ARCHITECTURE DEPARTMENT **CHINESE UNIVERSITY OF HONG KONG**

MASTER OF ARCHITECTURE PROGRAMME 2008-2009 DESIGN REPORT

THE GRAMMAR OF SULTANATE MOSQUES IN BENGAL ARCHITECTURE

KABIR Nujaba Binte Nov 2009

The Grammar of Sultanate Mosques in Bengal Architecture

KABIR, Nujaba Binte

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Philosophy
in
Architecture

The Chinese University of Hong Kong

November 2009

The Grammar of Sultanate Mosques in Bengal Architecture

Submitted By: Nujaba Binte Kabir
for the Degree of Master of Philosophy in Architecture
at The Chinese University of Hong Kong in June 2009.

Abstract

Bengal (both Bangladesh and West Bengal of India), which is a deltaic region of the three big rivers, includes one of the most heavily populated concentrations of Muslims in the world and is isolated from the core land of Islamic civilization. Almost three quarters mosques were built in Bengal during independent Sultanate period (1342 to 1576). The characteristics of these mosques have changed a lot over time compared to the typical features of Islamic architecture. Instead of importing the features of Islamic architecture Bengali integrated the elements found in the tradition, developed the characteristics of the mosques using the local features of their houses and the locally available materials. The architectural historians are trying to classify and differentiate the features of Islamic architecture based on the climate, geography and the cultural conditions of Bengal from decade to decade in a traditional way rather than emergent generation of a style.

But this analysis has no methodology to analyze a design in details to understand a style and does not show how a form can be constructed. Shape grammar which had been explored by Stiny & Gips (1972) is a rule based methodology for analyzing and generating designs of any style by using distinct features of that style to formulate a set of rules and that are also appropriate to the design generation techniques for generating languages of architectural designs with shape grammar have been studied in many research projects that include Frank Lloyd Wright's Prairie houses, the traditional Turkish houses, Central Asian Caravanserai and much more. The common aspects of these studies are to explain a language of designs in the style in a generative explanation by studying a given corpus of that style.

The aim of the study is to develop a grammar for Sultanate Mosques in Bengal architecture to give a new framework of understanding the style systematically by studying a corpus of mosques. Shape grammar methodology will be used to develop the grammar for Sultanate Mosques with the help of a shape grammar interpreter, Grammar Environment (Li et al, 2009). To develop and to run the grammar this interpreter has been used in this research. Along with generating designs the interpreter helps to organize the rules systematically and guides to choose the rules sequentially. The grammar will not only generate the new examples of the style but also give an explanation whether new examples belong to that style or not.

摘要

孟加拉 (包括孟加拉共和國及印度的西孟加拉)，是一個三江滙聚的三角洲，這地區雖然包含了世界上其中一個最多穆斯林聚集的地方，但遠離伊斯蘭文明的腹地。孟加拉約四分之三的清真寺建造於獨立王朝時期（1342-1576）。與典型的伊斯蘭建築比較，這時期的清真寺的特徵有很大的變化。除了輸入伊斯蘭建築的特點外，孟加拉人還融入了傳統的元素，清真寺吸收當地民居的特色，使用當地可得的材料，發展出自己的特點。現在的建築史家仍然利用孟加拉的氣候，地理因素以及文化狀況等沿用已久的傳統手法，為伊斯蘭建築分類以及區分特色，不涉及建築風格是如何發展而成的。可是這樣既不能通過深度的分析一個設計來理解建築風格，也不能解釋一種建築形態的是如何被建造的。

Stiny & Gips (1972) 探索了形狀語法（Shape grammar）。它是一個以準則為基礎的研究和設計方法。利用某一建築風格的特徵編寫一套準則，不但可以作為分析建築的工具，也是設計生產的技術。已經有多個研究項目利用形狀語法為建築生成設計語法，其中包括法蘭克洛伊萊特的大草原風格建築、土耳其傳統民居、中亞的商隊旅館等等。這些研究的共通點是利用已知建築風格中的實例來解釋該建築風格的設計語言。

本研究的目的是開發孟加拉建築中的王朝時期清真寺的建築語法，提供一個系統的新框架來理解清真寺的實例。這文法不只可以創造滿足此建築風格的新建築，更可以解釋這些新建築是否屬於此建築風格。

Acknowledgement

I acknowledge my sincere gratitude to my research supervisor Professor Andrew I Kang LI for his generous guidance and constructive suggestions at every stage of my work. It has been a pleasing experience to work under his supervision. I am also thankful for the thoughtful comments and suggestions of my former colleagues in shape grammar team: Wang Yang and Chen Liang. Especially, I thank Wang Yang for being extremely helpful to make me understand the Shape grammar methodology as I was completely new in the field.

I also want to deeply thank Mr. Maruf Hossain, Department of Architecture, Khulna University, Khulna, Bangladesh, who supplied me with the drawings of the mosques and offered his full co-operation in this research. I am also thankful to Mr. Tareef Hayat Khan, Department of Building and Real Estate, The Hong Kong Plytechnic University, and to my all former teachers of Ahsanullah University of Science & Technology, Dhaka, Bangladesh, especially Dr. M.A.Muktadir, Head of the Department and Dr. Jesmeen Ara, Mr. Mahfil Ali for encouraging me a lot for my study.

This would not have been possible without love, support and encouragement of my parents, my sister and my in- laws. I gratefully acknowledge the encouragement of my husband Dr. Kawser Ahmed and my little daughter Fairuz for helping me to complete the study.

TABLE OF CONTENTS

List of Figures

Introduction

The Islamic civilization has enormous and various involvement in the field of architecture. Depending on climate, geographical condition and availability of the materials Islamic architecture has its own characteristics in different regions. Bengal, which is a deltaic region of many rivers, is one of the most heavily populated concentrations of Muslims in the world and isolated from the core land of Islamic civilizations (Michell, 1984).

Islamic civilization already had passed half a millennium when it arrived in Bengal in 1203. From 1342 to 1576 was the period of independent Sultanate in Bengal and afterwards was the period of Mughal. During 1450 to 1550 almost three quarters of all the existing Sultanate mosques were built in Bengal (Hasan, 1989).

The characteristics of these mosques have changed a lot compared to the typical features of Islamic architecture. Instead of using minaret Bengalis used low domes, low facades and curved cornices in to their mosque (Michell, 1984). In Turkish mosque, stone had been used as the main building material where as in Bengal brick and terracotta decoration, was the main material for the enclosure. During this period square plan mosques were much more popular in Bengal than the long rectangular Turkish mosque. Actually Bengalis did not import the features of Islamic architecture but they integrated the elements found in the tradition. They developed the characteristics of the mosque using the local features of their houses and the local materials like brick (Hassan, 1989).

The architectural historians are trying to classify and to differentiate the features of Islamic architecture on the basis of climatic, geographic and the cultural conditions of Bengal.

Analysis done by architectural historian:

Architectural historians have been studying the Islamic architecture from decade to decade. Nath in his book "History of Sultanate Architecture" in 1978 described the mosques according to the influence of the ruling *Sultans*. How did these rulers express their dignity through these mosques? He described the characteristics very briefly and focused on the Sultanate mosques in the world.

The book "The Islamic Heritage of Bengal" edited by George Michell in 1984 contains research papers on 'Protection of the cultural heritage' launched by UNESCO. The papers depend on the overall survey of the Bengali mosques. With these field reports we can see the unity of tradition among the mosques of Bangladesh and West Bengal (India). These reports not only give the finite numbers of sultanate mosque in Bengal but also differentiate them according to their characters. It is also possible to know about the distinctive features of the Sultanate period through these field reports.

In the book "The early Muslim Architecture of Bangladesh Sultans and Mosques" Parween Hasan in 1989 has mainly described the Islamic architecture of South Asia. Bengal and its rulers had developed their own form before the Mughal style came to dominate South Asia. Through this book the author represented the most important features of the Islamic architecture of Bengal of the Independent Sultanate period (from the 14th to the 16th centuries). She described that the distinctive style of this region has an inspiration from the vernacular architecture of Bengal. In her book the author tried to illustrate all Bengal mosques in detail with necessary drawings and photographs. She also showed that this early Muslim architecture of Sultanate period in Bengal is unique in its character compared to the other Islamic architecture and even to the Mughal architecture.

But all those analysis has no explicit theory to understand a style comprehensively. Usually the mosque architecture has been analyzed in terms of their design elements or features. But this type of analysis only described the features separately. There should be some method which can identify and relate these features to each other explicitly. Shape grammar analysis is the method which not only generates the design in the style but also demonstrates every part and features of the design and relates to each other and explains its overall geometry. Traditional analysis only deals with those lists which belong to the styles, i.e. the corpus. On the other hand shape grammar analysis can generate new examples of the style that are not in the original corpus. Shape grammar could be a method to give a precise theory by developing a grammar for these Bengal mosques.

Traditional analysis has no methodology to analyze a design in details to understand a style and does not show how a form can be constructed. Koning and Eizenberg (1981, p295) had mentioned:

> "Architectural historians have typically been more interested in tracing sources of influences and technological advances in building construction than in uncovering and elucidating the compositional structure of designs."

Shape grammar method is an alternative method to analyze any architectural style of an architect or of a period. Analytical shape grammar is a formal and generative methodology for analyzing and generating designs of an architectural style. A set of rules is developed by using distinct features of that style. The grammar deals with every detail of the style. Shape grammar, which is a rule based methodology, is appropriate to the design generation techniques (Ahmed & Chase, 2004).

Stiny and Gips (1972) introduced shape grammar to analyze a design style. Stiny and Mitchell have described (1978, P17) this approach in the following way:

> "When several buildings each create a similar impression, they are said to exemplify a particular architectural *style*. Given a finite corpus of buildings that are perceived to be alike in some sense, the problem of style consists of characterizing the basis of this likeness. Ideally this characterization has three main purposes:1)It should clarify the underlying commonality of structure and appearance manifest for the buildings in the corpus. 2)It should supply the conventions and criteria necessary to determine whether any other building not in the original corpus is an instance of the style; and 3)It should provide the compositional machinery needed to design new buildings that are instance of the style."

It means that Stiny and Mitchell (1978) propose three criteria to evaluate the theory to understand a style. If I simplify those criteria they can be stated as follows:

- It should give a new example in the style.
- It should have the criteria to test whether a new example belongs to the original style or not.
- It should give the explanation of the basic compositional features of a style.

An analytical grammar can satisfy these criteria because a grammar is a generative method and can produce new designs in the language, the new design can be evaluated by using the grammar to generate and test it whether it is a member of the language or not and the grammar explains the common characteristics of the designs.

Analysis and generation of style with shape grammar:

For generating languages of architectural designs with analytical shape grammar have been studied in many research projects that include Frank Lloyd Wright's Prairie houses (Koning and Eizenberg 1981), the traditional Turkish houses (Cagdas1996), Queen Anne houses (Flemming1987), Palladian villas (Stiny and Mitchell 1978), Central Asian Caravanserai (Ahmed 2004) and much more. Stiny's Ice-ray grammar, which is a parametric shape grammar, describes and generates examples of a Chinese lattice design style (Stiny, 1977). This grammar describes the compositional principle of lattice designs into a set of rules.

Stiny and Mitchell (1978) defined the Palladian villas' grammar by describing villas' architectural plans that consist of walls, spaces, windows, and entrances. This grammar generates all the villa plans that Palladio designed as well as new examples which are not in the corpus of the Palladian style.

Flemming (1981) developed a parametric shape grammar of Queen Anne houses to generate plans by adding room around an entrance hall.

Koning and Eizenberg (1985) developed a 3D parametric shape grammar for Frank Lloyd Wright's prairie house style. The house design starts from the fireplace and then, a living zone is located around the fireplace creating a core unit. Three new Frank Lloyd Wright's prairie houses generate using the prairie house grammar.

Ahmed and Chase (2004) also developed a parametric shape grammar for the generation of the ground plans of Central Asian caravanserais and the grammar not only generates the present designs but also new ones in the style.

