COURTYARD DESIGN VARIANTS FOR OPTIMUM INDOOR THERMAL PERFORMANCE OF SINGLE STOREY FULLY-ENCLOSED COURTYARD HOUSE IN TEMPERATE-DRY CLIMATE OF NIGERIA

MARKUS BULUS

UNIVERSITI TEKNOLOGI MALAYSIA

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MARKUS BULUS

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DEDICATION

Particularly dedicated to GOD ALMIGHTY

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ABSTRACT

Courtyard houses are common in Nigeria due to their numerous benefits, one of which is the ability of the courtyard to enhance the indoor thermal performance of the building. However, such benefit may not be achieved if the appropriate application of the Courtyard Design Variant (CDV) are unknown to the architect, even right from the design stage. While previous studies on CDVs in different climatic regions have been common, the same cannot be said about the temperate-dry climatic zone of Nigeria. Therefore, the aim of this study is to propose the most suitable CDV for optimum indoor thermal performance of single storey fully-enclosed courtyard houses in Nigerian temperate-dry climatic region. The optimum parameters of the CDVs namely Courtyard Shape Factors (CSFs), Courtyard Aspect Ratio (CAR), Orientation, Courtyard Overhang and Window-to-Wall Ratio (WWR) were established and their impacts on indoor thermal comfort were determined. The documentary survey and field measurement methods were used to determine the types of CSFs and CARs and their indoor thermal performances; while the simulation software -Integrated Environment Solution-Virtual Environment (IES-VE) - was used for the simulation experiment. The software was validated with a digital model of the selected case study courtyard house. This study reveals fourteen (14) types of CSFs and CARs. The smaller CSFs were found to have favourable indoor thermal performance than the larger ones. Four (4) optimum CSFs were established and the North-south orientation was established as the optimum of all CSFs models. The optimum courtyard overhang depth and WWR were also determined. This study concluded that smaller CSFs improve indoor thermal performance than the larger ones, while 1200mm courtyard overhang depth and WWR 16% have significant impact on indoor thermal comfort. Finally, CDVs for the design of thermally conducive single storey fully-enclosed courtyard houses in Nigerian temperate-dry climate was proposed. The significance of this study lies in its quest for a conducive courtyard house while the proposed CDV is its main contribution.

ABSTRAK

Halaman dalam rumah adalah biasa di Nigeria kerana banyak faedahnya, salah satu faedah adalah keupayaan halaman untuk meningkatkan prestasi terma dalam bangunan. Walau bagaimanapun manfaat sedemikian mungkin tidak dapat dicapai jika aplikasi Pelbagai Rekabentuk Halaman Dalam (CDV) yang sesuai tidak diketahui oleh arkitek, bahkan dari peringkat reka bentuk. Walaupun kajian terdahulu mengenai CDV dijalankan di kawasan iklim yang berbeza, perkara yang sama tidak boleh dikatakan mengenai zon cuaca sederhana dan kering di Nigeria. Oleh itu, matlamat kajian ini adalah untuk mencadangkan CDV yang paling sesuai untuk prestasi terma dalaman yang optimum bagi halaman tertutup sepenuhnya dalam rumah kediaman setingkat di kasawan iklim sederhana kering di Nigeria. Parameter CDV yang optimum seperti Faktor Bentuk halaman (CSFs); Nisbah Aspek halaman (CAR), Orientasi; unjuran halaman dan Nisbah tingkap-ke-Dinding (WWR) telah dikaji dan kesannya terhadap keselesaan terma dalaman ditentukan. Kaedah dokumentari dan kaedah pengukuran lapangan digunakan untuk menentukan jenis CSF dan CAR dan prestasi terma dalaman mereka, manakala perisian simulasi: Intergrated Environmental Solution – Virtual Environment (IES-VE) digunakan untuk kajian simulasi. Perisian ini telah disahkan dengan model digital bangunan halaman kajian kes yan terpilih. Kajian ini mendedahkan empat belas (14) jenis CSF dan CAR. CSF yang lebih kecil didapati mempunyai prestasi haba dalaman yang lebih menggalakkan daripada yang lebih besar. Empat (4) CSF optimum telah disahkan dan orientasi Utara-Selatan dikenal pasti sebagai optimum untuk semua model CSFs. Kedalaman unjuran halaman dan WWR yang optimum juga ditentukan. Kajian ini menyimpulkan bahawa CSF yang lebih kecil meningkatkan prestasi terma dalaman berbanding denyen yang lebih besar manakala unjuran halaman 1200mm tidak terjejas dan WWR 16% mempunyai kesan yang signifikan terhadap keselesaan terma dalaman. Akhirnya, CDV untuk reka bentuk halaman tertutup sepelnahaya dalam rumah kediaman setingkat yang termal kondusif untuk cuaca sederhana dan kering di Nigeria dicadangkan. Kepentingan kajian ini adalah usaha untuk mendapatkan halaman rumah yang kondusif sementare CDV yang dicadangkan adalah sumbangan utama kajian ini.

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PLEA	-	Passive and Low Energy Architecture
PADS		Passive Architectural Design Strategies
CDV	-	Courtyard Design Variants
CSF	-	Courtyard Shape Factor
CO	-	Courtyard Overhang
WWR	-	Wall-to-Window Ratio
NIA	-	Nigerian Institute of Architects
ARCON	-	Architect Registration Council of Nigeria
CAR	-	Courtyard Aspect Ratio
IES-VE	-	Integrated Environmental Solution and Virtual Environment
GM	.	Greenwich Meridian

CHAPTER 1

INTRODUCTION

1.1 Background of the study

The courtyard is defined as an unroofed space within building which is totally or partly surrounded by the building walls (Amirhosein *et al.*, 2015). It is a space within the building envelop which offers a lot of benefits to the structure and to its occupants. Because of its benefits, its presence in buildings predated 2000 B.C. (Berkovic *et al.*, 2012; Adil, 2001). The benefits of the courtyard to the building include daylighting and cooling, while the occupant also benefits from the visual and thermal performances thereof (Ignacio *et al.*, 2018; Rabia, 2015; Yuan, 2014; Adil *et al.*, 2018; Mohammad, 2018). Due to such, it is considered as a passive component in the architectural design (Lopez *et al.*, 2018; Heras *et al.*, 2005). Most of the early human settlements had the courtyard space incorporated in them. For instance; the ancient residential building of Ur in Mesopotamia, the ancient house of Matmata in Tunisia and that of Beijing in China (Ayhan and Neslihon, 2011; Schoenauer and Seeman, 1962).

