY	Symbolic
	E	Evaluate	Domain of Knowledge	PRO	Process
	M	Move		CON	Content
			Transformation	L	Lateral
				V	Vertical

By indicating *exact* and *directional* qualities in a segment, we have a dynamic and rich depiction of studio interaction. This will be useful in providing a systematic *description* for each cognitive action segment. Such a description would entail the following information: Who acts? Who initiates? What kind of action and organisation is involved? What kind of knowledge is utilised? Is the action a new or continuing action? For example, we can describe segment 45 by tutor T2 in Table 4 as the following:

> Tutor T2 inquired how movements (Cognitive action-Formulate), i.e. arrival, circulation and departure, integrate into existing building programme (Cognitive organisation-Structural). He spoke this as a kind of framework that

> structures overall design of building (Domain of knowledge-Process). This 'formulative' inquiry is a shift from a previous segment (Transformation-Lateral) generated also by the same Tutor T2 (segment 44, not shown).

And a description of segment 46 by Student S2 would be as follows:

> Student S2 identifies and frames the entrance position (Cognitive action-Formulate), which he recalls from memory (Cognitive organisation-Symbolic) on a working model during tutorial. He articulates on what he knows about a specific product, i.e. doors (Domain of knowledge-Content). This 'formulative' statement is development of a previous segment (Transformation-Vertical) generated by Tutor T2 (segment 45).

b) Filtering and analysing relevant information in the table

In addition to having *exact* (Cognitive action, organisation and domain knowledge) and *directional* (Transformation) qualities, each segment is also *quantifiable* in terms of frequency and duration. This is especially important for the current study; in which comparing design expertise between two different groups of designers (tutors and students) is the primary focus of investigation.

By using a 'drop-down' filtering menu in Microsoft Excel, we are able to extract and calculate overall frequencies and durations of segments that form specific case studies for further analyses and evaluations. This would allow us to have a 'macroscopic' overview of, and therefore, discriminate between, tutors and students' cognitive strategies in tutorial conversations in relation to those specific case studies. In the following parts, we describe some important considerations to the filtering operations in current study.

c) Dependency Links: Relationship between Current and Preceding Segments

A studio tutorial is an interactive and dynamic activity. What sets it apart from other environments of observation is the fact that tutor and student's utterances intertwine extensively and unpredictably in a tutorial conversation. Thus, filtering tutorial conversations is by itself a demanding task. Prior to filtering information in a segment, it is always important to ask the following question: how do we determine the relationship between segments? We highlight *current* and *preceding* information in a segment as a sub-category under the main four categories of Cognitive actions, Cognitive organisation, Domain of knowledge and Transformation type (Table 4). This is to denote a link between a current and previous segment. Suwa and Tversky (1997), who defined the relationship between adjacent segments as a 'dependency link', made a similar approach.

Such a link shows the presence of basic 'chunk' formed, at least, by two adjacent segments. Through the concept of 'dependency link', we are able to track the immediate origin of certain ideas, propositions or issues in a segment and infer their likely role in tutors and students' cognitive actions during tutorials. We could establish the affinity of a succession of segments, as had been done in the studies by Suwa and Tversky (1997) and Goldschmidt and Weil (1998). The critical number of segments involved in a dependency link depends on what we are looking for in a study.

In the investigation by Suwa and Tversky (1997), possessing 'chunks' consisting of either two or more than two segments in 'length' provide the critical threshold in differentiating the abilities of novice (students) and expert (architects) designers. For Goldschmidt and Weil (1998), the threshold for having critical 'chunks' is substantially more, six segments in total. Both studies were about design productivity. Therefore, the involvement of high number of segments for a critical 'chunk' is not surprising.