But all these analytical grammars concentrate on the language of designs. The authors of the grammars sometimes did not finish the generation so it is

difficult for a reader to understand the grammar whether the grammar generates finite or infinite number of designs in the language. The common aspects of these studies are to explain a language of designs in the style in a generative explanation by studying a given corpus of that style. And in many grammars, it is not easy to get the information to see a rule that when and how a rule will be applied. The reader has to rely on the author's description about the grammar to know what a rule does. The grammar should be structured in such a way so that it is easily understandable for the reader to generate the designs (Knight, 2000). Using a shape grammar interpreter is helpful for ones to write the grammar and structure the grammar systematically and generates the possible finite and infinite numbers of designs in the language.

The aim of this research has two parts. First one is to develop mosque's grammar and second one is to use a grammar interpreter to develop the grammar. Shape grammar methodology is going to be used to analyze Sultanate mosque's architecture in Bengal to develop the grammar with the help of a shape grammar interpreter, Grammar Environment (Li et al, 2009). To develop and to run the grammar this interpreter has been used in this research. Along with generating designs the interpreter helps to organize the rules systematically and guides to choose the rules sequentially. The grammar explains the style of Bengal mosque's architecture in a generative characterization by creating a language of designs. The grammar is a hypothesis and gives a framework for the question of understanding and generates the predictions and is able to test it. The grammar is a mechanism to generate the designs which is subjective and formal. The grammar generates the designs which are in the corpus and also the new designs that are not in the corpus of a style with an explanation whether the new examples belong to that style or not. That means the grammar exposes the common features of designs in the corpus and gives the criteria to decide the new designs in the corpus and states how to generate new designs. Though the grammar depends on the sets of rules and these rules are generated by the basic characteristics of the style, it is possible to find out the way in which designs should belong to which style. Traditionally if we want to design a mosque using the same characteristics, we can actually produce one design at a time but by

using grammar it is possible to generate a set of designs at once. The number could be finite or infinite.

The grammar of Sultanate mosque's architecture

To develop a grammar for Sultanate Mosques in Bengal architecture I followed the framework described by Stiny and Mitchell (1978) – examine the corpus, write the grammar, generate the designs and test the designs whether these belong to the style or not. The test might depend either on the writer of the grammar or on the experts of the style to judge the newly generated designs. Usually for analytical grammars authors of the grammar judge the results. For this grammar either I have to judge the new designs or I should find a historian of Sultanate mosques to judge the result. May be I should go for second option to find out a historian to judge my result.

According to above discussion to develop the grammar firstly I have to set a corpus of Bengali mosques. To know about the mosques in detail, information will be collected from literature review, books, drawings, photographs and the fieldwork report. According to these sources there are 70 extant mosques found in this region. These mosques set the corpus.

With the information, each mosque will be analyzed to find out the common features of the style. According to the first step of the framework, the mosques in the corpus should have some common characteristics to develop an outline of the grammar. May be there is some example which does not fulfill the same characteristics of the style as the other mosques do. In that case this example should be omitted from the corpus.

Secondly to write the grammar, all these features assist to construct the rules of the grammar. The grammar has four different stages to generate the complete plan of the mosques. Each stage is different from other. First stage is generating the initial forms of the mosque and consecutively generating the complete plan of the mosques.

At end the grammar should be able to generate the designs in the corpus and also the new designs in the language and also give an explanation whether

the new examples belong to Sultanate mosque's style or not. If not then grammar could be modified thoroughly to define the languages of design.

With the help of the framework the grammar is developed by the Grammar Environment (Li et al, 2009), a prototype system for developing two and three dimensional shape grammar, will be used. This shape grammar interpreter provides an interface for users to make and test the grammar.

Organization of the study

This dissertation is organized into nine chapters excluding introduction and are divided into two major parts. Part I consists of two chapters. These chapters describe the history and origins of Sultanate mosques and about the shape grammar analysis. Part II describes the corpus and how the grammar constructs the rules on the basis of the features of part I and generate the designs in the language. This part consists of seven chapters. Chapter seven concludes with a discussion about the language that is generated by the grammar and identifies topics for future work.

PART I.

HISTORY & THE STYLE OF SULTANATE MOSQUES ARCHITECTURE IN BENGAL

Chapter 01.

History and Origins of Sultanate Mosques

Mosque Architecture was introduced by the Muslims for the ritual demands of their religion 'Islam' when Muslim rule in Bengal was established (1205-1765). Mosque architecture was different from those of Buddhists and Hindus due to the different nature of participation of their ritual worship. Before Muslim period Buddhist and Hindu rulers established lots of temple in this region. So that the mosque's plan also had an influence from the temple's plan but other functional layouts were completely different for the ritual purpose. Depending on climate, geographical condition and availability of the materials Islamic architecture has its own characteristics in different regions. Various mosques were built during Muslim rule in Bengal (both West Bengal and Bangladesh), but few have been chosen to explain the styles developed in this area.

1.1 Historical context:

1.1.1 Early Muslim period of Bengal:

The victory of Ikhtiaruddin Mohammad Ibne Bakhtiar Khalji over Nadia in 1204 A.D is associated with the establishment of Muslim rule in Bengal. Firstly the history of Bengal concentrated on Gour, the Muslim capital of Bengal. But at the same time the south-eastern part of Bengal remained beyond the influences of the Muslim rulers for the next hundred years. During the time of Hindu *Moharajas* (rulers) this part of the country was called 'Lakhnouti'(Muslim name of Nadia, the term 'Bengal' comes later) (Hasan, 2007). Giasuddin Iyaz Khalji tried to take into custody east Bengal in 1227A.D and later in 1236 A.D. After that Delhi (Mughals Capital of Sub continent during this time) seized the control of Lakhnouti and made it a province until 1287. As it was one of the fareast provinces from Delhi and for its forested topography

and heavy monsoon climate it was set apart from other places in north India. The central administration could not control the administrative work in this area. For that reason the independent Sultan of Lakhnouti, Shamsuddin Feroz Shah took over a part of east Bengal in 1300 A.D. In 1324 the Tughluq sultan marched to Lakhnouti and divided the country into three administrative units, Lakhnouti, Shatgaon and Sonargaon (fig, 1.1). In 1338 Sultan Mubarak Shah declared his independence from Sonargaon (centre of east Bengal) against Delhi administration. In 1342 Shamsuddin Illyas Shah became the Sultan and united the three units to form Bengal in 1352. He successfully protected his independent country from the attacks of central Delhi. And from 1352 to early 16th century the independent Sultanate period in Bengal prevailed. Under the jurisdiction of Emperor Jahangir (1605-1627) Mughal rule was established in Bengal. (Hassan, 2007 pp.7-13).

In the Sultanate period, the rulers of Muslim society were concerned with presenting Islam in a language that was actually a common practice among Bengali people. Even today the rural Muslim, who has a very limited knowledge of his religion, is very particular about his identity as a Muslim. The cultural identity and the spiritual mould of today's Bengali Muslims are rooted in the independent Sultanate period. The Sultan of this time flourished Bengali culture and combined it with Islamic influence which was brought from the central Islamic lands. For these reasons from 1450 to 1550 almost three quarter of total mosques were built in Bengal (Hasan, 1989).

1.2 The Geographical & climatic context:

The history of Bengal is the interaction between people and its geographic conditions. Bengal has her own outstanding characteristics and traditions among all the regions of Indian sub-continent. The unfriendly nature, the great rivers and flood, jungles, the muddy plain land all these spiraled from the fertile soil of this spiritualist land (Naqi, 2002).

The term Bengal refers to a territory that has been defined during the Muslim rule and stretches from the Himalayas in the north to the Bay of Bengal in the south and many rivers in the east and west. Bengal is the product of a long

process of geographical formation. The large alluvial area of Bengal is flooded with sediments deposited by the rivers and their numerous streams. Bengal is the largest and possibly the most fertile delta of the world. This land is irrigated all through by the rivers.

Brick which is made from this alluvial soil was the most favorite building material because of its availability and low cost. Stone architecture has never been popular to the people of Bengal, though the sculptures were carved out of imported stone. It is obvious that the monsoon rains, the rise and fall of river levels and changes in river courses form the both cultural and the physical geography of the area (Naqi, 2002).

Climatically Bengal falls within the monsoon zone. This fact along with the high humidity and dampness help to grow the vegetation and create a serious threat to any structure of this land. Each year a large number of huts and houses are washed away by the currents of rivers. The building or the houses constructed on this soft and unstable soil of this land are weak and do not last very long. That is why people trend to build their house or building on a raised level from earth. Because of the glary sky buildings are constructed with projections over the openings and to protect the built environment from damaging effects of heavy rainfall. Due to the climate we can not find any courtyard mosque in Bengal where as use of courtyard in the mosque is very important in the central Islamic world. I am going to elaborate on this fact in the next chapter. The roof of the mosque architecture is normally influenced by the roof of this traditional village houses to protect the mosque from this tropical climate.

1.3 Origins of Bengal mosque architecture:

The land of Bengal as an active delta is always in a developing stage. People from the older declining delta areas, where land is not that fertile, migrate to this southern region. The Muslim missionaries in this area were involved in two levels of activities. During early 13th century at the first level of their activities they built several mosques, tanks, roads and other monuments and simultaneously they were involved themselves to make the land cultivable by

clearing jungles. In this way they were very successful to become religious leaders of the local people. The development of the mosques was also depending on the style of these religious leaders. These leaders normally came from the central land of Islam and with them they also brought the idea of religious buildings. Depending on climate, topography, availability of the materials and the number of population, they developed their own style to build these sultanate mosques which are different from the central Islamic land. Mainly they acquired the features for the mosques from the traditional village hut, Hindu temples and combined them with traditional Islamic architecture.

1.3.1. Ordering principal of Muslim architecture:

The geometry of the Muslim designers metaphysical and cosmological principals are surrounded naturally. The basis of the Muslim ordering principals largely depends on the moves of geometry. The basic form in Muslim architecture is a circle formed by a point. In a generative stage these circles produce the square form which is a symbol of 'Kaaba' the 'purity'. Interaction between the square, the circle and the space in between is the basic and most highlighted order that have been practiced through out the Muslim world (fig 1.6) (Naqi, 2002).

The interaction between circle and square takes two different approaches for two different conditions. Firstly the single dome mosque takes the square as base and rotates another square to 45 degrees around the center point. The process produces an octagon and then putting the circle over it. This circle represents the dome over the square plan and the octagon is the basic to give the guideline for positioning the *mehrab,* the doors and the openings in the interior space. The Dome of the Rock built in 692 inside the great mosque at Jerusalem is the perfect example of this method (fig1.7). The dome is supported on four piers for this famous mosque. Bengalis took the same concept but applied it in their own way. Instead of using big dome they used small dome supported on heavy masonry wall for single dome mosque. Secondly for the multi domes mosque a circle directly rest on the square with the help of four columns and the unit is then multiplied to define the desired length and width of the mosque. For the large mosque the center bay becomes wider with *chouchala* (four segmented

roof) vaulted roof. This type of roof is typical Bengali feature which had first introduced in Bengal mosques and has been widely used in the other large mosques and monuments in Bengal.

1.3.2. The features help to assemble the Sultanate mosque in Bengal:

Most of the mosques were generally built in the rural area. Small mosques were built for daily prayer but the big mosques were built for Friday afternoon prayer when a large number of people gather to do their prayer. Basically the mosques were based on forms and concepts resulting from the village hut which are small unit constructed of mud or woven bamboo with a thatched roof (*chala*) and curved cornice (fig. 1.2).