An overview of the courtyard house revealed that it is the focal point of the house because most of the rooms of the house are connected with it. The courtyard provide privacy and promotes interraction between the interior rooms with the built environment (Swasti and Bandyopadhyay, 2014). Its not only used as a space for social gathering for the members of the household, but as a source of ventilation and thermal comfort. The courtyard is common to residential buildings in all climes because of its benefits. It comes in different forms, it could be square, rectangular, oval, semi-enclosed, fully-enclosed, or formless (Fatma *et al.*, 2016). The courtyard is a major source of comfort, but, its dimensions and propotions determine its contribution to thermal performance (Muhaisen, 2006a). The amout of shade due to the courtyard-form and ventilation are influence by the courtyard design variants (CDV).

Besides the daylighting and cooling benefits, in most of the African nations and Nigeria in particular, the courtyard house is celebrated because of its traditional inclined benefits rather than its passive ability (Adeyemi, 2008). These benefits include the provision of outdoor space for traditional outdoor functions such as cooking, washing, children playing area, family meetings and privacy for the household. The courtyard promotes the cultural values of the Nigerian people (Adeyemi, 2008).

Although scholars have confirmed that the courtyard is a passive architectural design component, more about its design awareness is required in Nigeria (Akande, 2010; Kabiru 2011). In Nigeria, the electric generator is an alternative source of power for cooling in buildings because of the lack of sufficient power supply. This has led to an overdependence on the use of an electric generator which acts as a major source of environmental pollution (Adediran *et al*., 2015; Uche, 1999). But the courtyard can enhance cooling in buildings because of its passive cooling ability (Manio and Oral, 2015; Abel *et al*., 2004). Therefore, a shift to the passive architectural design approach of buildings may be one of the most suitable alternatives to be considered in Nigeria (Ezeabasili and Okonkwo, 2013).

Studies on Passive and Low Energy Architecture (PLEA) have emphasized the need for architects to adhere to the passive architectural design strategies rather than the active strategies (Havel, 2016; Agboola, 2011; Tablada *et al*., 2005). Givoni (1994) believed that the courtyard is one of the most suitable passive design concepts. According to Tablada *et al*. (2005), the application of the courtyard in the building could enhance indoor thermal comfort. Akande (2010) also concurred with Tablada *et al*. (2005) opinion, he concluded in his study that the use of certain passive design strategies such as the courtyard and suitable building orientation can improve cooling naturally and thereby minimize the energy required for cooling in buildings.

The fully-enclosed courtyard residential building is very common in most of both the ancient and contemporary human settlements in Nigeria (Adetokunbo *et al.*, 2013). Table 1 in Appendix A shows that 61.3% percent of the residential building types in Kafanchan are of the fully-enclosed courtyard building. This is perhaps due to the advocacy of two paramount organizations: the Nigerian Institute of Architects (NIA) and the Architect Registration Council of Nigeria (ARCON). These institutions have emphasized the preservation of traditional architectural design elements rather than a preference for the western style. As revealed by scholars (Ade, 2014; Osasona and Hyland, 2007; Adeokun, 2013; Adetokunbo *et al.*, 2013), the traditional fully-enclosed courtyard residential building can be integrated with the western concept of residential building design to give a mix of the two. They continued that such integration can be achieved when a greater courtyard building design awareness is achieved. Therefore, further design awareness for the effective design of the fully-enclosed courtyard residential buildings in Nigeria will result in the fulfillment of both NIA and ARCON goals. It will promote the delivery of fully-enclosed courtyard residential buildings with conducive indoor thermal performance.

Amirhosein *et al*. (2015) opined that effective courtyard building design could contribute by reducing the long duration of discomfort to shorter duration in a building. Abdulbasit *et al*. (2013a) asserted that the possibility of the courtyard building to effectively modify the indoor thermal condition of the building is realistic only when the key Courtyard Design Variants (CDV) are put into consideration. Therefore, for the courtyard to fulfill its tasks of cooling, thereby providing a conducive indoor thermal condition, the knowledge of the optimum CDVs and their application in courtyard building is required by architects (Kharseh *et al*., 2014).

Researchers have made contributions regarding to the CDV highlighting that it includes; the Courtyard Shape Factor (CSF), Courtyard Aspect Ratio (CAR), Courtyard Overhangs (CO), Window-to-Wall Ratio (WWR), Courtyard Wall Components (CWC), vegetation, Water Pond (WP), and orientation (Enes and Ok, 2014; Aldawoud and Clark, 2008; Mohsen, 1979; Muhaisen, 2006a; and 2006b; Muhaisen and Gabi, 2005a; Muhaisen and Gadi, 2005b; Rajapaksha *et al.*, 2003; Tablada *et al*., 2005; Abdulbasit *et al.*, 2013b, 2014 and 2015; Amirhosein *et al*., 2015;

Safarzadeh and Bahadori 2005; Farzaneh *et al*., 2016a; and Farzaneh *et al*., 2016b; Manio and Oral, 2015; Berkovic *et al*., 2012; Al-Masri and Abu-Hijleh, 2012). The scholars concurred that the knowledge and application of the optimum CDVs in courtyard building design are required in all climates. Despite this surplus studies, further studies on the optimum CDVs for the temperate-dry climatic region of Nigeria is required (Maina, 2013).

Most of the previous studies on CDVs focused on improving the thermal performance of the courtyard space rather than the entire indoor of the courtyard building. Therefore, this study seeks to improve the indoor thermal performance of the single-storey fully-enclosed courtyard residential building in the Nigerian temperate-dry climatic region. The study focused on five CDVs: CSF, CAR, orientation, courtyard overhang, and WWR, because, such variants are very crucial in courtyard building design (Abdulbasit *et al*., 2015; Manio and Oral, 2015). The main purpose of this study is to propose the optimum CDVs for the design of conducive single-storey fully-enclosed courtyard residential buildings.

1.2 Problem Statement

1.2.1 Indoor Thermal Discomfort in Courtyard Residential Buildings

Hot indoor thermal discomfort is a major challenge faced by the occupants of buildings in Nigeria (Eziyi *et al*., 2013; Ruth, 2014; Nasrollahi *et al*., 2017). Thermal discomfort has been a source of concern in residential buildings in Nigeria because of certain factors: hot climatic conditions; the architects poor choice of building components; poor building layout and orientation; insufficient knowledge and application of passive design approach to buildings (the courtyard building in particular), and lack of adherence to urban planning and regulations (Tarek, 2015; Raul, 2015).