The size of 'dependency link' between segments in the current study is different from those considered by Suwa and Tversky (1997) and Goldschmidt and Weil (1998). For the current study, we are only concerned with the link between *two consecutive segments*: a *current* and *preceding* one. In a one-to-one tutorial conversation between a tutor and student, a 'dependency link' would be in any of the following configuration:

1. A current tutor segment that follows a tutor-made preceding segment
2. A current tutor segment that follows a student-made preceding segment
3. A current student segment that follows a tutor-made preceding segment
4. A current student segment that follows student-made preceding segment

To illustrate**,** Links 1 and 2 correspond to segments 45 and 47 respectively under the column marked 'contributor' in Table 4. These links belong to Tutor T2. Links 3 and 4 belong to Student S2; the former corresponds to segment 46 while the latter is absent from the same table.

d) Productive segments

We consider a current segment that forms this 'dependency link' to be *productive* if it follows a preceding segment made by either the tutor or student. For example, we list segment numbers 45, 47, 49, 51, 52, 54, 55 and 57 in Table 4 as those that constitute Tutor T2's eight productive segments. Three of these segments had followed tutor-made preceding segments (segments 45, 52 and 55), while five others had followed student-made preceding segments (segments 47, 49, 51, 54 and 57). In the same table, student S2 has five productive segments (Segments 46, 48, 50, 53 and 56). All five segments had followed tutor-made preceding segments and, due to the range of segments selected in Table 4, none had followed student-made preceding segments. Besides having a 'dependency link', a productive segment also possesses attributes in the coding categories of Cognitive actions, Cognitive organisation, Domain of Knowledge and Transformation. A segment is 'complete' once it fulfils all four categories.

IDENTIFYING, ASSESSING AND COMPARING CASES INVOLVING COGNITIVE ACTION SEGMENTS

Within the examples shown in Table 4, every segment has its own unique configuration. We could then select relevant segments for specific, case-by-case analysis through Excel's 'filtering' tool. This would allow us to gather crucial information on specific cases of Cognitive interactions in terms of segment frequency and mean duration. The following *example* demonstrates how we identify, assess and compare between specific cases of interactions.

- Example 1: Comparing two groups of Tutor T2's formulate actions, where one followed student-made preceding segment and the other followed tutor-made preceding segments

This example refers to the following Tables 5 and 6. In this example, there is a difference between the two groups of formulate actions. Tutor T2 produced *more* formulate actions that followed student-made preceding segments (n=4) than formulate actions that followed tutor-made preceding segments (n=2). However, Tutor T2 took longer time to produce formulate actions that followed tutor-made preceding segment (mean=0.167min) than those that followed student-made preceding segments (mean=0.158min). We could then deduce the significance of such findings. However, whether these differences are significant is a separate matter. In any case, this exercise is only an example involving a group of samples that ranged only between segments 45 to segments 57 as originally shown in Table 4.

Table 5: Tutor T2's formulate actions that followed tutor-made preceding segment

Seg. No	Contributor		Cognitive Action		Cognitive Organisation		Domain of Knowledge		Transformation		T (min)
	Precede	Current	Precede	Current	Precede	Current	Precede	Current	Precede	Current	
45	T2	T2	F	F	ST	SY	PRO	PRO	L	L	0.333
52	T2	T2	M	F	SY	SY	PRO	PRO	V	L	0.333

Segment frequency 2 Mean duration 0.167 min

Table 6: Tutor T2's formulate actions that followed student-made preceding segment

Seg. No	Contributor		Cognitive Action		Cognitive Organisation		Domain of Knowledge		Transformation		T (min)
	Precede	Current	Precede	Current	Precede	Current	Precede	Current	Precede	Current	
47	S2	T2	F	F	SY	SY	CON	PRO	V	V	0.100
49	S2	T2	F	F	CO	SY	CON	CON	V	V	0.083
54	S2	T2	M	F	SY	SY	PRO	PRO	L	V	0.100
57	S2	T2	E	F	SY	SY	CON	PRO	L	L	0.350

Segment frequency 4 Mean duration 0.158 min

Many other types of analysis are possible through this simple method. For instance, based only on segments contained in Table 4, the following Example 2 compares the distribution of Formulate actions between Tutor T2 and Student S2 in cases that involve the distribution of Transformation type (lateral and vertical transformation).