The resemblance of these village huts can be found in the 11th century temple's paintings from Buddhist manuscripts and the temples from 8th to 12th centuries from the neighboring country Burma (Myanmar), when Bengal had strong cultural and religious attaches with it. Because of the temporary nature of these huts and the unstable climate none of these huts has survived from Sultanate times. But the basic design of the huts has remained the same (fig.1.3) (Hassan, 1989). Each hut consists of a single room rectangular or square in shape with woven bamboo or mud walls and wooden posts. The roof was either *do chala* (two segments) or *chau chala* (four segments) often made of thatch over bamboo framing. Bamboo which is a very strong but flexible material helps to make the thatch *chala* roof and the cornice curve. The curvature of the roof is not for drainage but to prevent the sag of the bamboo. A *chau chala* roof is constructed of the same material like the *do chala* but it slopes down in four directions. Sometimes a second roof in reduced scale is added on the central chamber if there is a surrounding *chala* verandah. Evidence from the manuscripts painting also shows that sometimes palaces were also based on the hut type. Only difference is in the material and in the scale. This kind of palace was illustrated in the *Iskander Nama* made for Sultan Nusrat Shah of Bengal in 1531-1532; give us an idea of this grand residence. There is a miniature painting of this palace where we can see that the king sitting in the square chamber made of brick decorated with terracotta and tiles. The building has a triangular *chala*

roofed pavilion on the upper level and a projecting verandah with curved roof. The square brick building with verandah in front and decorated with terracotta tiles is common to the Sultanate mosques (fig1.4).

Another influential feature is the pre-Islamic temple of Bengal. There are two types of temple- the *Shikhara* (tower) and the *Bhadra* (horizontal platform like divisions of the structure). The second type had a stepped roof over the sanctuary, and consisted of a number of receding stepped stages. The form of the *bhadra* was derived from rural hut construction (Hassan, 1989). This type of temple was popular in east Bengal beside norther India, Nepal, Myanmar, and the other parts of Bengal. This type of temples have a cruciform plans with a central square core, lift up on a platform with single stepped sloping roof (fig 1.5). But no early brick temple of this type exists in Bengal today. From the paintings, manuscripts and the sculpture we can find that the type was common in Bengal throughout the pre-Islamic period. The design and the implementation of the features those tie the Bengali monuments with the temple is so close with the square domed type of building of central Asia (fig 1.5).

1.4 Pre-Muslim architectural traditions of Bengal:

During the Buddhist and Hindu rule in Bengal many new settlements flourished and later become dumped and turned into ruin. Bengal buildings were built of heavy walls to support the structural system by the burnt brick. The structural cores in many cases were covered with terracotta tiles to protect the building from warm humid climate. These tiles gave a distinct architectural character as well as a finest piece of architecture (Hassan, 1989).

The basic approach of the pre Muslim architecture of Bengal was to create angles, recesses, projections to accommodate brick and terracotta decorations. This was done from a basic square and then dividing it into a special regular proportion. We can find the intention to design a heavy architecture by applying corners and moldings in the massive brick walls (fig 1.6). With the introduction of Islam and establishment of Muslim rule in Bengal in1204, a new style emerged. More attentions gave to the achievement of their own style than the basic characteristics. With the large dimension and their Muslim culture

these mosque architecture were used to dominate on the political and cultural stages in Bengal. Muslim rulers of this region added towers on the four side of the mosque instead of minaret, which is a distinct feature of Islamic architecture (Naqi, 2002).

1.5 The common characteristics of the Sultanate mosque:

The Muslims of this region developed the characteristics of the mosque using the local features of their houses and the local materials like brick (Hasan, 1989). The basic features of the Sultanate mosques in Bengal are:

- The *chala hut* (traditional segmented roof of the village house).
- Brick construction (the important feature to identify the Bengal's mosque architecture).
- Square domed unit (the basic module for Sultanate mosques).
- Pointed arch.
- Multiple *mihrabs*. (Situated at the *Qibla* or west wall).
- Curved cornice.
- Engaged corner towers (resulting from the corner post of the village huts).
- Minarets (traditionally associated with mosque).
- Terra-cotta decoration on the surface.
- Ponds or large tanks.
- Inscriptions or '*Quranic*' text. (Hasan, 1989).

The architectural historians are trying to classify and to differentiate the features of Islamic architecture on the basis of climatic, geographic and the cultural conditions of Bengal.

- The *chala hut* (traditional segmented roof of the village house): The mosques were based on forms and concepts resulting from the village hut which are small unit constructed of mud or woven bamboo with a thatched roof (*chala*) and curved cornice (fig 1.2 & fig 1.8). In the villages of Bengal each hut had a different function like bedroom, storeroom, and kitchen cum dinning room, cattle pen, but the hut, used as mosque, had a simple *mihrab* projection in the west wall to express its

function. The mosque which was built by brick truly followed this model and reproduced forms that are natural to bamboo-thatch construction. Adding dome and the change to the square plan needed to construct the dome were the main variation. The symbolic value of the dome differentiates the mosques from the temples of other religions.

- Brick construction: Another feature which helps to identify the Bengal mosque from 14th to 16th century was the brick. Because of the topography, Bengal is a deltaic land and clay is easily available in this region. So brick is the easily available material in this region compare to stone. Lime was used for mortar and the parapets, domes and roofs were plastered to resist water. The outer sides of the brick walls were the dressed masonry with lime mortar (fig 1.8). The thickness of the walls are huge to support the structure and also keep the prayer hall cool in the summer and hot in the winter.
- Square domed unit: The basic modular unit for Sultanate mosques. In Bengal architecture we can find single or nine domed square mosques or multi domed rectangles. Multi domed mosques in Delhi during Tughluq period (13th century) had internal courtyards but not in Bengal. But for developing the grammar this type of mosque is avoided as this type did not belong to Independent Sultanate period. Without the dome these buildings specially the single unit mosques in their plan and external elevation resemble the temples of other religions (fig 1.9).
- Pointed arch: There are no pre-Islamic examples of pointed arch in Bengal but they appear in the Buddhist temple in Bihar, India and pointed brick arches and vaults are found in the 11th century temple at Pagan (Nath, 1978). Therefore the form and the technology of the arch were known in Bengal in pre-Islamic times but when Muslim captured it was widely used (fig 1.9).
- Multiple *mihrabs*: *Mihrab* is situated at the *Qibla* or west wall of the mosque. The *mihrab* is an indicator of the direction of prayer but it is also considered as both a symbolic doorway to Paradise and a memorial to the Prophet Mohammad (S) as the first *Imam* in Islam. In Bengali mosque the entrance is always on the east, opposite the *mihrab* on the

west and other doors and windows are on north and south. More than one *mihrab* on the west wall appeared only in the Bengal mosque, sometimes in the mosque of North India but never in the mosques in other parts of Muslim world. In Bengal, no matter how small or big the mosque is, the number of *mihrabs* has been given on the *qibla* wall; the same number of entrances has been given on the east wall. They are in axial alignment. The central *mihrabs* are always bigger than the succeeding *mihrabs* for that reason the central entrance on the east wall is also bigger and most decorated element in the mosque (fig 1.10 & fig 1.11).

- *Minbar* or Raised platform inside the prayer hall: Some times in the multi aisles mosque a raised platform with two flights of stair was given. Normally they were placed next to the *mehrab* at the north-west corner of the prayer hall. This is with or without handrails, leading to a small platform which is crowned by a copula. Muslims assemble this feature into large mosques. *Imam* (leader of the prayer) stand on it and lead the prayer on Friday. This is a distinct feature for all large mosques in the Islamic world. In some large Sultanate mosque this feature also can be found. But for developing the grammar I shall skip this feature of the mosque as it was not a prominent feature of Bengal mosque compare to the mosque of central Islamic world (fig 1.11).
- Curved cornice: The curved cornice of the thatched roof was used to reproduce familiar building form with unknown material. In the mosque to keep the curvature of the cornice the roof has to be built curved (fig 1.9).
- Engaged corner towers: In the temples the engaged towers were resulting from the corner post of the village huts. But in the temple they are not visible. They are for the first time seen in Eklakhi Mosque of Hazrat Pandua (Hassan, 1989). It is not clear whether the source of this features are Muslim or pre Muslim. They are not integral part of the mosque in the Muslim world but in the mosque of Damascus (706) they are used for Islamic ritual (fig 1.9).
- Minarets: This is an Islamic architectural feature traditionally associated with mosque but it is absent in Bengal except the Shatgumbaj mosque in

Bagerhat. The main purpose of the Minarets is to call for prayer but for the mosque of Bengal minarets is not needed as the mosques were built in a small village. The call for prayer was generally given from the front court or from inside the prayer hall.

- Terra-cotta decoration: In North India the external surfaces of the Sultanate mosques are either plastered or plain but in Bengal the external surface of the Sultanate mosque are un plastered but filled with brick work and terra-cotta decoration. From the pre Islamic temple it has clearly been observed that non- Muslim architecture of that period used terra-cotta decoration in their places of worship. Conversely, Muslim used vegetal or geometric forms. In the Mosques of the central Islamic world Muslim applied huge stone decoration on the wall surface. But when they came in to Bengal they started to use terra-cotta instead of stone and this terra-cotta decoration became the identity of the Sultanate mosque in Bengal (fig. 1.12).
- Ponds or large tanks: Almost every mosque in Bengal has a pond or a large tank beside and also in the rural dwellings. The pond beside the mosque replaces the ablution fountain found in other Muslim countries (fig.1.13).
- Inscriptions or '*Quranic*' text: The commonly used *Quranic* text in Bengal is found over doorways of the mosque. The inscriptions mark the separation between the believer nonbelievers at the entrance. (Hasan, 1989).

Above mentioned features are the basic characteristics of every mosque. To develop the grammar I choose the distinct features of the mosques from the corpus. For developing a grammar, I am going to discuss the features require to develop the grammar in chapter 3.

Chapter 02.

Shape Grammar: Analysis of Style and Grammar Interpreter

This chapter has two main parts and the first part will discuss computational approaches to the analysis of style. The other part explains about the generative system for designs.

2.1 Analysis of style:

An architectural style is a design knowledge that can be analyzed, learned and then used in the design process which I already mentioned by the explanation of Stiny & Mitchell in introduction (p3). An architectural style can be analyzed by recognizing their drawing elements and their relationships. Shape grammar is a methodology which helps to analyze a design style to understand and learn the style clearly and support the user to develop his or her own style using the same methodology. Since Stiny and Gip's (1972) introduced shape grammar to analyze a design style, many shape grammar systems have developed to analyze a design style or an architectural style. To analyze the style and to develop the grammar of Sultanate mosques in Bengal, the Grammar Environment (Li et al, 2009), a shape grammar interpreter, will be used.

2.1.1 Shape grammar:

Shape grammar was introduced by Stiny to explain visual shape composition. A grammar consists of a set of rules (R) that specifies how one shape or part of a shape can be replaced by another. This simple process is used to explain a design style. A shape grammar is a method which helps to define a design style in the form of algorithm to organize the designs elements. Several

design styles have been analyzed with a set of rules and explain how the rules can be used to generate new designs in there styles (Knight, 2000).

There are two types of shape grammar: non-parametric and parametric shape grammars (Stiny, 1985). Both types contain a set of rules. In the rule (A→B) application, shape on the left side (A) of an arrow which is a sub shape of an initial shape(C) determines which part of the shape will be replaced. The shape on the right side (B) of the arrow specifies the sub shape (C′) after the transformation (T) by C′= [C-T(A)]+T(B). Then the grammar defines a set of shapes called a language which contains all the shapes generated by the grammar. Each of the shapes is developed from the initial shape by applying the rules and the new shapes are sub shapes of the shapes in the set S (which is a finite set of shapes and is used as a vocabulary for the configuration of other shapes) (Stiny,1980).

Figure 2.1 shows a generation of a shape using a non–parametric shape grammar. The grammar which consists of an initial shape and two set of rules is represented in figure 2.1a. Figure 2.1b shows how the rules apply repeatedly to generate a complex pattern. The shapes generated by the grammar are shown in figure 2.1c.

Like a non parametric shape grammar, a parametric shape grammar also has a set of rules that indicate how shapes replace sub shapes of a composition. It uses parameters for shape organization. Shapes have proportional parameters and the values of the parameters can be changed. The parametric shape grammar creates shapes with more variation than the non parametric shape grammar. Figure 2.2 shows a parametric grammar.