The challenge is common to all building types, but, it is more serious in courtyard residential buildings due to the fact that the occupants of such buildings cannot afford to use the active means such as air-conditions, fans, and other mechanical devices for cooling (Adesoji, 2012; Maina, 2013; Tofigh and Begun, 2015). Besides, the active means require power to function and the shortage of electric power supply being experienced in Nigeria has made indoor thermal comfort a serious challenge to all (Osasona, 2012). Also, most of the architects used the courtyard in their residential building design not to benefit from its cooling potential, but, for mere coincidence (Farzaneh *et al*., 2016b).

Abdulbasit *et al*. (2013b), Berkovic *et al*. (2012) and Moonen *et al.* (2011) concurred that the occupants of courtyard residential buildings could experience indoor thermal distress conditions than those of non-courtyard residential building. Antonio and Carvalho (2015) opined that if the knowledge of CDVs is lacking, indoor thermal discomfort may not be avoided in courtyard buildings. Fatma *et al.* (2016) concurred with the opinion of Abdulbasit *et al*. (2013b), Berkovic *et al*. (2012), Nwofe (2014), and Moonen *et al.* (2011). The result of a survey to compare the indoor thermal performance of a courtyard residential building with that of the non-courtyard residential building in Kafanchan confirmed the challenge of hot thermal discomfort in courtyard buildings. As illustrated in Appendix B, the study concluded that hot discomfort in the courtyard building may be due to inappropriate application of the optimum CDVs at the design stage of the courtyard building. Therefore, the application of the optimum CDV for a conducive single-storey fully-enclosed courtyard building in Nigeria is required.

1.2.2 Thermal Performance of the Fully-Enclosed Courtyard Residential Buildings

Meir *et al*. (1995) opined that the thermal performance of the semi-enclosed courtyard is conducive than that of the fully-enclosed courtyard building. This is because of the effect of orientation which seems to have favored the former. This assertion was confirmed by Li *et al.* (2010). In a survey study conducted in Kafanchan, the Hobo Weather Data Logger was used to study the difference in the courtyard and indoor thermal performances between the two courtyard building types. Section 3.3.2.2 in Chapter 3 revealed that the semi-enclosed courtyard residential building performed better due to the effect of orientation. But, the fully-enclosed courtyard residential building type is the most common in Nigeria because it is enshrined in the Nigerian traditional architecture (Adeyemi, 2008). Secondly, the findings of residential building types in a pilot study as revealed in Appendix C showed that the fully-enclosed courtyard building type scored 72.3%. Thus, its optimization for a favorable indoor thermal performance is required in Nigeria.

1.3 Research Gap

Previous research on the courtyard building and its thermal performance had focused mainly on three distinct climatic regions: the hot-dry, hot-humid, and cold temperate climates. Scholars such as Enes and Ok (2014), Abdulbasit *et al.* (2013b), Abdulbasit *et al.* (2015), Berkovic *et al.* (2012) and Manio & Oral (2015) conducted their studies on the hot-dry climate, while Muhaisen (2006a), Muhaisen (2006b), Muhaisen and Gadi (2005a), Muhaisen and Gadi (2005b), Rajapaksha *et al*. (2003), Mohsen (1979), Safarzadeh and Bahadori (2005), Aldawoud and Ray (2008), Aldawoud and Clark (2008) focused on the hot-humid climate. Other studies such as Abdulbasit *et al*. (2014) and Al-Masri & Abu-Hijleh (2012) were on the cold temperate climate. But, little has been said on the temperate-dry climatic region, particularly, that of Nigeria.

The scholars have agreed that the CDVs affect the thermal performance of the courtyard building. But, most of the studies considered the courtyard outdoor thermal performance rather than the indoor thermal performance of the entire building (Enes and Ok, 2014; Abdulbasit *et al.,* 2013; Abdulbasit *et al.,* 2015; Berkovic *et al.,* 2012; Manio and Oral, 2015; Muhaisen, 2006a; Muhaisen, 2006b). Courtyard optimization for better thermal performance is important, but the impact of such optimization on the indoor thermal performance of the building is much better because most of the functions performed in a building are being conducted inside the building rather than in the courtyard space alone. Only a few of the studies focused on determining the optimums of the CDVs. Mosen (1979) and Manio and Oral (2015) were able to determine the optimums, but their studies were not focused on the temperate-dry climates. They focused only on the optimum of the courtyard geometry. However, they concurred that the impact of such CDVs on the thermal performance of the courtyard is very significant.

Another issue with the previous studies is that the scholars (Abdulbasit *et al.,* 2013a; Abdulbasit *et al.,* 2015; Berkovic *et al.,* 2012; Muhaisen, 2006a; Muhaisen, 2006b; Muhaisen and Gadi, 2005a; Muhaisen and Gadi, 2005b; Rajapaksha *et al*., 2003; Tablada *et al*., 2005; Safarzadeh and Bahadori, 2005; Al-Masri and Abu-Hijleh, 2012; Amirhosein *et al*., 2015) seem to have emphasised more on the CAR and little attention has been given to the CSF. This connotes that most of the studies were not focused on the single-storey courtyard building because CAR refers to the relationship between the height and width of the courtyard building. Furthermore, the majority of such studies have only been carried out in the developing countries of Asia, such as Malaysia, Iran, Turkey, and Israel. African countries and Nigeria, in particular, should have been focussed because they are underdeveloped and the courtyard building is being celebrated there.

The single-storey (3,000mm height) fully-enclosed courtyard residential building type is the most common in Nigeria (Adeokun, 2013). Therefore, this research focuses on the single-storey fully-enclosed courtyard residential building in the Nigerian temperate-dry climatic region. It seeks to investigate the optimums of the CDVs: CSF, CAR, orientation, courtyard overhang, and Window-to-Wall Ratio. Finally, a comparison of all previous studies related to this study to further highlight the research gap that this thesis seeks to fill is presented in Table 1.1.