- Example 2: Comparing distribution of Tutor T2 and Student S2 Formulate actions in relation to Transformation type

We have selected the relevant information for analysis in the following Tables 7 and 8. In comparing the cases in question, we found that Tutor T2 had produced more formulate actions in the lateral transformation (n=3) than Student S2 (n=0) did. In terms of formulate actions that transformed vertically, the number of segments produced by Tutor T2 and Student S2 is the same (n=3). However, the situation is not the same in relation to mean duration. Student S2 clearly took longer time to make such actions (mean=0.422 min) than Tutor T2 did (mean=0.094 min). In a real analysis, such difference in duration would have been further scrutinised. Then again, this is only an example of how we could apply the current tabulation method of analysis to conversational data obtained in the current study. Thus, it is an exercise to explain to rather than to inform.

Table 7: Tutor T2's formulate actions and distribution of Transformation type

Seg. No	Contributor		Cognitive Action		Cognitive Organisation		Domain of Knowledge		Transformation		T (min)
	Precede	Current	Precede	Current	Precede	Current	Precede	Current	Precede	Current	
45	T2	T2	F	F	ST	SY	PRO	PRO	L	L	0.333
47	S2	T2	F	F	SY	SY	CON	PRO	V	V	0.100
49	S2	T2	F	F	CO	SY	CON	CON	V	V	0.083
52	T2	T2	M	F	SY	SY	PRO	PRO	V	L	0.333
54	S2	T2	M	F	SY	SY	PRO	PRO	L	V	0.100
57	S2	T2	E	F	SY	SY	CON	PRO	L	L	0.350

Segment frequency Lateral 3 Mean duration Lateral 0.339 min
Vertical 3 Vertical 0.094 min

Table 8: Student S2's formulate actions and distribution of Transformation type

Seg. No	Contributor		Cognitive Action		Cognitive Organisation		Domain of Knowledge		Transformation		T (min)
	Precede	Current	Precede	Current	Precede	Current	Precede	Current	Precede	Current	
46	T2	S2	F	F	SY	SY	PRO	CON	L	V	0.167
48	T2	S2	F	F	SY	CO	PRO	CON	V	V	0.983
50	T2	S2	F	F	SY	SY	CON	CON	V	V	0.117

Segment frequency Lateral 0 Mean duration Lateral 0 min
Vertical 3 Vertical 0.422 min

There is a need to emphasize that examples 1 and 2 serve only to inform us *how* we could use the tabulation and analytical methods derived in the approach stipulated so far in order to examine interactions that occur in tutorial conversations. Obviously, they are *not* real findings and the data presented in the original Table 4 does not represent the true picture of what generally transpires during Tutorial Session 2. In fact, these examples merely represent *simulations* of actual analyses carried out on potential protocol data elicited from tutorials and many other types of design conversations. Generally, eliciting, assessing and differentiating design abilities through design conversations are a real and stimulating prospect for the future of design research. Equally promising is the fact that through such an approach, it is possible to enumerate design processes that occur within a seemingly elaborate, volatile and protracted environment like the design studio. Furthermore, such a study provides a fair representation of what actually transpires during design tutorials. This is particularly true on tutor-student cognitive differences.

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11

APPLICATION OF MEANS-END CHAIN MODEL IN ARCHITECTURAL RESEARCH

Mahmud Mohd Jusan

INTRODUCTION

This chapter discusses a research methodology potentially useful in investigating person-environment relation in architectural research. The model has been widely employed in marketing researches. However, its application in architectural research is still scarce. The author has employed the model in a case study research on personalization practices in a housing scheme in Malaysia. In the research, the model was used together with questionnaire survey, aiming at enhancing predictive power of the result in explaining the achievement of person-environment congruence in the renovated houses.

Basically, the survey was employed to establish characteristics of the personalization practices. However, results from the survey were unable to explain the relationship between human psychological factors and the environmental attributes. This is partly due to the nature of variables in the questionnaire being objective and established by the researcher. In order to obtain results with better predictive power, subjective data elicited from the respondent are needed (Kahana et al, 2003). Means-End Chain (MEC) research model was found to be appropriate in linking environmental attributes (such as spaces, building components, etc.) to personal psychological factors. This chapter will explain in detail the application of MEC research method in architectural research.