A user arranges shapes either by translation, rotation, or scaling using labeled rules. The label is a symbol that indicates how to apply the rule to the initial shape in a derivation. The label in the shape is also used to control the generation process. Each rule generates different derivation results with the labels at different position (Fig 2.3).

The above mention rules can also be applied to 3 dimensions. Similar to the previous 2D rules, the 3D rules also have labels. These rules are used for generating the derivations (Fig 2.4). For design style analysis both non parametric and parametric shape grammar can be used.

2.1.2 Analysis and generation of style with shape grammar:

Stiny and Mitchell (1978) developed the grammar for 16th century Palladian's villas. This Palladian's villas grammar describes architectural plans which include walls, spaces, windows, and entrances. The grammar consists of 72 rules which generate all the existing villas plans and also new plans in the style. This grammar starts from a single point which indicates the location of the plan on a site and the generation of the plan starts with the definition of a tartan grid and that defines possible locations of internal and external walls at a later stage (fig 2.5).

Ahmad and Chase (2004) developed the caravanserai grammar which also generates the ground plan of a courtyard with an arrangement of corner towers, entrances and the external wall. This parametric grammar starts with a labeled polygon and 15 sets of rules can be applied to this shape in 4 different stages to generate rectangular or square ground plans (fig 2.6)

2.2 Generative application:

2.2.1 Shape grammar interpreters:

To develop a new grammar it is important to test it. To do that Grammar Environment (Li et al, 2009), which is a prototype system for developing two and three dimensional shape grammars, provides an interface for users to make and test the grammar.

Through this system it is possible to draw the shape instead of encoding the shape by typing parameters into the text file. The initial shapes and the rule shapes of a grammar, all are displayed graphically by this system. The system has two shape editors – the internal shape editor and the external shape editor. With the help of the internal shape editor it is hard to draw complex shapes. But on the other hand it is easy to draw and edit any kind of shapes including 3D shapes in external editor which is an Autocad applet (Li et al, 2009). After that the shapes can be exported to Grammar Environment. After choosing an initial shape and a rule it is possible to generate the sub shape by this system. It is also

possible to test and edit the grammar by the interpreter. Actually the interpreter helps to run the grammar to do the design work.

This chapter discussed about the shape grammar method and several design analysis by this method as well as generative systems for design analysis. In the following chapters the paper describes how shape grammar method was used to analyze Bengal's Sultanate mosque style and helps to develop the grammar to generate the language of the same style using Grammar Environment.

PART II.

DEVELOPMENT OF THE GRAMMAR FOR SULTANATE MOSQUES

Chapter 03.

The Style of Sultanate Mosques and the Features Require Developing the Grammar.

The Sultanate mosque could be in any size, shape (square or rectangle), and plain or decorated, with or without verandah, but they all had a common consistency in design and had a set of features that helped to identify them as a Sultanate Mosque of Bengal. A number of features are similar to the Islamic architecture of the central Islamic land and north India but others are totally new.

According to Stiny and Mitchell (1978) an architectural style contains a finite number of buildings (corpus) with some similar characteristics. Based on the knowledge of the style it is possible to develop a standard feature of the style, write a grammar, define a language of design and test the language against that standard feature and revise the grammar to generate the designs that fulfill the criteria of the standard feature. And the process also helps to understand the style very well.

In this chapter the same steps will be followed to develop the Sultanate mosque's grammar and make a standard to test the language encoded by the grammar. The characteristics of the mosques were modified from dynasty to dynasty but they kept the same basic features. To develop the grammar I will focus on these basic features of the mosques.

3.1 The corpus of the Sultanate Mosques in Bengal:

Most of the mosques were built between 1450 and 1550 when Muslim culture flourished (Eaton, 1993).

Depending on the source the grammar for Sultanate mosques would be based on a corpus of seventy mosques in Bengal from independent Sultanate period (1338 to 1575). Observing the mosque in the corpus one by one helps to understand the style and to define the rules of the grammar.

The simplest and most common form of Bengal architecture is a single square with a dome. Sometimes a verandah was added in the front of a single square mosque like in a village hut. This single square mosque sometimes has either one or three doors on east wall or exactly the same number on the opposite wall. Side entrances are also opposite to each other on the north and south walls. To form a large mosque with central aisle and equal number of aisles on other side, the basic square module was multiplied and this made either a large square with equal number of bays and aisles like a nine domed mosque or a rectangular mosque with unequal number of bays and aisles. In a rectangular mosque the number of aisles in X (east-west direction) axis could be even or odd but the number of bays in the Y (north-south direction) axis are always odd. This feature of the mosque is the main concept to develop the grammar. In these mosques domes are used to give a symbolic value. Each dome roof consists of a square bay formed by four columns (fig 3.1). The mosques in this corpus represent all categories of all Sultanate mosques (fig 3.2) (table1).

Table 1- List of the mosques in the corpus:

Type of mosque	No.	Name of mosque	Place	Year
	01	Molla Simla mosque	West Bengal	1320
	02	Binat Bibi mosque	Dhaka	1457
	03	Khan Jahan Ali mosque	Bagerhut	1459
	04	Bibi chinni mosque	Borguna	1465
	05	Bandar Shahi mosque	Narayangange	1481
	06	Arshonagar mosque	Khulna	1501
	07	Goaldi mosque	Sonargoan	1519
	08	Hammad mosque	Chittagong	1538
	09	Jorbangla mosque	Barobazar	1538
	10	Bibi Bigni mosque	Bagerhut	Mid 15
Square mosque	11	Ranbijoypur mosque	Bagerhut	Mid 15
	12	Singra mosque	Bagerhut	Mid 15
	13	Chanukhola mosque	Bagerhut	Late 15
	14	Yusufgange mosque	Sonargoan	Late 15
	15	Shakurmalik mosque	Barobazar	Early 16
	16	Noongola mosque	Barobazar	Early 16
	17	Pathagar mosque	Barobazar	Early 16
	18	OsmanpurGayebi mosque	Sylhet	Mid 16
	19	Shial Ghani mosque	Barisal	Mid 16
	20	Shuvohara	Jessor	Late 16
	21	Jindapir	Bagerhut	Late 16
	01	Shatoir mosque	Faridpur	1481
Nine Dome Mosque	02	Bagerhut mosque	Bagerhut	Mid 15
	03	Kasba mosque	Barisal	Mid 15
	04	Masjidkar mosque	Khulna	Mid 15
	01	Gopalgange mosque	Dinajpur	1460

	02	Mashjidbari mosque	Potuakhali	1474
	03	Chamkathi mosque	Gaur	1478
	04	Shankarpasha mosque	Habigange	1519
	05	Nabogram mosque	Shirajgange	1526
Square mosque	06	Kadamrasul	Narayangange	1530
with verandah	07	Gorar mosque	Barobazar	Early 16
	08	Kaniadeghi mosque	Gaur	Early 16
	09	Lattan mosque	Gaur	Early 16
	10	Shatkhira mosque	Paharpur	Early 16
	11	Sura mosque	Dinajpur	Mid 16
Single aisle	01	Fath shah mosque	Sonargoan	1484
mosque	02	Kherua mosque	Sherpur	1582
	03	Qutub shah	kishoregange	Late 15
	01	Muzammpurshai jami mosque	Sonargaon	1432
	02	Faqir mosque	Chittagong	1474
	03	Danichalk mosque	Gaur	1480
Double aisle	04	Baba Adam mosque	Rampal	1483
mosque (6	05	Baba Adam Shahid mosque	Dhaka	1485
domes)				
	06	Rezal Khan mosque	Bagerhut	1523
	07	Jahaniyan mosque	Gaur	1535
	08	Kusumba mosque	Nogaon	1558
	09	Golakata mosque	Barobazar	Mid 15
	10	Shailkupa mosque	Jhinaidah	Mid 15
	01	Zafar Khan Gazi mosque	West Bengal	1298
Double aisle	02	Bagha mosque	Rajshahi	1523
mosque (10	03	10 domes mosque	Bagerhut	Early 15
domes)	04	Qutub Shahi mosque	Pandua	1583
	05	Majlish Awlia	Faridpur	Late 15

	06	Tantipara mosque	Gaur	Late 15
	01	Macadam Shah mosque(15 domes)	Shahzadpur	1483
	02	Pirpukur mosque (15 domes)	Barobazar	Early 16
Multi aisles mosque without vaulted nave	03	Manohardeghi mosque (35 domes)	Barobazar	Early 16
	04	Shatgachia mosque (35 domes)	Barobazar	Mid 15
	05	Barosona mosque	Gaur	1526
	06	Choto pandua	West Bengal	1342
Multi aisles mosque with vaulted nave	01	Shatgumbad mosque	Bagerhut	Mid 15
	02	Darabari mosque	Gaur	1480
	03	Gunmant mosque	Gaur	1484
	04	Choto Sona mosque	Gaur	1493

To understand the mosque with different characteristics the plan types have been grouped into 2 categories. First the square shape plan which includes 38 mosques and the rectangular shape plan which includes 32 mosques. The following chart will help to understand the categories into which mosques have been classified:

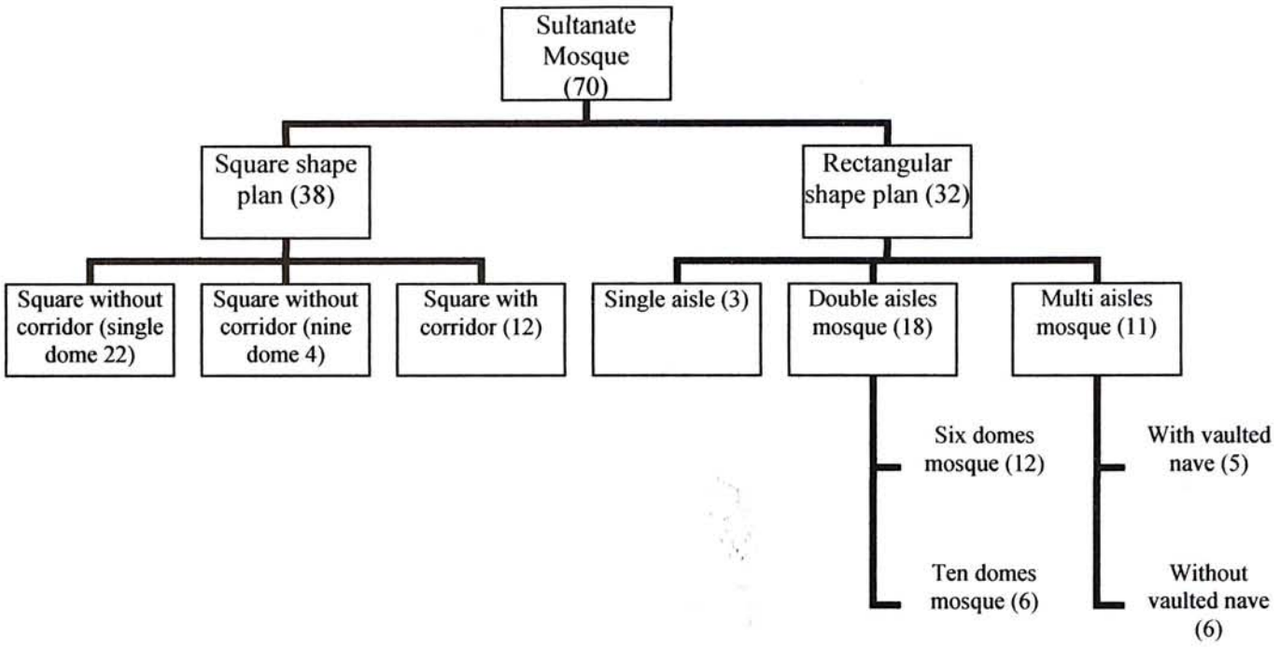


Figure 3.3- The different types of Sultanate mosque.

To develop the grammar the above chart will help to generate the plan of the mosques according to their categories. In the square shape mosque, the plan can be subdivided according to the openings or the doorways on the east, north and south wall.