Table 1.1 Summary of previous research in courtyard building optimization

Authors	Methods			Climates				Courtyard Design Variants								Performance Variables						
	Survey	Measurement	Simulation	Hot-Dry	Hot-Humid	Cold	Temperate-Dry	Courtyard Shape Factor	Courtyard Aspect Ratio	Orientation	Courtyard Overhang	Window-to-Wall Ratio	Materials & Openings	Vegetation	Water Pond	Air Speed	Solar Radiation	Shading	Energy	Air	Relative	Mean Radiant Temperature
Enes & Ok (2014)		√	√	√				√									√		√			
Abdulbasit *et al*. (2013)		√	√	√					√	√										√		
Abdulbasit *et al*. (2015)			√	√					√							√				√		
Berkovic *et al*. (2012)		√	√	√					√									√		√		
Manio & Oral (2015)		√	√	√				√		√			√						√			
Muhaisen (2006a)			√		√				√									√		√		
Muhaisen (2006b)		√	√		√				√	√	√							√				
Muhaisen & Gabi (2005a)			√		√				√									√				

Table 1:1 Summary of previous research in courtyard building optimization (continued)

Authors	Methods			Climates				Courtyard Design Variants								Performance Variables						
	Survey	Measurement	Simulation	Hot-Dry	Hot-Humid	Cold	Temperate-Dry	Courtyard Shape Factor	Courtyard Aspect Ratio	Orientation	Courtyard Overhang	Window-to-Wall Ratio	Materials & Openings	Vegetation	Water Pond	Air Speed	Solar	Shading	Energy	Air	Relative	Mean Radiant Temperature
Muhaisen & Gabi (2005b)			√		√				√									√				
Rajapaksha *et al*. (2003)		√	√		√				√							√				√		
Tablada *et al*. (2005)		√	√		√				√	√						√			√	√		
Mohsen (1979)			√		√			√									√		√			
Safarzadeh & Bahadori			√		√				√	√						√				√		
Aldawoud & Ray (2008)		√	√		√	√							√						√			
Aldawoud & Clark (2008)		√	√		√	√							√						√			
Farzaneh *et al*. (2016)	√	√				√				√				√	√	√						
Farzaneh *et al*. (2016b)	√	√				√				√				√	√	√	√					

Table 1:1 Summary of previous research in courtyard building optimization (continued)

	Methods			Climates				Courtyard Design Variants								Performance Variables						
Authors	Survey	Measurement	Simulation	Hot-Dry	Hot-Humid	Cold	Temperate-Dry	Courtyard Shape Factor	Courtyard Aspect Ratio	Orientation	Courtyard Overhang	Window-to-Wall Ratio	Materials & Openings	Vegetation	Water Pond	Air Speed	Solar Radiation	Shading	Energy	Air Temperature	Relative Humidity	Mean Radiant Temperature
Abdulbasit *et al.* (2014)		√				√		√								√	√			√		
Al-Masri & Abu-Hijleh (2012)		√	√			√			√		√								√			
Amirhosein *et al.* (2015)		√	√		√				√	√									√			
Present Study	√	√	√				√	√	√	√	√	√								√	√	√

1.4 Research Questions

This thesis provided answers to the following research questions: -

a) What are the types of CSFs and CARs as well as their impact on the indoor thermal performance of the single-storey fully-enclosed courtyard residential buildings in temperate-dry climate?

b) What are the optimum CSFs and CARs for indoor thermal performance of single-storey fully-enclosed courtyard residential buildings in temperate-dry climate?

c) What is the optimum orientation for indoor thermal performance of single-storey fully-enclosed courtyard residential buildings in temperate-dry climate?

d) What is the optimum courtyard overhang depth for indoor thermal performance of the single-storey fully-enclosed courtyard residential buildings in temperate-dry climate?

e) What is the optimum WWR for indoor thermal performance of single-storey fully-enclosed courtyard residential buildings in temperate-dry climate?

1.5 Research Aim and Objectives

The aim of this study is to propose optimum CDVs for the design of conducive indoor thermal performance of single-storey fully-enclosed courtyard residential buildings in the Nigerian temperate-dry climatic region. In order to achieve the above-mentioned aim, this research seeks to accomplish the following objectives:

(a) To investigate the types of CSFs and CARs in single-storey fully-enclosed courtyard residential buildings (1a), and to compare their indoor thermal performance (1b).

(b) To determine the optimum CAR, CSF, and orientation for indoor thermal performance.

(c) To assess the impact of courtyard overhang depths on the CSFs.

(d) To evaluate the impact of WWR with the CSFs.

(e) To propose optimum CDV for single-storey fully-enclosed courtyard residential building in Nigeria temperate-dry climate.

1.6 Research Hypothesis

The indoor thermal performance of single-storey fully-enclosed courtyard residential buildings in Nigerian temperate-dry climatic region can be improved by using the optimum CDVs such as:

(i) Using optimum courtyard geometry (CAR and CSF).

(ii) Choosing the optimum courtyard orientation.

(iii) Applying the optimum courtyard overhang depth.

(iv) Selecting the optimum window size.

Figure 1.1 illustrates the relationship of the CDVs with the indoor space of the courtyard building. This hypothesis may improve the indoor thermal performance of the single-storey fully-enclosed courtyard building in the temperate-dry climatic region of Nigeria.