THE THEORY OF MEANS-END CHAIN

The objective of MEC theory is to understand what makes products personally relevant to consumer by modelling the perceived relationships between a product which is defined as a collection of attributes, and a consumer as a holder of values (Pieter et.al (1995). Attribute is defined as the objective physical aspects of a product (Lancaster, 1966. c.f. Keinonen (1998). According to Lancaster (1966. cf. Keinonen 1998), people do not acquire products for the utility that is produced by attributes of the products. According to Grunet (1989) attribute is any aspect of the product itself or its use that can be used to compare product alternatives. Consumption of attributes of products are conceptualised as leading to various benefits (termed as "consequence") which in turn satisfy consumers' value. According to Rokeach (1973) values are conceptualized as important life goals or standards, which serve as guiding principles in a person's life (Rokeach 1973). Values are an imperative to action, standards or yardsticks to guide action, attitudes, comparisons, evaluation, and justifications of oneself or others (Rokeach 1972). Values function as an organized system and are typically viewed as determinant of attitude and behaviour (Olson and Zanna 1994). Values are expressions of culture (Rapoport, 2001)

Attribute-Value relationship Gutman's Means-end chain framework is indirect with "consequence" as the intervening factor (figure 1).

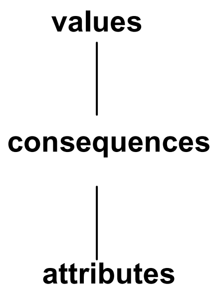


Figure 1. Original Means-end chain model. Source; Coolen and Hoekstra (2001)

The meanings of attributes are given by their consequences. There are two categories of consequences in Gutman's MEC namely functional and abstract consequences (Gutman 1982). Functional consequences are practical benefits and performance outputs (such as satisfying physiological needs), while abstract consequences are feelings or social considerations (such as self-esteem, enhance status). Categories of consequence suitable for architectural research will be discussed later.Consequences can be either positive, i.e. benefits, or negative, i.e. perceived risks. Consequences are followed in the continuum of increasing abstraction by user values, which are mental representations of the consumer's most fundamental goals. Depending on the consumers' product knowledge, the means-ends chains are not always complete, i.e. they do not reach to the level of values.

VALUE DOMAINS FOR MEC RESEARCH

So far, values are seen as closely related to culture. They are expression of culture (Rapoport, 2000; Rokeach, 1973). Values represent socially shared abstract ideas about what is good, right and desirable (Hofstede, 1994). They serve as the criteria used to determine what behaviour is appropriate; to guide self presentation and to justify one's choice to others (Rokeach 1973, Smith and Schwartz 1997). Understanding a country's core culture is of paramount importance, they are regarded as a powerful influence on a country's characteristic and consumer behaviour. In housing, values help to define groups and make housing particularly important, because dwellings play an important role in acculturation and, hence the survival of groups through the transmission of values, linking values to family (Rapoport 1982, 1990). Values is also suggested to influence housing preferences and choice (Rapoport 2001, Coolen and Hoekstra 2001).

Earlier, there were two types of values used in MEC research namely terminal and instrumental values. Terminal values concern with preferred end states of existence, and instrumental values are related to modes of conduct to achieve terminal values (Rokeach, 1972). Stemming from the earlier Rokeach value system, Schwartz (1992, 1994) developed another value system which are considered to be universal across all people. The system is composed of 52 value items that represent ten value domains (Table 1). The ten value domains can be grouped into four categories namely: openness to change, conservatism, self transcendence and self enhancement. In architectural research, the ten value domains have been used by Coolen and Hoekstra (2001) and Mahmud (2007) as value domains in their modified MEC framework. In the framework, values are not measured *per se* but are linked with attributes.