3.2 Examining the corpus of the Sultanate Mosques in Bengal:

From the philosophical point of view architectural monuments were designed on the basis of pure geometry and use of natural light. Throughout the centuries *Sufis* (the person engaged in strict worship of God) wrote the significance of light as a spiritual matter. The holy *Quran* (the holy book of Islam) teaches us that God is the light of the heavens and the earth and a prophetic saying adds a cosmological dimension that the first element created by God was light. Islamic architecture makes full use of light and shade, the heat and coolness of wind, the water and the cooling effect on earth, the insulating features of earth. Traditional Islamic architecture merges with the environment (Rehman, 2002). So that the composition of the large mosque not only includes a big sacred interior space but also includes open spaces like courtyard, garden.

Only one such example is found at the Adina mosque of West Bengal (1375) with a wide central bay and with large enclosed courtyards which was built in this region because this type of mosque did not suit the climate and

needs of the rural community (fig 3.4). Another reason was that this building has 306 domes and forty one *mehrabs* and perhaps the local craftsmen were not experienced enough to execute these number of domes. A Large, open courtyard mosque was not very useful in a monsoon region like Bengal. But the large mosques without courtyard were built to hold the entire population of a community during the Friday prayer.

Searching for prototypes of the Bengal mosques, some have referred to the earlier buildings in Islam. The square single domed Bengali mosque and the Dome of Rock of Jerusalem are similar to the extent that they are both square buildings with a single dome and strictly follow the ordering principal of Muslim architecture (fig 1.7). To form a large mosque with a central wider bay and equal numbers of bays on either sides, this single square module was multiplied. This formed either a rectangular mosque or a large square mosque with an equal number of aisles and bays. But the large rectangular mosque of Bengal is only elongated in east- west direction facing *qibla* (Mecca) i.e. the west wall. On the other hand there are some examples from the central Muslim world which are elongated parallel to the *qibla* wall. For instance Kairouan, the great mosque of the 9th century, the mosque in Algeria of the 11th century, mosque of Mansura of the 14th century are some examples of this type (fig 3.5 and fig 3.6). There is not even a single mosque of this type in Bengal. Further elaboration on this topic will be discussed in the 'observation' part (section3.3.2).

3.3 Features required for developing the grammar:

As mentioned before, the Bengalis integrated the features of Islamic architecture rather than importing external features. Because of the climate and availability of materials they had to omit some traditional features of Islamic architecture like courtyard, minarets, *iwan* (four gateway or hall at the end of two axes) and had to introduce some new features like curved cornice, four towers, multiple *mehrabs*, etc. And kept some features as same as they were used in the large mosques of Islamic architecture (fig 3.1).

3.3.1 Distinct features of the plan:

Beside the plan types some other characteristics of the plans had to be analyzed to develop the grammar. These characteristics were analyzed according to the shape of the mosques, number of bays and aisles, wall thickness, number of openings on the walls, and the corner towers of the mosques. The grammar will describe how these characteristics are encoded into the rules to define the language of Sultanate mosques in Bengal.

- **Plan types:**

Analyzing the plan on a more abstract level will help to discover how the grammar will be constructed. The features of the plan create the rules of the first stage. As we know from the above chart, Sultanate mosques can be divided in to 2 types and each type has secondary types. This chart helps to organize the grammar

But in the case of Square shape mosque (total 38) their secondary type could be subdivided according to their openings on the east, north and south wall. Secondary types of the Square shape mosques are:

Square without corridor (single dome) - this type of mosque was very popular all over Bengal during Sultanate period. This mosque is a small building with a single square chamber and a dome on the top. The basic ordering principal of the Muslim architecture can be found in this type of mosque. A single square cell contains a circle on the top resting on four piers (heavy walls). This square domed mosque became the basic module for Sultanate mosque in Bengal in spite of having one dome or nine or multi domes rectangles. A total of 22 mosques are listed in this category. Analyzing these single domed mosques, three types of variation can be found according to their wall openings (fig 3.7 a,b).

- One *mihrab* in the middle of the *qibla* or the west wall and one entrance either on the east, north, or the south wall.
- Three *mihrabs* and three entrances on the west and east walls. As we know, the numbers of entrances on the east wall depend on the

numbers of *mihrabs* on the west wall. But the central *mihrabs* and the central entrance on the east wall are bigger than the succeeding *mihrabs* and doorways. And one entrance was given on the north and the south walls.

- Three *mihrabs* on the west wall and three entrances on the east, north, and south wall (fig 3.7 a,b).

Square without corridor (nine dome) – to keep the basic unit of a single domed square Muslim just enlarged the mosque into nine domed structure by adding equal number of aisles and bays on either side of the central *mehrab*. They did not make it four domed as the number of bays had to be odd in number. To keep the symmetry of the plan they still used central *mihrabs* and an equal number of small *mihrabs* on either side of the wall. To enlarge the mosque, Bengali Muslims did not use the same principle as the mosque will become huge with 25 bays. So, for the large square mosque they stopped in nine domed square (Hassan 2007). Compared to the single domed mosque, the nine domed mosques were large and built for Friday worships. In this mosque, four columns in the center of the square assembly room divide the interior into nine square cells covered by nine domes. Though the nine domed mosque is known to have been imported from the central Islamic land but this type of mosque gradually became popular in Bengal. The reason may be for the large covered space that helped to provide shelter for the worshippers from heat and rain.. 4 mosques are listed in this category. These mosques could also be of 2 types:

- Three *mihrabs* and three entrances on the west and east wall. One entrance was given on the north and the south walls.
- Three *mihrabs* on the west wall and three entrances on the east, north and south walls (fig 3.8).

Square with corridor- It means that sometimes a verandah or a narrow corridor was added at the front of a square chamber as done in village huts. Mosques verandahs are either divided into small bays covered with domes and *chau-chala* vaults or one large *chau-chala*. The main function of the

verandah was to accommodate the worshippers when the interior was filled. 12 mosques are listed in this category .This type of mosque is also of 2 types:

- Three *mihrabs* and three entrances on the west, east, and the verandah walls. And one entrance was given on the north and the south walls.
- Three *mihrabs* on the west wall and three entrances on the east, north, and south walls and also in the verandah wall (fig 3.9).

Rectangular mosques- Generally the basic square domed unit was multiplied to form an oblong shape mosque with the longer sides on the west (*qibla* wall) and east to accommodate a long prayer row. In the process of enlargement a dome covered each four columned cell of the interior space. These types of hypostyle mosques were very popular in Bengal. Each bay ends on the west with a *mehrab* and on the east with an entrance. The aisles running north to south also end in entrances or niches. The number of bays is always odd because the wide *mehrab* has to be placed in the center. But the number of aisles could be even or odd. Features like courtyard, minaret, and *iwan* that are always present in the rectangular mosques of central Islamic land, are absent in Bengal rectangular mosques. But a central vaulted nave is also present in the large mosques of Bengal. From the chart (fig3.3) the rectangular mosques are divided into 3 types- single aisle, double aisles and multi-aisles. Double aisles and multi-aisles have sub categories.

Single aisle rectangular mosque: Single aisle mosque actually consists of one aisle and three bays with three *mihrabs* on the west and three entrances on the east. Sometimes two or one entrance on the north and south walls are found. In this type of mosque the dome rests on a square formed by the east and west walls. This type of mosque was not very popular in Bengal (fig 3.10). Single aisle five bay mosques were found during the Mughal period but not in the Sultanate period (fig 3.11). For this category the maximum number of bays is 3. Three mosques are listed in this category.

Double aisles mosque: As the single aisle mosques were not very popular, *Bengalies* (the people of Bengal) added one more aisle to make the

mosque more proportionate. From the name of the mosque it is clear that this type of mosque has two aisles and an odd number of bays. The numbers of *mihrabs* depend on the number of bays of the mosque. This type of mosque can be found in 2 types.

- Six domed mosque has double aisles and three equal bays with three entrances on the east wall and three *mihrabs* on the west wall. 12 mosques are listed in this category (fig 3.12 a,b).
- Ten domed mosque has double aisles and five equal bays with five *mihrabs* on the west wall. 6 mosques are listed in this category (fig 3.13).

Multi aisles mosque: The multi aisles mosque are quite similar to the large mosque of the central Islamic world. The main difference is the absence of courtyard and the minaret. This mosque has multiple numbers of aisles and an odd number of bays in the plan. In this type some mosques have a bigger central bay with vaulted nave and a *chau chala* roof on the top. The *mehrab* of this central bay is wider than the others. There are an equal number of bays placed on the either side of the nave. 12, 24, 70 domed mosques are found under this category (fig 3.14). Normally multiple aisles mosques are large in size.

- Another category of this mosque has no vaulted nave. This type of mosque contains the bays which are equal in size. 15 domed (total 2), 35 domed (total 2), 44 domed and 63 domed mosques are the categories of this type (fig 3.15 a,b,c).

- **Wall thickness:**

The buildings are all constructed of thick, unplastered brick wall with terracotta decoration. The thickness of the walls in these Bengal mosques was heavy to keep the inside of the mosque cool during summer and also because these were used as structural members to hold the dome beside the columns. Generally the thickness of the wall is more or less half of the bay. For instance, for a single dome mosque, if the width of the bay is 1m then the wall thickness will be ¼ m and for a multi dome mosque if the width of the

bay is 1m then the wall thickness is ½ m. After examining the plans, this hypothesis will help to develop the rule for adding the wall (fig3.16 a,b,c).

- **Columns:**

Each cell contains four columns which hold the dome on the top. For the nine-domed mosque, the double aisles mosque and the multi aisles mosque columns are placed in a row to define the aisle. The shapes of the columns are circular, octagonal or square with a square base. But for developing the grammar the square shape has been chosen to make generative system simpler.

- **Corner towers:**

The corner towers are another feature common to all Sultanate mosques. Two types of corner towers were added at the four corner of the mosque to represent the posts of the hut – circular and octagonal. In the Shaitgumbad mosque the two front towers have staircases (fig 3.14).

- ***Mihrabs* and openings on the wall:**

The *qibla* wall of the prayer hall must be faced towards Mecca. At the mid point of this wall is placed the *mehrab,* which is the central and the most decorated niche of any mosque. In the Bengal mosque, the numbers of *mehrabs* on the west wall depend on the numbers of the openings on the east wall. Multiple *mehrabs* are used in the Bengal mosque. In large mosques, a vaulted *chou chala* roof represents the central wider bay. That is why the central *mehrab* is wider than the succeeding *mehrabs*. The forms of *mehrab* are varied in two shapes either semicircular or half square in plan and having either a semicircular arched top or a stagger flat roof on the top. The grammar will generate only two dimensional plans of the Sultanate mosques so that three dimensional features are omitted in the development of the grammar. The *qibla* wall and the *mehrab* are prominent features in all mosques except *Kabbah* (Mecca) itself. The worshippers during prayer must face Mecca and stand in a line parallel to *qibla* wall – this is the explanation for the conventional rectangular plan of most mosques

The openings on the north and south walls become windows or doorways or niches.

3.3.2 Observation:

The mathematical structure of the holy *Quran* provides a relationship between Islamic religious concerns and mathematics. The mathematical nature of Islamic art and architecture are, in a sense, the externalization of the mathematics hidden in the *Quran* and the geometric symbolism of its letters and words (Rehman 2002). The basic geometric module is the perfect example of this statement (fig 1.7).

Examining the corpus in detail helps to think about the style and also helps to think about hypotheses for the grammar. Different hypotheses can lead to different rules.

Observation of the plan: It is very clear from the above section 2.3.1 that if a user wants to design any kind of mosque, he or she has to start with the basic square module.

-Second observation is that for the multi domes mosque this square module is simply multiplied.

-For large mosques the central bay is 1.5 times wider than the square module (according to the plans of the corpus).

- There are no five bays and single aisle mosque or seven bays single aisle mosque in the corpus. But there is one single aisle mosque in Dhaka dated 1704 that has five bays (Banglapedia). But this mosque belongs to the Mughal period. There are no other mosques of this type from the Sultanate period. This characteristic will help to fix the number of bay for single aisle mosques. The maximum number of bays is 3.