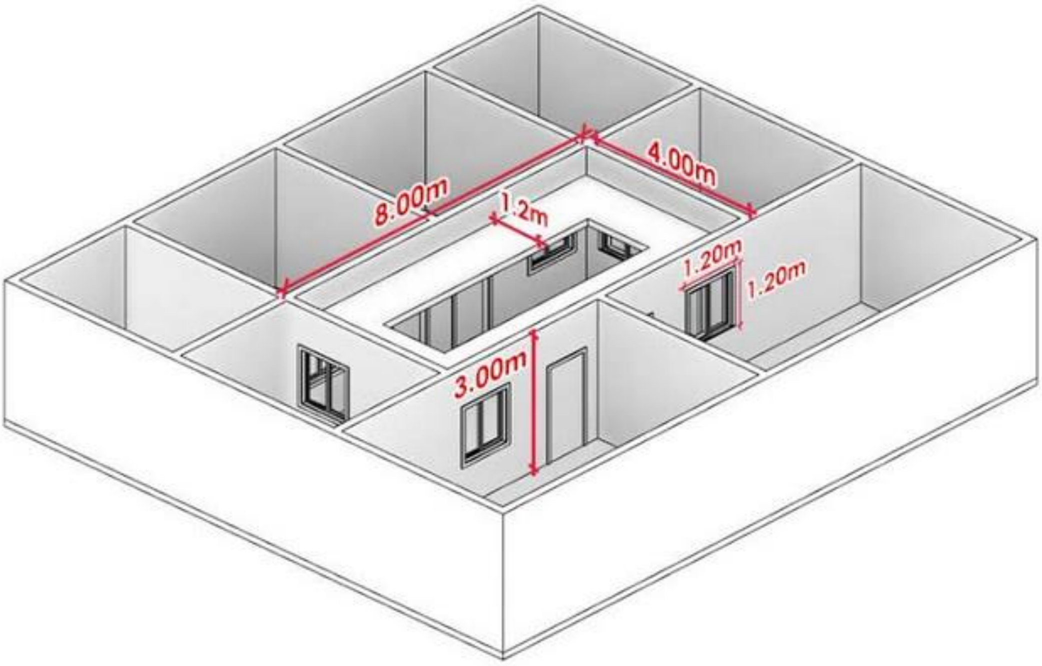

Figure 1.1 Relationship of CDVs for optimum indoor thermal performance

1.7 Research Scope

This study covers only the single-storey fully-enclosed courtyard residential building type. It was chosen because it is the most common in Nigeria (Adetokunbo *et al*., 2013). It is rooted in the architecture of the residents of the study are (Appendix A and C). The indoor thermal performance of the courtyard building is the main issue that this study addressed.

Appendix C shows that 72.3% of courtyard buildings in the study area are of the fully-enclosed courtyard type, while 27.7% are of the semi-enclosed. The fully-enclosed courtyard residential building was chosen because it is the most commonly used by the people. Its choice for this study was not based on this fact alone. A further comparison of its indoor thermal performances with the semi-enclosed courtyard building was required because this will further identify the most conducive courtyard building type. The fully-enclosed was used because its thermal performance was worse.

The study covers the entire temperate-dry climatic region of Nigeria with latitude 8^{o}N – 11^{o}N and longitude 3^{o}E-15^{o}E. The study parameters did not cover all the CDVs. Only CSF, CAR, orientation, courtyard overhang, and WWR were considered. The study employed a documentary survey, field measurement and simulation methods to achieve its aim. The limitations of this study are discussed in Chapter 5 Section 5.4.

1.8 Research Significance

The need for more information on courtyard building design awareness, especially the single-storey fully-enclosed courtyard residential building in Nigeria cannot be overstated. Even though the Nigerian architects have been using the courtyard concept in their design of residential buildings, a greater design awareness is required, and this study has contributed by adding to the existing knowledge.

This study has proposed the optimum CDVs for the effective design of the single-storey fully-enclosed courtyard residential building in the Nigerian temperate-dry climatic region. It recommended the optimums of CSFs, CARs, orientation, courtyard overhang depth, and WWR. With these findings, therefore, a more conducive single-storey fully-enclosed courtyard house can be achieved. The application of the recommendations of this study will definitely mitigate the challenge of hot indoor thermal discomfort encountered by the occupants of courtyard buildings, and thereby, effectively enhancing their well-being and productivity. The overdependence on the use of electric generators as an alternative source of generating power for cooling in buildings in Nigeria can be reduced too.

Finally, this study has opened the window by providing the research background for future courtyard building studies in Nigeria, particularly the Nigerian temperate-dry clime. The methodology of this study, especially the field measurement and simulation methods have provided a new research approach for scholars in Nigeria. Due to such, future allied courtyard building studies in Nigeria can refer to this thesis for critical review and information gathering.

1.9 Structure of the Thesis

This thesis is made up of five chapters. The **First Chapter** introduces the key issues and emphasis of this study. It discusses the problems which it has addressed, research questions, aim and its objectives and the research hypothesis. The scope, limitations, and significance of the study are all discussed. The overall organization of the thesis is considered.

The **Second Chapter** reviews the previous studies on courtyard buildings. A review of the courtyard house type was discussed. The courtyard house in Nigeria: the northern and southern viewpoints were achieved. Adaptation of the courtyard in contemporary Nigerian architectural design with its benefits was discussed. A review of previous studies on the CDVs such as the CSF, CAR, courtyard overhang depths, WWR, and orientation of the courtyard was studied. The impact of the CDVs on courtyard building thermal performance was equally examined. Thermal comfort, its parameters, and the study parameters were discussed. The climate of Nigeria is reviewed. A survey study was conducted to justify the choice of the courtyard house-type for this study (Appendix A, B, and D). A review of the methodology adopted in previous courtyard building studies and the one adapted for this thesis was considered.

The **Third Chapter** consists of three (3) major parts. The first part considered the research approach, design and methods (Section 4.2). The second part is the research methodology for this study (Section 4.3). Details of the research methods, IES-VE software validation, and the simulation procedure were discussed (Section 3.3). The analysis of results and discussion of findings constitutes the last part (Section 3.4) of the chapter.

The **Fourth Chapter** presents, analyzes and discusses the results of the study. The types of CSFs, CARs and their impact on the indoor thermal performance of the courtyard building were investigated. The optimums of the CDV: CSF, CAR, courtyard overhang depth; orientation and Window-to-Wall Ratio were determined. CDVs proposal for a conducive single-storey fully-enclosed courtyard residential building for the temperate-dry climatic region of Nigeria was suggested.

Finally, **Chapter Five** recaps the whole study objectives and findings. The application of such findings in single-storey fully-enclosed courtyard residential buildings in the temperate-dry climatic region of Nigeria was discussed. A number of recommendations for future studies are outlined. Figure 1.2 is the organization and flow of this thesis.