CLASSIFICATION OF ATTRIBUTE AND CONSEQUENCE FOR ARCHITECTURAL RESEARCH

Attributes

To use MEC in architectural research, Mahmud (2007) suggests a set of attribute categorization that are summarised and modified from various authors (Rapoport 2000, Onibokun 1974, Garling and

Friman 2002, Despres 1991, Somerville 1992, and Bernard et.al 1993)

Table 1. Value-items from Schwartz values instrument.

Self-transcendence	**Self-enhancement**	**openness**	**Tradition**
Universalism	***power***	***Self-direction***	***Tradition***
Protecting the environment	Social power	creativity	Devout
	Authority	Curious	Respect for tradition
A world of beauty	wealth	freedom	Humble
Unity with nature	Preserving my public image	Choosing own goals	Moderate
Broad-minded		independent	Accepting portion in life
Social justice	Social recognition		detachment
Wisdom		***stimulation***	
Equality	***Achievement***	daring	***Conformity***
A world at peace Inner harmony	Successful	A varied life	politeness
	Capable	An exciting life	Honouring parents and elders
	Ambitious		obedient
Benevolence	Influential	***Hedonism***	Self discipline
helpful	Intelligent	Pleasure	
Honest	Self-respect	Enjoying life	***Security***
Forgiving			Clean
Loyal			National security
Responsible			Social order
True-friendship			Family security
A spiritual life			Sense of belonging
Mature love			Reciprocation of favours
Meaning in life			healthy

Source: Schwartz (1994)

According to him attributes can be categorized into tenure, location, cost, intrinsic-housing unit, and neighborhood. However, in his research on house personalization, Mahmud (2007) concerned mainly with intrinsic attributes (housing unit attributes) that are divided into “concrete” and “abstract” attributes. These attribute classification, which are originally developed by Gutman (1982), can be used to identify users’ housing expectations in design process.

- **Concrete attributes**

  Concrete attributes can be conceptualized as the physical characteristics of the product itself. They are tangible attributes which are observable and touchable.

- **Abstract attributes**

  Abstract attributes are meanings perceived by the user. Mahmud (2007) established a list of abstract attributes based on Somerville’s (1992) six or seven dimensions of meaning of home namely, house as shelter, hearth, heart, privacy, roots, abode and paradise. Each of these dimensions connotes different level of user expectations or definition of a house. Depres (1992) semantic meaning of home are also included, but they have been categorized into symbolic expression and personal identity, social relationship and use of home.

Consequence

Several dimensions of design outcomes can be assumed as consequence of architectural products such as houses. Mahmud, (2007). In his research modified categorisation of consequence from the original categories suggested by the previous authors (Gutman, 1982; Reynold and Gutman, 1988, 2001; Olson and Reynold, 2001).

The suggested categorization is based on the previously established three-dimensional levels of dwelling (Aragones, 2000). These levels can be used to classify the consequences elicited from the respondents: -

i. The physical (all aspects relating to space, structure, and amenities)
ii. Psychological (subjects that contribute to personal well-being, such as comfort, self expression, identity, privacy)
iii. The social (close relationship and enjoyment of the company of close friend and family, neighbours).

METHODS OF DATA COLLECTION

The MEC method for architectural research was derived from both the traditional MEC method (Reynold and Gutman, 2001) and the modified method by Coolen and Hoekstra (2001). The data collection process is a semi structured interview, aiming at probing respondents' own perception (respondents' own words) on the attributes-value-consequence (A/C/V/) elements. The set of linkages (as shown in figure 1) between the key perceptual elements across the range of attributes, consequence and values is called "ladder".

For identification of users' housing design expectation a slight modification is needed. In particular, house attribute investigation is not necessary. This process is where the renovated houses were compared to the original design (Mahmud, 2004). This process is obviously irrelevant for new house buildings. Therefore, the data collection, analysis and interpretation are in seven phases only:-

- Elicitation of the attributes
- Identification of functional benefits and selection of attributes
- Performing laddering interviews

- Determination and coding of means-end chains

Elicitation of the attributes

Elicitation of the attributes basically follows the techniques used by Coolen and Hoekstra (2001). A set of housing/house unit's attributes checklist and coding is used to compare the original and the modified living environments.