- In the multi domes mosque, the number of bays and the number of aisles are not limited. According to the corpus Shatgumbad mosque is the largest mosque and it consists of seven aisles in the 'X' direction (east-west) and eleven bays in the 'Y' (north-south) direction (fig 3.14). This mosque has a wider central bay with a *chou-chala* vaulted roof. And Choto Pandua of West Bengal is

the longest mosque of the corpus and it has three aisles in the 'X' direction and twenty one bays in the 'Y' direction (fig 3.15).

-For the multi aisle square mosque the evidence shows that this type of mosque has only three bays and aisles in both directions (fig 3.8). The limit is three for this type of mosque. There are no four, five, six or a higher square mosque in the corpus as the even number is not acceptable for 'Y' direction which is also parallel to the *qibla* wall. In the 'Y' direction the number of cells is odd just to keep the *meharb* in the center. And 5×5, 7×7, 9×9 will be volumetrically too big for rural mosque (Hassan, 2007). So we can say that for multi aisle square mosque the maximum value is X=Y=3.

From the chart (fig3.17a) representing the number of mosques in the corpus by the medium gray color, it is seen that there are no mosques with more than 11 bays in the Y direction. This means there are no mosques in between the numbers of 11 to 21 bays except for only one with 21 bays. The Chota pandua mosque consists of 63 domes (3×21) and was built in the early 14th century. No other mosque of this type was built during the sultanate period. One more thing to consider is that, Bengal mosques are oblong in shape in the north south direction rather than linear. And the mosques should not be too linear in east-west direction since Muslims like to do their prayer in one long line facing towards the *qibla* wall. The proportions may be varied but should not be too linear so that every person may conveniently hear and see the *Imam* (the leader of the religious worshippers) during their prayer (Naqi, 2002).

So the hypothesis for 63 domes is that this mosque was built in the early period of Islam in Bengal. According to the historians this type of mosque is not very popular among the Bengalies for its linearity. As I mentioned before no other mosque was built, so this mosque can be omitted in the development of the grammar.

The grammar should be developed in such a way as to construct or generate not only the designs that belong to the corpus but also all designs that are not in the corpus. The top right corner of the chart 3.17b will guide us to predict among all the designs in the corpus (D), which are possible but do not fulfill the conditions fully (D'), which are fully acceptable or fulfill the conditions completely (D") and also those designs which do not belong to the style.

The conditions for the above mentioned predictions are as follow:

1. The dark grey colors represent the mosques that are not acceptable. Because in these type of mosques, plans are either elongated parallel to the *qibla* wall or too long towards the north-south direction. The mosque should not be elongated too long parallel with *qibla* wall because while doing their prayers the worshippers like to stand in one long line facing Mecca. If the *qibla* wall is shorter the line parallel to the *qibla* wall will be shorter too, which is not acceptable. But these types of elongated mosques are available in the Islamic world (fig 3.5). From the figure it is seen that this elongated mosque has a big courtyard inside the mosque that divides the mosque into a rectangle and a square courtyard surrounded by walkways. But for the Bengal mosques the courtyard is not suitable due to climatic purposes.

Generally, the proportions of the mosques vary from 1:1 to 1:3. For the largest mosque the proportion is 1:1.6, for the 10-domes mosque the proportion is 1:2.5, for the 6-domes mosque the proportions is 1:1.5 and for the single aisle mosque the proportion is 1:3. So in the north-south direction the mosque should not be too long that the proportion exceeds 1:3. If the mosque proportion exceeds 1:3, it may cause visual and hearing problems in the last rows.

2. The medium grey colors represent the mosques which are already in the corpus (D). Depending on the source the total number of these type mosques is 70.

3. Possible mosques that do not fulfill the conditions fully are marked in light gray color (D'). For instance 4 aisles and 3 bays and 6aisles and 5bays are new type of mosques that do not fully fulfill the conditions. Although these two mosques are elongated parallel to the *qibla* wall, they are not long enough to provide a courtyard and they can still accommodate the worshippers doing their prayer in one line.

4. Acceptable mosques are marked in light gray color with a star (D"). These mosques fulfill all the conditions of Sultanate Mosque of Bengal. 9 types of new mosques could be generated in the language.

These observations will help to define what will be the maximum value of 'X' and 'Y' in the development of the grammar.

Observation of the other features of the plan:

1. The thickness of the wall is half of a bay's width for multi domed mosques and one fourth of the bay's width for single domed square mosques.
2. The shape of the column considered square in the development of the grammar. The spacing between two cells will be the dimension of the column.
3. The central bay will be wider in large mosques. The central *mehrab* is always bigger than the other succeeding *mehrabs*. The number of the openings on the opposite of the *qibla* wall or east wall depends on the number of the *mehrabs* on the west wall.

3.4 The Grammar:

The purpose of the grammar is to understand the style of the Sultanate mosque in Bengal. A grammar is a hypothesis for encoding an architectural style that is constructed by a set of rules that codify distinct features of that style. A grammar should be able to generate a new example in the style and should provide for the criteria for testing it, and should also give an explanation of the basic compositional features of the style.

The grammar takes a square or a rectangular cell as its initial shape. Then all the rules in the grammar should be applied to these initial shapes so as to generate all and only the designs of the Sultanate mosques that are in the style. The derivation of a design follow in the grammar goes through 4 stages:

1. Generation of the Starting Unit.
2. Formatting the Grids and Forming the Columns.
3. Formatting the Walls around the Complete Grid.
4. Locating the Corner Towers and the Openings on the Walls.

	Number of Bays in X Axis:							
Number of Bays in Y Axis:	0	1	2	3	4	5	6	7
	1	square dome						
	3	1 aisel	6 domes	9 domes				
	5		10 domes	15 domes				
	7				With vault	35 domes		
	9			With vault				
	11				44 domes			With vault

Fig 3.17a-- Chart showing the number of mosques in the corpus

	Number of Bays in X Axis:							
Number of Bays in Y Axis:	0	1	2	3	4	5	6	7
	1	square dome						
	3	1 aisle	6 domes	9 domes				
	5		10 domes	15 domes	*			
	7			*	With vault	35 domes	*	
	9			With vault	*	*	*	*
	11				44 domes	*	*	With vault

Fig 3.17b- Chart showing the number of possible mosques in the language. The mosques represented by dark grey colors are not legal, medium grey are already in the corpus (D), light grey with star are new and legal (D") and light grey without star are other possible mosque(D'). White color represents mosques that the grammar can not generate.

Chapter 04.

The Vocabulary of Sultanate Mosques.

A language of design can be generated in different phases and shape grammars construct the designs in the language. The vocabulary elements of the design, shape rules and initial shapes construct the grammar and then this grammar will generate a language of designs. Vocabulary elements can sustain a variety of spatial relations which will help to develop the shape rules. Finally a language of design will be defined after applying these shape rules to the initial shapes (Stiny, 1980b). This chapter will describe the vocabulary elements of Sultanate mosque's grammar, which are tied to the features described in the previous chapter (3). I propose an analytical grammar for generating the plans of the Sultanate mosque's style which will help to understand and describe the style systematically. The grammar will not only generate the new examples of the style but also give an explanation whether the new designs, not found in the corpus belong to the style.

4.1 Vocabulary elements:

To the extent of my knowledge, all the architectural shape grammars developed so far to create an architectural plan is the first stage of the generation process and these plans determine other characteristics of the design. Mitchell, Liggett and Pollalis (1991, p19) stated that:

> "The shapes that appear in rules may be actual construction elements and spaces, or they may be abstract shapes and volumes that serve as construction lines, grids, axes, placeholders for later substitution of something else, and other devices that guide the development of a design."

A shape grammar contains a vocabulary, a set of shape rules, and an initial shape and it defines the shapes that can be generated in the vocabulary. By applying the shape rules recursively to the initial shape, we can generate a design

in the language. (Stiny and Gips,1972, pages 1461-1462). Downing and Flemming (1981, p269) also stated that:

"All shape grammars dealing with the generation of architectural plans create, at the initial stage, a geometric pattern which determines the compositional characteristics of the plans"

There are two approaches that one can follow in the definition of a grammar for generating plans. In the first approach a rectangular shape or grid is first generated and then developed in order to generate a detailed plan in further stages. This approach can be found in the Palladian grammar where the generation of a Palladian plan starts with the definition of a tartan grid and define the possible locations of internal and external walls at the later stage (Stiny and Mitchell, 1978). In the Bungalow's grammar a rectangular plan is divided into two horizontally and two or three vertically rooms in first stage of the generation process (Downing and Flemming,1981) and in the grammar of Japanese tea rooms, the initial shape of the grammar is the smallest bilaterally symmetric grid with the proportions of 2m×n (Knight,1981).

In the second approach, the grammar starts by locating a space and the other spaces are added to the plan composition in further stages. Queen Anne grammar is an example of this type of approach. In this grammar the hall is the main design element and is located in the first stage of the generation process. In further stages spaces for other functions like the kitchen, the bedrooms and the stair halls are located to generate the plan layout following the shape grammars rules (Flemming, 1987). In the grammar of traditional Turkish houses the generation process starts by placing a polygonal hall. The main vocabulary elements are rooms and halls with polygonal forms (Cagdas, 1996, page 443-464).

According to the description in chapter 2, large mosques are constructed by simply multiplying the square module. So in the proposed grammar the first approach has been chosen to generate the plan of Sultanate mosque. The main vocabulary elements of the grammar are two-dimensional square and rectangular forms, and these represent a cell underneath a dome or a four segmented vaulted roof (*Do chala roof*), and are used as initial shapes (fig 4.1, fig 4.2). A bilateral symmetric grid is defined that consists of the square cells. The various categories

of the mosques are defined in the first stage of the grammar depending on the number of cells added in the east–west and north–south directions. The generation process begins by locating equal square cells bilaterally to the initial shapes in north south direction and one cell at a time in the west direction as the number of cells in the north-south direction should be odd in number and the number of cells in the east-west direction could be odd or even in number. Each cell is separated from its immediate adjacent cell by the distance of a column thickness (fig 4.5). The other vocabulary elements of the plans are columns, towers, wall and *mehrab* on the west wall and the openings on the east wall. The other vocabulary elements of the grammar are used and combined together to generate a complete mosque layout in the remaining stages.

The generation process of a design in this grammar encompasses four stages. The composition of the plan for a mosque is obtained in the first three stages. The detailing of a plan layout will be generated in the last stage. Towers, *mehrabs,* wall niches, windows and doors are added to the basic plan according to the Sultanate style of Bengal to produce a complete plan.

4.2 The formation of the grammar:

A non parametric shape grammar is presented in this paper using the above mentioned characteristics. According to the observation described in chapter 2, this grammar develops the plans in a bottom-up approach, where simple elements that are added to generate more complex forms, and it defines the architectural language of the Sultanate mosque. The grammar is composed of two set of rules that encode the architectural characteristics described in chapter 2. As the corpus contains a large number of square mosques with a single dome and square mosques with verandah and single aisle mosques with 3 domes, a separate set of rules are created for this category. For multi aisle mosques another set of rules are created. The rules, that form the grammar, will determine the expression of the language. Starting from square and a rectangle, which are the two initial shapes for this grammar, the rules will compose a grid by adding squares in 'T' directions to formulate the basic plan of the mosque.

The walls, columns, corner towers and *mihrabs*, doors and windows will be added in advanced stages.

To generate the complete plan of the mosque, the grammar includes a starting shape and two sets of rules that operates through four different stages. Each stage is either deterministic or nondeterministic. The first and the fourth stages are nondeterministic. The sub shape of each stage will be created with the help of the user following his or her decision. The second and the third stages are deterministic. The rules of the second and third stages are applied to the sub shape from the first stage deterministically and there is only one possible output. In the last stage, the output again depends on user's decisions. For the rule set A there are only three stages. In the second stage, rule set 'A' is omitted as the rules set 'A' generates the single square dome mosques and single aisle mosque. Briefly, this non parametric shape grammar consists of two initial shapes and two sets of rules, which will be described clearly below. The two initial shapes are a square and a rectangle. And the two sets of rules are:

- Rule set 'A' belong to the single dome and single aisle mosques plans;
- Rule set 'B' belong to the multi aisles mosques plans.