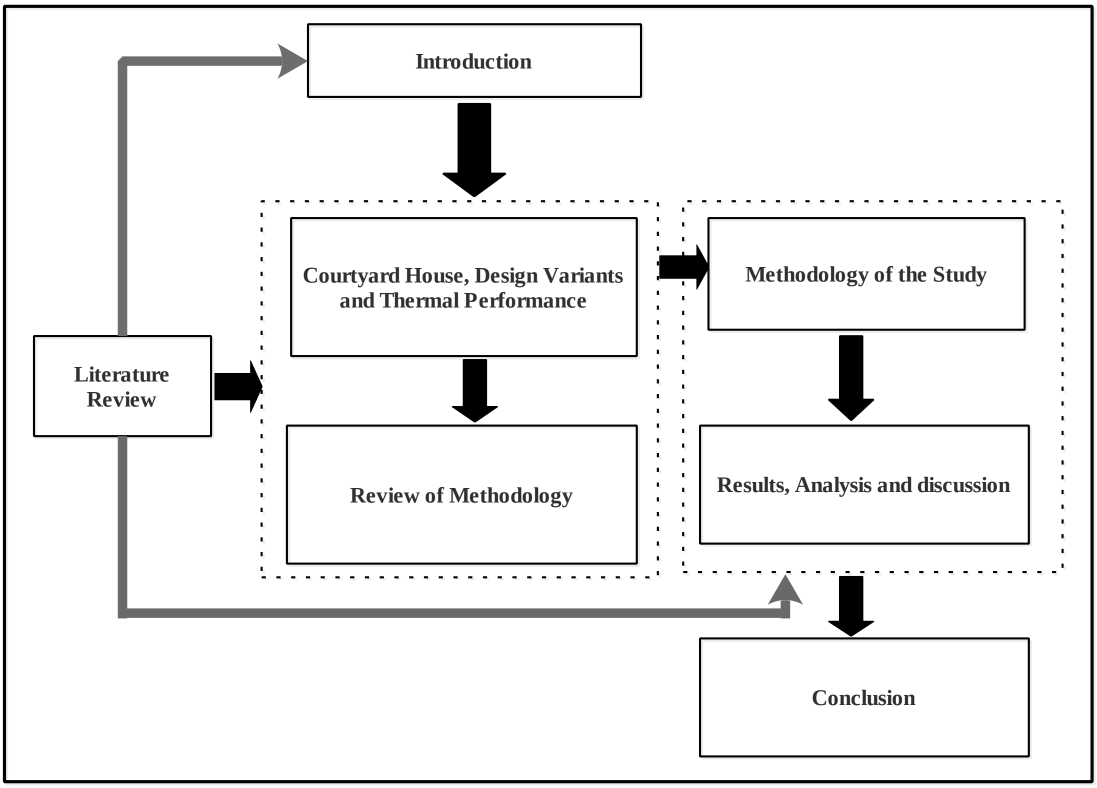

Figure 1.2 Organization and flow of thesis writing

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APPENDIX A

TYPES OF RESIDENTIAL BUILDINGS IN STUDY AREA (KAFANCHAN)

Figure A(1) and Figures A(2-5) show a copy of the survey sheets for residential buildings and fully-enclosed courtyard buildings respectively, while Figure A(6-74) are the photos of all the 69 courtyard building surveyed. Table A.1 and A.2 are the summary of the results while Figures A (75-78) are the maps of the study area showing the survey area and buildings. Figures A (79-83) are the type of residential buildings in the study area.

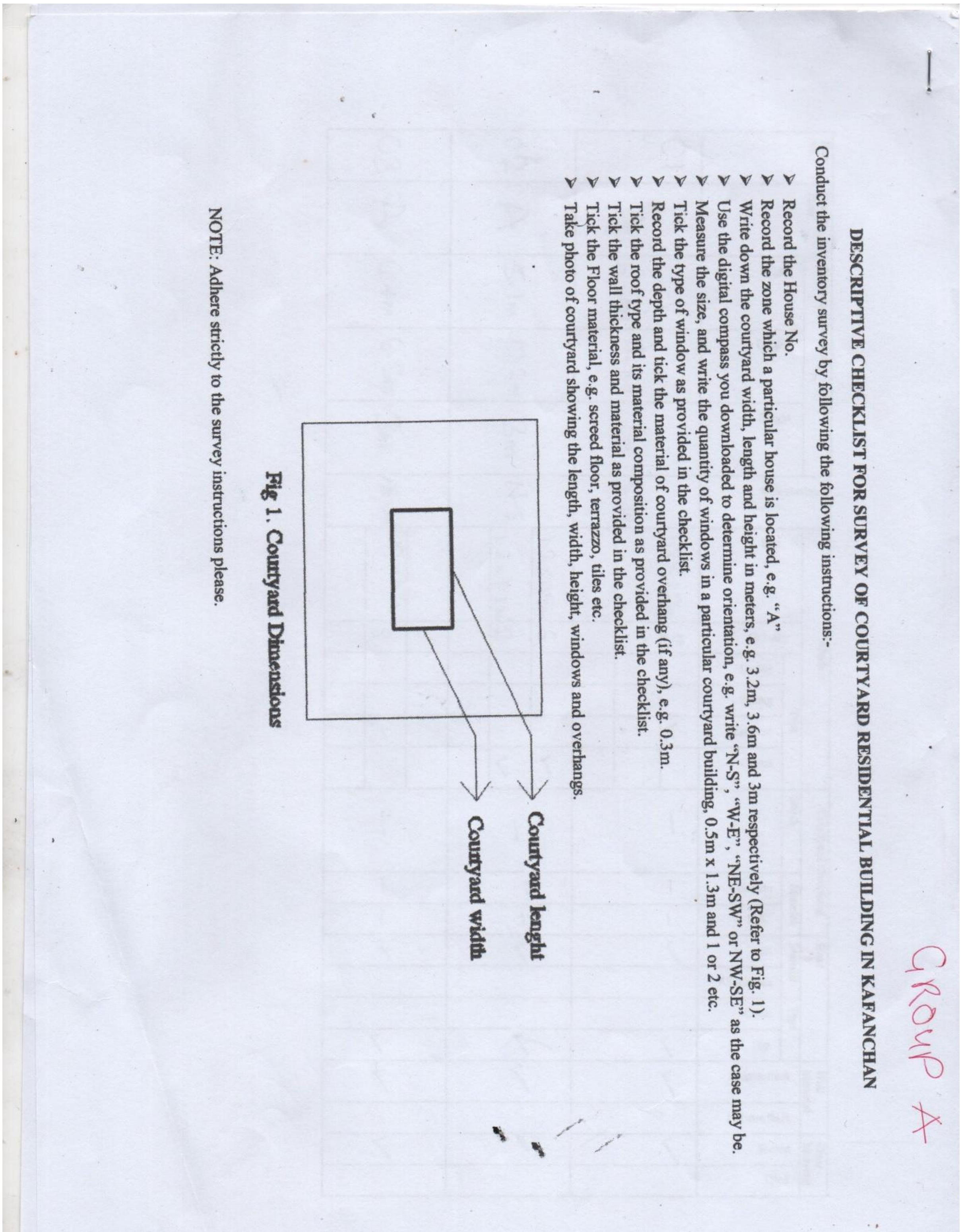
1

DESCRIPTIVE CHECKLIST FOR SURVEY OF RESIDENTIAL BUILDINGS IN KAFANCHAN

S/No	Residential Area			House-type						Storey Height
	Low-Density	High-Density	GRA	Apartment house	Courtyard house		Family house	Comp house	Duplex	
					S	F				
1						✓				1
2						✓				1
3						✓				1
4						✓				1
5				✓						1
6						✓				1
7						✓				1
8							✓			1
9							✓			1
10							✓			1
11							✓			1
12							✓			1
13							✓			1
14							✓			1
15							✓			1
16						✓				1
17						✓				1
18							✓			1
19							✓			1
20						✓				1
21						✓				1
22							✓			1
23						✓				1
24						✓				1
25						✓				1
26							✓			1
27							✓			1
28				✓						1
29				✓						1
30						✓				1
31						✓				1
32							✓			1
33							✓			1
34							✓			1
35							✓			1
36							✓			1
37									✓	1
38				✓						1
39						✓				1