The method of selecting attributes does not necessarily start by directly selecting from the list of attributes as in Coolen and Hoekstra's (2001) method. The eliciting of attributes is done by firstly probing for the functional benefits expected from the "dreamed" houses. The process will be effective by probing the respondents with "what" questions. For example "what are the functional benefits expected from the house ". Functional benefits may be obtained from the probing. Once established, the interviewer may proceed to the next phase. The bottom-up probing will be dominated by the "why is it important to you" question as in the traditional MEC method. Pen and paper technique can be used to record every each of the ladders. Tape recorder can be also used to help the construction of the ladders and analysis in the later phase.

Identification of functional benefits and selection of attributes

The next phase of the laddering is identification and selection of expected house attributes, a downward probing to attributes levels for changes that produced these benefits. In order to do this, the respondent will be shown the house attributes checklist (HAC) and ask "what or which (from the HAC) attributes that concern the users for his or her future house". Limit the attributes to 8 only. This limitation follows the method used by Coolen and Hoekstra (2001). If the respondent mentioned more than eight attributes the interviewer will ask him/her to choose eight most important ones.

Performing Laddering Interviews

Once the relationship between functional benefits and attributes is established, probing shall go bottom-up to get at "psychosocial benefits" (consequences) and eventually personal values. The bottom-up probing will be dominated by the "why is it important to you..?" questions. Tape recorder will be used to help the construction of the ladders and analysis in the later phase. The questions will be in a comparative manner by referring to the situation before and after personalization. Some of these questions may be useful, For example, if the respondent chose a kitchen layout to be one of the identified attributes, the respondent may be asked "Why is it important to you to have a bigger kitchen?" The interviewer may receive some responses. Say the response is "I have a big family, and we like to have dinner together". This can be noted in the ladder as "everyday activities" or consequences. More probing may be made to elicit more "consequences".

Determination and coding of means-end chains

The means-end chains will be determined in the interviews. The raw data generated by the laddering interviews are the (transcribe) verbalizations of the respondents. The content analysis will follows the following sequence:-

- Constructing a set of ladders for each respondent.
- Coding the elements of means-end chains based on Schwartz's value domains (Table 1).
- Dividing the elements according to topics and levels in the hierarchy (attribute, consequence, value).
- Constructing summary score matrix. Code numbers will be used to score each element in each ladder producing a matrix with rows representing individual

an individual respondent's ladder. Hierarchical Value Map (HVM) is constructed from this matrix.