The starting shape: Every shape grammar usually starts with a basic geometric form to generate the plans of any architectural language. In this mosque's grammar, the two initial shapes will generate the grid using a 'T' algorithm (fig 4.4). As soon as these initial shapes are finalized the set of rules of stage 1 will be applied to generate the 'T' in further stages.

Stage 1 (Generation of the Starting Unit): This is a nondeterministic stage. This stage will determine which type of mosque's grid the user wants to produce. Through this stage it is possible to fix the number of the cells in both the X and Y directions ('X' will represent the east-west direction and 'Y' will represent the north-south direction). For the square initial shape both sets of rules are applicable but for the rectangular shape only the 'B' set rules are applicable. As this grammar has two initial shapes, two set of rules are needed to generate the grid system in this stage. For the square initial shape the 'A' set of rules will be applied to formulate the square shape mosque and its categories, as well as the single aisle mosque. The rules of this stage will add one square cell bilaterally in the Y or north-south direction (representing the aisles of the

mosque) for the single aisle mosque separate rules will be applied to the initial shape to formulate the basic shape for the square shape mosque's plan. And the sub shape of this stage will be ready for stage 3. Stage 2 is not applicable to the sub shape of this stage as the shapes do not need to generate the grid or insert the columns in the plan types (fig 4.3).

For the square initial shape the 'B' set of rules will also be applied in 'T' direction to formulate the double aisles and multi aisles mosques. The rules of this stage will add square cells bilaterally in the Y direction (representing the aisles of the mosque) and then add square cells (representing the bays of the mosque) in the X direction (fig 4.4).

But for the rectangular initial shape, which is one and half of the square, the 'B' set of rules will applied in 'T' directions to formulate the multi aisles mosque with a vaulted nave in the center. The rules of this stage will add square cells bilaterally in the Y direction (representing the aisles of the mosque) and then add one rectangular cell (representing the central bay of the mosque) in the X direction. When the numbers of cells for both initial shapes are equal in both directions then the rules of stage 2 will be applicable to the sub shape of stage 1(fig 4.5).

Stage 2 (Formatting the Grids and Forming the Columns): This is a deterministic stage. The rules of stage 2 will be applied to the sub shape of stage 1 to fill the corner of the 'T' to complete the grid (fig 4.4 & fig 4.5). At the same time the rules will be applied to form the columns along with the square cells. The labels of the shape help to define the deterministic approach. This approach will continue to stage 3.

Stage 3 (Formatting the Walls around the Complete Grid): This stage continuous the process from the previous stage. The rules of this stage will help to locate the walls around the grid plan and change the labels to make the grid suitable for further stages. This stage will generate only one possible subshape formed by placing walls around the grid from stage 1, which is then ready for locating openings and *mehrabs* on the walls (fig 4.4 & fig 4.5).

Stage 4 (Locating the Corner Towers and the Openings on the Walls): This is again a non deterministic stage. The user decides the position of the towers, doors, windows and *mehrabs.* The corner towers of the mosque will be placed with the help of the rules. The doors, openings, *mihrabs* of the plan will

be located according to the defined rules. And it will remove all the labels from the complete plan. In this last stage it will be possible to have the complete plan of the mosque. And the grammar may be able to generate all (and only) the designs in the language (fig 4.4 & fig 4.5).

As the grammar will be developed by the Grammar Environment (Li et al, 2009), there are some limitations to develop an actual architectural plan through this interpreter. Actual architectural plan needs to show the line variations to express the different levels of the plan. With the help of the shape grammar methodology it is possible to express the line weights but the interpreter does not able to illustrate the line weights. For that reason the final plan from the grammar will have some small points inside the walls to guide the user regarding which is a cut or a non cut surface in the plan.

Chapter 05.

Stage 1: Generation of the Starting Unit.

As mentioned in the previous chapter this is a nondeterministic stage. This stage will determine which type of mosque (according to the corpus) the user wants to produce. Through this stage it is possible to fix the number of cells in both the X and Y directions ('X' will represent the east-west direction and 'Y' will represent the north-south direction). In other words, 'X' will represent the number of aisles, which can be odd or even in number and 'Y' will represent the number of bays which is odd in number.

5.1 Concept:

In this stage the basic frame will be generated to define a complete grid. So the question remains, what is the basic concept to generate the unit? In the multi domes mosque, the number of bays and the number of aisles are not limited. According to the examples in the corpus these mosques are bilaterally symmetric and the largest mosque in the corpus consists of seven aisles in the 'X' direction and eleven bays in the 'Y' direction. And the longest mosque of the corpus has three aisles in the 'X' direction and twenty one bays in the 'Y' direction (fig 5.1). As described in chapter 2, the multi aisle square mosque has only three bays and aisles in both directions. The limit is three for this type of mosque. So we can say that for the multi aisles square mosque X=Y=3 and for the multi aisle mosque $X \leq 7$ and $Y \leq 11$ and if we look at the chart (fig 2.17a) representing the number of mosques in the corpus in the light gray color, we can see that there are no more mosques after 11 bays in the Y direction. One more thing we have to consider, that Bengal mosques are oblong in shape in the north south direction rather than linear. And the mosques should not be too linear in the east-west direction since Muslims prefer to say their prayer in one long line facing the west. The proportions may be varied but should not be too linear so that every person may conveniently hear and see the *Imam* (leader of the

religious worshippers) during their prayer (Naqi, 2002). So the main constraints to generate the basic unit are:

- The maximum number of bays for single aisle mosque is 3.
- The maximum number of bays and aisles for the multi square mosque is 3.
- For multi aisle mosques, the maximum numbers of aisles in the 'X' direction is 7.
- For multi aisle mosques the maximum numbers of bays in the 'Y' direction are 11.
- The center bay of the multi aisle mosque with a vaulted nave is wider than the adjacent bay.
- The center bay represents the central *mehrab* and is faced towards Mecca on the west.
- The mosques should not be too linear in the east-west direction and in the north-south direction.

5.2 The algorithm:

Stage 1 is a non deterministic phase. An inverted T is used for this grammar as in the Palladian grammar (Stiny and Mitchell, 1978) and in the *Yingzao fashi* grammar (Li, 2001). Both of these grammars start by generating the center cell and then add cells in width and in depth to form a T of a preferred size. Lastly, the corners of the T are filled out to generate a complete rectangular grid.

For this grammar to compose the T, the first center cell is generated and then cells are added one by one in the Y or north south direction, and then cells are added adjacent to the center cell in the X direction or east-west direction. But the process of filling out the corners of the T is different from the Palladian and the *Yingzao fashi* grammars. Since the generation process is carried out with the help of Grammar environment it is not possible to follow the same procedure due to limitations of the system. This will be discussed in the next chapter.

Initial shape:

For this grammar there are two initial shapes (fig 5.2) namely a square (IsA) and a rectangle (IsB) of standard size. But the length of the rectangle is one and half of the square. The dimensions of a plan are based on multiples, n' and n", of a modular length m. The labels of the square shapes are w1x, sy, a, ny where w, s, n represents the west, south, and north directions. Label a will be changed to e to represent east in a later stage. And the labels for the rectangle shape are the same, except for the w2x1 label and label a will be changed to e1 in the second stage.

- Labels ny and sy indicate that the cells can be added to the north and south ends of the inverted T on the north-south axis.
- Labels w1x for square and w2x1 for rectangle indicates that cells can be added in the west direction on the east-west axis.
- Label a will change to e in the case of square shape and e1 in the case of a rectangular shape. These labels will be used in Stage 3.

Rules sets:

Both sets of rules are applicable at this stage.

- Rule set 'A' belongs to the single dome and single aisle mosques' plans;
- Rule set 'B' belongs to the multi aisles mosques' plans with and without a vaulted nave.

Rules set A is applicable to the square initial shape IsA only, but rules set B is applicable to both initial shapes IsA and IsB.

Rule set A: The first 6 rules are applicable to the IsA shape (fig 5.3 a,b). When the first rule A01 is applied to the initial shape the label point a is replaced with the point e so that the first rule cannot be applied again. Then the rules A04, A05, A06 are applied to the sub shape one by one to replace labels ny, sy, w1x to n, s, and w1. The sub shape of this stage will be used in stage 3 to generate the single dome square shape mosque (fig 5.4).

Rule A02 is applied to the initial shape to add a cell which is ½ of the square cell at the label point a. And the label point a is replaced with the point e so that the first rule cannot be applied again. Each cell is separated from its adjacent cell with the distance of a column thickness. Then rules A04, A05, A06

are applied to the sub shape one by one to change labels ny, sy, and w1x to n, s, and w1 respectively. The sub shape of this stage will be used in stage 3 to generate the single dome mosque plan with verandah (fig 5.4).

Rule A03 is applied to the initial shape to add square cells at the label point ny and sy. And the label point a is replaced with the label e so that the first rule cannot be applied again. Then rules A04, A05, and A06 are applied to the sub shape one by one to replace labels ny, sy, w1x to n, s, w1.The sub shape of this stage will be used in stage 3 to generate the single aisle mosque plan (fig 5.4).

Rule set B: The first 10 rules are applicable at this stage to the both shapes IsA and IsB. Rules B01, B03, B04, B05, B07, B08, and B09 are applicable to the initial shape IsA to generate the inverted T for double aisles or multi aisles mosques and rules B02, B03, B04, B06, B07, B08, and B19 are applicable to the initial shape IsB to generate the inverted T for multi aisles mosques with vaulted nave.

The first rule B01 is applied to the IsA shape to add square cells at the label point ny and sy. Each cell is marked with the label yn and ys on the west side of the cell and the label e on the east side of the wall. And the label point a is replaced with the point e at the center cell. The center cell also has the label w1x on the west side and label x at the both sides of the center cell. Rules B03 and B04 increase the number of square cells bilaterally at the label point ny and sy. Rule B05 is applied to increase the numbers of cells at the label point w1x. Each cell is separated from its adjacent cell with the distance of a column thickness. The value of X and Y depend on the user. When the user decides the number of cells in both directions then rules B07, B08, and B09 are applied to the sub shape one by one to change labels ny, sy, and w1x to n, s, and w1 to fix the end point of the inverted T. So that more cells can be added after these rules have been applied. In this way the rules of this stage generate the inverted T to define the complete grid in stage 2 (fig 5.5a).

The rule B02 is applied to the IsB shape to add a square cell at the label point ny and sy respectively. Each cell is marked by the label yn and ys on the west side of the cell and the label e on the east side of the wall. And the label point a is replaced with the point e1 on the center cell. The center cell also has the label w2x on the west and label x1 on both sides of the center cell. Rules B03

and B04 increase the number of square cells bilaterally at the label points ny and sy. Rule B06 is applied to increase the numbers of cells at the label point w2x1. Each cell is separated from its adjacent cell with the distance of a column thickness. The value of X and Y depend on the user. When the user decides the number of cells in both directions then rules B07, B08, and B09 are applied to the sub shape one by one to change labels ny, sy, and w1x1 to n, s, and w2 to fix the end point of the inverted T. So that more cells cannot be added after these rules have been applied. In this way, the rules of this stage generate the inverted T to define the complete grid in stage 2 (fig 5.5b).

5.3 Result and discussion:

The sub shapes generated by the A set of rules are fixed in this stage. In this stage, the rules can only generate sub shapes of three types. As per the observation for the single aisle mosque no such rules were created that can generate single aisle mosques with five or seven bays as these mosques would be too linear and would create visual and hearing difficulties for those saying their prayers. That is why the rules have been fixed to generate only single aisle mosque with three bays. The sub shapes, generated by this rule set do not regenerate to go through stage 2.