NOTE: S = Semi-Enclosed Courtyard, F = Fully-Enclosed Courtyard

Figure A(1): A Copy of Survey Sheet for Residential Buildings in Study Area



GROUP A

DESCRIPTIVE CHECKLIST FOR SURVEY OF COURTYARD RESIDENTIAL BUILDING IN KAFANCHAN

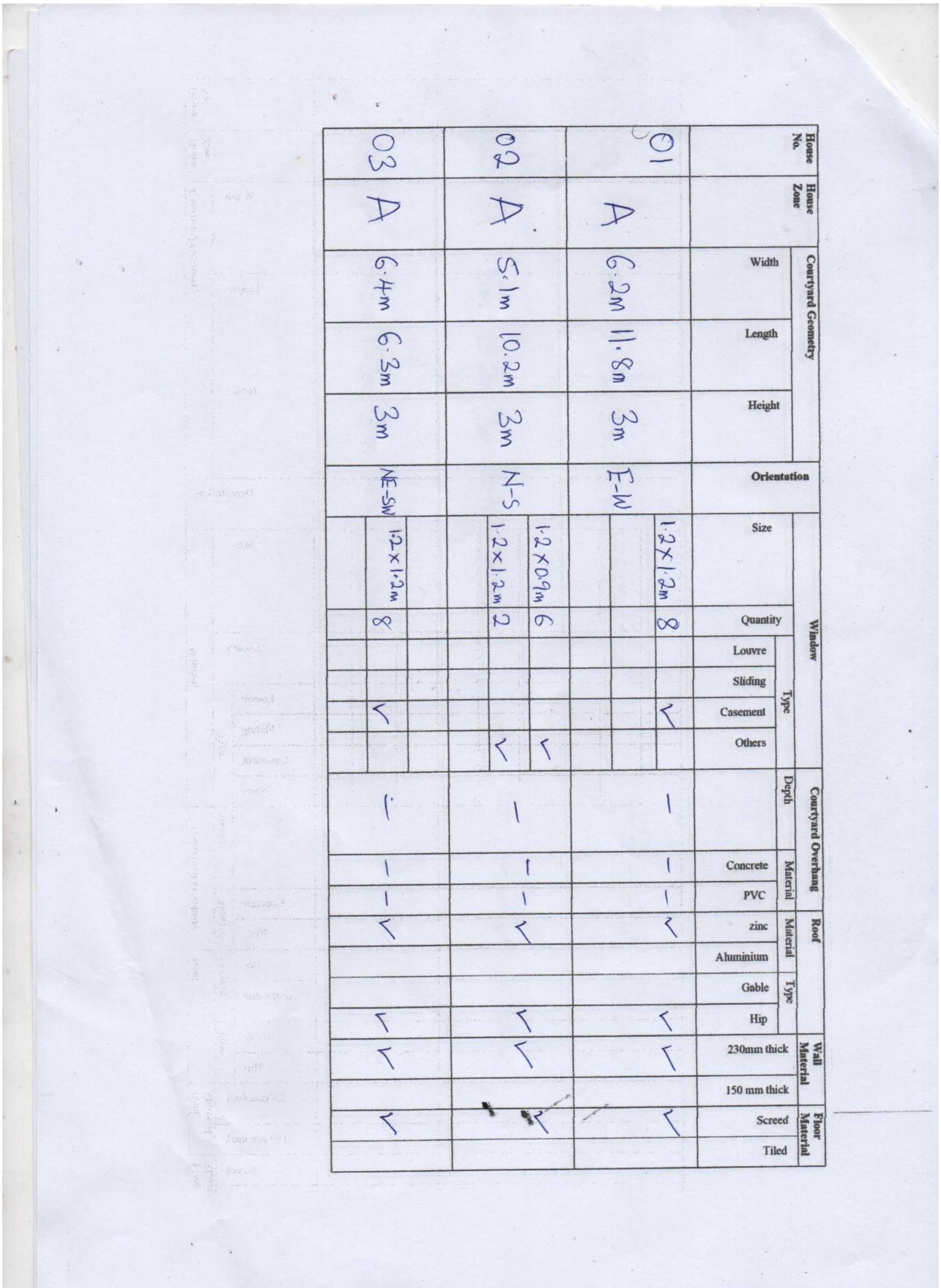
Conduct the inventory survey by following the following instructions:-

- Record the House No.
- Record the zone which a particular house is located, e.g. "A"
- Write down the courtyard width, length and height in meters, e.g. 3.2m, 3.6m and 3m respectively (Refer to Fig. 1).
- Use the digital compass you downloaded to determine orientation, e.g. write "N-S", "W-E", "NE-SW" or NW-SE" as the case may be.
- Measure the size, and write the quantity of windows in a particular courtyard building, 0.5m x 1.3m and 1 or 2 etc.
- Tick the type of window as provided in the checklist.
- Record the depth and tick the material of courtyard overhang (if any), e.g. 0.3m.
- Tick the roof type and its material composition as provided in the checklist.
- Tick the wall thickness and material as provided in the checklist.
- Tick the Floor material, e.g. screed floor, terrazzo, tiles etc.
- Take photo of courtyard showing the length, width, height, windows and overhangs.

Fig 1. Courtyard Dimensions

NOTE: Adhere strictly to the survey instructions please.