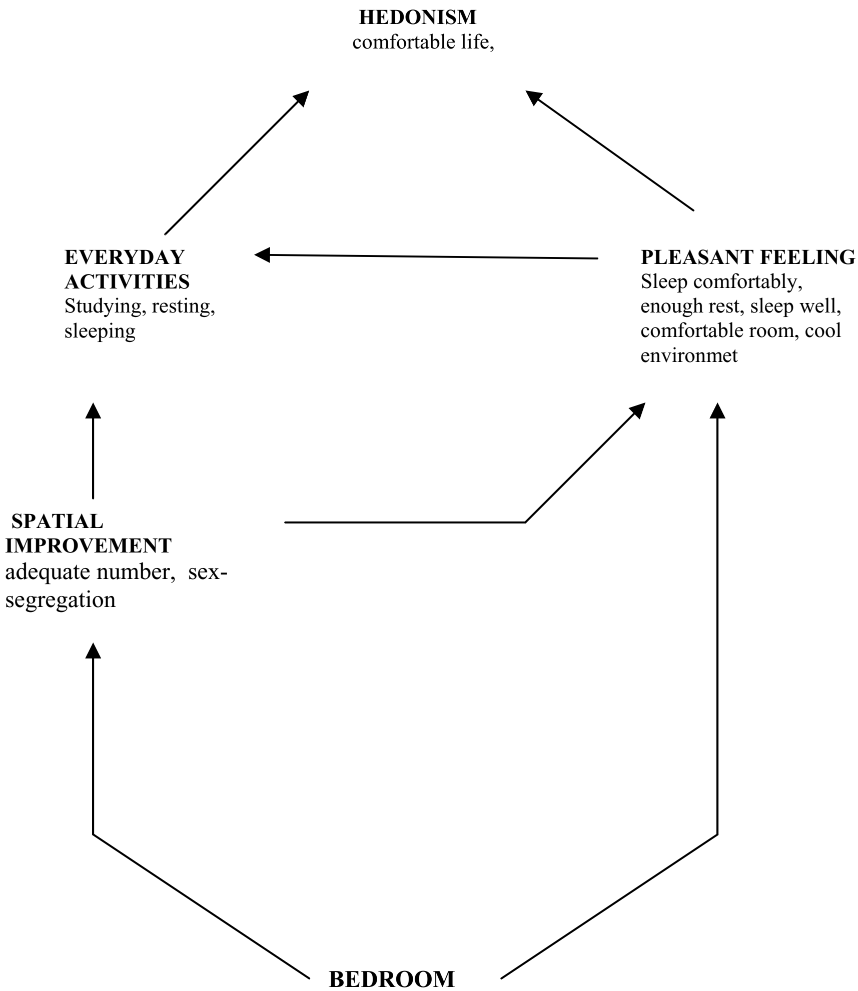
METHODS OF ANALYSIS

The original MEC method of analysis consists of four main stages 1) content analysis 2) The Summary Implication Matrix, 3) Construction the Hierarchical Value Map (HVM), and 4) Interpretation of the HVM (Reynold and Gutman, 2001). The same method can be used, but Mahmud (2007) some modification to the original methods, particularly with regard to content analysis and the construction of the HVM. The tape-recorded interviews of every respondent were transferred into written form. The actual conversations were transcribed exactly the way the sentences were uttered. The transcribed interviews were written in table form for content analysis. Weber's (1985) methods of content analysis were used to support the methods discussed by Reynold and Gutman (2001), and Coolen and Hoekstra (2001).

Summary Implication matrix (SIM) and Construction of hierarchical value map (HVM)

Summary Implication Matrix (SIM) was established from the ladders. The Summary Implication Matrix (SIM) was to display the number of times each element leads to each other element. Before tabulating the elements for SIM, the coded elements were tabulated for frequency of mention.

The result of a means end chain analysis is a hierarchical value map (HVM) or consumer decision map (Reynolds et.al 1994) showing the salient linkages between attributes, consequence, and values for a group of consumers in some product class (Figure 2).



"Chains" in the HVM are constructed from the SIM. To avoid confusion, the term "ladders" refer to the elicitations from individual respondents; the term "chain" is referring to the sequences of elements that emerge from the aggregate in the SIM (Reynold and Gutman, 1988). The technique of constructing a single HVM for all attributes as applied in the traditional method was not used by

Mahmud (2007) in his research to avoid loosing certain important elements. Instead, Coolen and Hoektra's (2001) method in constructing HVM was employed. Hierarchical Value Map for each major attribute was constructed separately. However, Reynold and Gutman (2001) guidelines with regards to types of elements' relation and their validity (or cut-off level) to be mapped in a HVM were applied. As an example, if 4 is used as the cut-off level, attribute having less than four linkages to consequence, will be excluded from the HVM. Inclusion of an attribute in the HVM indicates that the particular attribute is needed by the user values to achieve certain benefits.

Interpretation of the HVM

The method of HVM interpretation explained by Reynold and Gutman (2001) can be adopted with some modifications. The process can be carried out either by observing the items and the linkages they have with other items in the HVM, or by identifying unique pathways linking the main attributes to user values. Identification of unique pathways allows a more meaningful identification of the important attributes, consequences, and user values in the HVM (Reynold and Gutrman, 2001). This was done by tabulating the items included in the pathways, and calculating the frequency of linkages among them. The frequency of linkages was derived from the table of implication matrix. The higher the value of the pathway the more important the items in the pathway were in personalization. This method is able to identify which attributes are more meaningful and relevance to the users, and more appropriate to be considered in house design manipulations.

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Chapter 11