Figure A(2): A Copy of Survey Sheet for Fully-Enclosed Courtyard Buildings

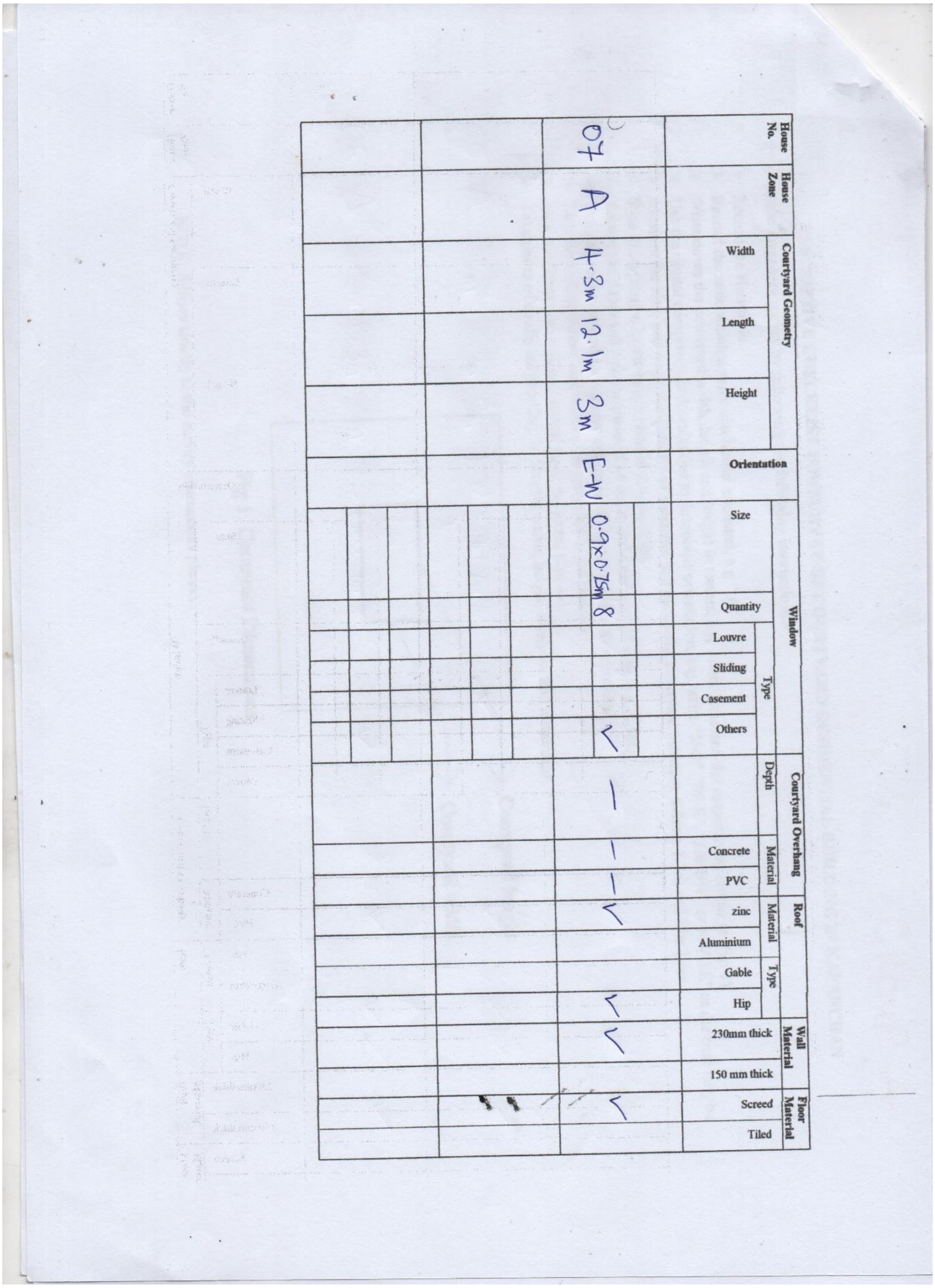


House No.	House Zone	Courtyard Geometry: Width	Courtyard Geometry: Length	Courtyard Geometry: Height	Orientation	Window: Size	Window: Quantity	Window Type: Louvre	Window Type: Sliding	Window Type: Casement	Window Type: Others	Courtyard Overhang: Depth	Courtyard Overhang Material: Concrete	Courtyard Overhang Material: PVC	Roof Material: zinc	Roof Material: Aluminium	Roof Type: Gable	Roof Type: Hip	Wall Material: 230mm thick	Wall Material: 150 mm thick	Floor Material: Screed	Floor Material: Tiled
01	A	6.2m	11.8m	3m	E-W	1.2×1.2m	8			✓		-	-	-	✓			✓	✓		✓	
02	A	5.1m	10.2m	3m	N-S	1.2×0.9m	6				✓	-	-	-	✓			✓	✓		✓	
						1.2×1.2m	2				✓											
03	A	6.4m	6.3m	3m	NE-SW	1.2×1.2m	8			✓		-	-	-	✓			✓	✓		✓	

Figure A(3): A Copy of Survey Sheet for Fully-Enclosed Courtyard Buildings

House No.	House Zone	Courtyard Geometry			Orientation	Window						Courtyard Overhang			Roof				Wall Material		Floor Material	
		Width	Length	Height		Size	Quantity	Type: Louvre	Sliding	Casement	Others	Depth	Material: Concrete	PVC	Material: zinc	Aluminium	Type: Gable	Hip	230mm thick	150 mm thick	Screed	Tiled
04	A	5m	14.9m	3m	E-W	1.2x0.9m	12	✓				–	–	–	✓			✓	✓		✓	
05	A	5m	15.2m	3m	E-W	0.9x0.75m	10			✓		–	–	–	✓			✓	✓		✓	
06	A	5.3m	15.3m	3m	N-S	1.2x0.9m	8				✓	–	–	–	✓			✓	✓		✓	

Figure A(4): A Copy of Survey Sheet for Fully-Enclosed Courtyard Buildings



House No.	House Zone	Courtyard Geometry: Width	Courtyard Geometry: Length	Courtyard Geometry: Height	Orientation	Window: Size	Window: Quantity	Window Type: Louvre	Window Type: Sliding	Window Type: Casement	Window Type: Others	Courtyard Overhang: Depth	Courtyard Overhang Material: Concrete	Courtyard Overhang Material: PVC	Roof Material: zinc	Roof Material: Aluminium	Roof Type: Gable	Roof Type: Hip	Wall Material: 230mm thick	Wall Material: 150 mm thick	Floor Material: Screed	Floor Material: Tiled
07	A	4·3m	12.1m	3m	E-W	0·9x0·75m	8				✓	–	–	–	✓			✓	✓		✓	

Figure A(5): A Copy of Survey Sheet for Fully-Enclosed Courtyard Buildings