With the application of B set rules, the user can generate both new and mosques in the corpus. The configuration of such mosques depends on the linearity in the east west direction and in the north south directions of the mosque. Too linear mosques are not suitable to do the prayer. It is better for the user to choose which type of mosque he or she wants to generate in this stage. For instance, here I show the generation of three types of mosques- double aisles, multi aisles without vaulted nave and multi aisles with vaulted nave. The mosques generated according to this process may be or not acceptable but after completion of the generation process the resulting mosques can be judged using the basic criteria described in the chapter 3.

As I am developing the grammar with the help of the Grammar environment it is not possible to generate the inverted T in the same way as in the Palladian grammar and in the *Yingzao fashi* grammar. The rules of these

grammars add two cells at a time beside the center cell and then add one at the top of the center cell to generate the T but for the current grammar it is not possible to add two cells at a time because the prototype system is unable to encode a parametric grammar. Thus, instead of adding two cells at the same time it adds cells one by one beside the center cell to define the T.

Chapter 06.

Stage 2: Formatting the Grids and the Columns.

This is a deterministic stage. This stage will fix the grid of a mosque's plan by adding cells to the 'T' generated in stage 1. At the same time columns are added to the plan.

6.1 Concept:

This stage will generate the complete grid of a mosque's plan. In the previous stage the total numbers of bays and aisles have already defined by constructing the 'T'. As we know that the width of the bays and the width of the aisles are equal, no other types of cells could be added to the 'T' except for basic square cells. This square cell is the basic module for all Sultanate mosques. For instance, this square cell is simply multiplied to form a large mosque with a central bay or with a central bay with vaulted nave and equal number of bays on either side. This produces either a large square mosque with equal number of aisles and bays (9 domes) or a rectangular mosque with unequal number of bays and aisles. The width of each cell represents the width of an aisle and the length of each cell represents the width of a bay. Each bay is represented by a small dome roof formed by four non monolithic columns. These columns are established in the nine-domed, double aisles mosque and in the multi aisles mosque to support the domes above. Normally columns are either circular or octagonal in shape with a square base, but there are no fixed dimensions for these columns. The columns are used with different dimensions in different mosques. Sometimes the dimension of a column may 1/3 or ¼ or 1/5 of the square module. To make the grammar simple, the column that has been chosen is a square shape column with a dimension that is 1/5 of the square unit.

So the main constraints to define the grid and the column are:

- The square module is multiplied to generate a large square or rectangular mosque.
- Each square is represented by a small domed roof formed by four monolithic columns.
- The columns are normally circular and octagonal in shape with a square base.
- The dimensions of the columns are also variable.
- To make the development of the grammar simple, it was decided to use only columns with a square shape and with a width that is ¼ of the square module.

6.2 The algorithm:

Stage 2 is a deterministic phase. Modular square cells are added to the either side of the inverted- T to complete the grid. But the algorithm for adding cells in this grammar is different from the ones in the Palladian grammar (Stiny and Mitchell, 1978) and in the *Yingzao fashi* grammar (Li, 2001). In both of their grammars firstly two cells are added bilaterally next to the middle arm of the 'T'. And lastly the corners of the T are filled out by adding the cells to generate a complete grid.

The algorithm used in the current grammar fills out the corners a different way because the generation process is carried out with the help of Grammar environment (Li, 2009) which presents some limitations. With the help of this system the rules of the grammar can only add one cell at a time next to another cell. But if I want to add two cells at a time along with the center cell, I have to create the rules in such a way that when each rule will be applied to the sub shape it will only add two cells for that shape. But the same rule cannot be applicable to the sub shape to add a cell. I need to apply another rule for adding more cells. For instance if the 'T' contain seven cells in the north-south direction and three at the east-west direction, so six cells should be added in north south direction with the middle cell. If one rule can add two cells at a time then three rules are needed to complete one line of the grid. If I want to reduce the number

of the rules, I need to generate the rule in such a way so that one rule could add six cells to the 'T' consecutively. In this stage the grammar will run deterministically which means that the user has no choice. When the user gets the sub shape from the previous stage he can only choose the suitable rule which should be applied first in this stage.

For that reason to run the grammar deterministically it is better to start from one side to fill the 'T'. The algorithm of this stage generates the grid by adding cells with a column together from the bottom corner of the 'T' and move upward to the label point 'ny' in the north direction. Then the labels will be changed to suitable labels for adding cell and column by moving downward to the label point 'sy' in the south direction Then the cell and a column will be again added by moving upward to the label point 'ny' in the north direction and this jig-jag process is continued until the label points 'w1' or 'w2' are placed. As soon as these two labels are placed cells and columns are no longer added and a complete grid is ready for stage 3.

Rules sets:

One set of rules is applicable at this stage. Rule set A is not applicable at this stage but rule set B is applicable to the 'T' formed in the previous stage (fig 6.1).

Rules set B: Rule B11 to rules B21 are applicable at this stage to both shapes IsA and IsB. Rule B11 to B21, except for rules B13a, B14a, and B18a are applicable to shape IsA to generate the grid for double aisles or multi aisles mosques without vaulted nave and rules B11, B12, B13a, B14a, B15, B16, B17, B18a, B19, B20, B20a and B21 are applicable to shape IsB to generate the grid for multi aisles mosques with vaulted nave.

The sub shape 'T' represents south and north part by the labels sy, ys and ny, and yn. Different rules will be applied for these two parts. Firstly rule B11 is applied to the square cell at the south side of the 'T'. The label sy and ys of this cell specify how to add a new cell for the first time and then label sy is replaced by label s. Each new cell is also marked with the new label w on its west side and the label y1 on its north side. Label y1 is a state label and it is only used in this stage for adding cells. At the label y1, rule B12 locates a column and one cell labeled w and y1. The process is continuous until the label x is placeed. Rule

B13 locates only a column and changes the label x to y1. Rule B13a is applicable to the shape IsB and to label x1. The function of this rule is the same as rule B13. Rule B14 is applicable to the north side of the 'T'. This rule is applied to a cell with label yn to add a new cell and this new cell will be also marked with the new label w on the west side and the label y1 on the north side. Rule B14a is applicable to IsB and the function of the rule is the same as rule B14. Rule B15 changes the label y1 to n when the last cell contains label n and this terminates the addition of cells in the Y (north) direction. Rule B16, B17, B18, and B19 alter the label w to yn and ys by moving downward to the south direction. Rule B18a is applicable to shape IsB and label x1. After alter the labels again rule B11 is applied to add a cell at the label ys. And the process is continued until the label w1 or the label w2 is identified. Then the process of adding cells is stopped and rule B20 removes the cell from the bottom of the cell containing label w1 or label w2 in double aisles grid, and rule B20a removes the cell and column in multi aisles grid. These rules also change label ys to w and keep the label y1 and complete the grid. Rule B21 changes label from w to w3 at the south-west corner to make the grid ready for stage 3 (fig 6.2a & fig6.2b).

6.3 Result and discussion:

The shape used as input for this stage is the sub shape generated in the previous stage. This stage generates the complete grid with fixed values of X and Y and the generation process can define only one complete grid at a time.

In the first plan the value of X is 5 and the Value of Y is 3. It has 4 rows of columns. This type of mosque is not available in the corpus of Bengal mosque but it can be found among early mosques of Islamic architecture. So may be it is an acceptable design. In the second plan X=2 and Y=3 and it has one row of columns and it is present in the corpus. In the third example the value of X is 3 and the value of Y is 5 and it has two rows of columns, and it is also present in the corpus. All the examples are generated by shape IsA

In the first example generated by shape IsB, the value of X is 3 and the value of Y is 5 and it contains two rows of columns. In the second example the

value of X is 4 and the value of Y is 7 and it contains three rows of columns and it exists in the corpus.

The mosques generated after stage 2 may or may not be acceptable, but acceptance may be checked after the derivation process is terminated using the basic criteria described in section 3.3.

In stage 3 a wall will be added to the grid and both sets of rules are applicable at this stage.

Chapter 07.

Stage 3: Formatting the Walls around the Complete Grid.

This is also a deterministic stage. Walls in this stage are added around a single dome, a single aisle, and a complete grid plan. The users have also no choice in this stage.

7.1 Concept:

As mentioned in chapter 2 the wall thicknesses of the mosques are huge and *mehrabs*, windows, doors, and niches are placed in these thick walls. The main constraints to define the walls are:

- For single dome mosque and for the single aisle mosque the thickness of the wall is ¼ of the square cell.
- For multi domes mosque the thickness of the wall is ½ of the cell.

7.2 The algorithm:

Stage 3 is a deterministic phase. Only one sub shape is generated in this stage. Modular line segments are added beside the square cells to complete the plan diagram. The algorithm of this stage starts by adding a wall from the south-west corner of the grid where the cells were stopped being added by label w3 in stage 2 and move forward with the wall in a clock wise manner. Label point 'z1' helps to add a wall to each cell at a time by moving around the grid. When label z1 meets label tw at the south-west corner the sub shape of this stage is ready for the final stage.

Rules sets:

Both sets of rules are applicable at this stage.

- Rule set 'A' belongs to the single dome and single aisle mosques' plans;
- Rule set 'B' belongs to the multi aisles mosques' plans without vaulted nave and with vaulted nave.

Rule set A is applicable to the shape that is generated in stage 1 and rule set B is applicable to shapes that are generated in stage 2.

Rule set A: Rules A07 through A15 are applicable at this stage to the sub shape generated in the stage 1 (fig7.1). The first rule A07 is applied to the shape at the point w to replace the label with a wall which width is ¼ of the cell. And label w is placed in the middle of the outer line of the wall and label o is placed in the middle of the inner line of the wall. These two labels will help to place the *mehrab* on the west wall in the final stage. Another label tw is also placed in the south-west corner to add a tower in the final stage and label z1, which is located on the south-east corner, controls the application of a rule for adding a wall to the next side. Rule A08 and rule A09 add walls on the south and the east sides of the cell with label ts on the south-east corner and the label z1 move forward to the north-east corner of the cell. Rule A10 and Rule A13 will add a wall to the middle cell of the single aisle grid. And label w1 is replaced by label w1 in the outer line of the wall. Rule A11 adds a wall on the north side of the wall and label te is added on the east-north corner of the cell. Rule A12 adds a wall with the label tn on the west-north corner of the cell. Rule A14 also adds a wall on the west side of the cell in a single aisle grid. Label o is added in the middle of the inner line of each cell. On the south, east, and north sides label o will add doors, windows, and niches and the *merabs* will be added on the west side of the cell. At the end, label z1 stops adding a wall and the sub shape of this stage is ready for the final stage.

Rule A15 is applied to the sub shape that is generated by rule A02 in the first stage to add wall around the cells. The shape has the labels tw, ts, te, and tn on its four corners. And the label point o is placed in the middle of the four sides of the wall.

The sub shapes of this stage will be used in stage 4 to generate plans of the single aisle mosque, the single dome mosque and single dome mosque with corridor. (fig 7.3).

Rules set B: Rules from rule B22 to rule B32 are applicable at this stage to the shapes generated in stage 2. Rule B26a and rule B32 are applicable to the wider cell containing the label e1 and w2 (fig 7.2).

Rule B22 starts adding the wall from the south-west corner cell, which has labels w3 and y1, and adds label z1. Label tw is added on this corner. Rule B23 adds a wall on the south side of this corner cell with labels s and o. Rule B24 adds the wall to the middle cells which are in between the south-west and south-east corners. Label s and o are placed in the outer and inner lines of each cell. Rule B25 adds a wall to the south-east corner cell and places label ts on this corner. And label z1 moves clockwise to add the wall and generate only one sub shape at each step. Rule B26 adds the walls to the middle cells from the south-east corner to north-east corner. And labels e and o are added in the middle points of the outer and inner lines of each cell. B26a is applicable to the wider cell at label e1. Rule B27 adds the wall on north-east corner cell and places label te on this corner. Rule B28 adds the walls to the middle cells that are in between the north-east and north-west corners. And labels n and o are added in the middle point of the outer and inner lines of each cell. Rule B29 adds the wall on north-west corner cell and places label tn on this corner. Rule B30 adds the walls to the middle cells that are in between the north-west corner and south-west corners. And labels w and o are added in the middle points of the outer and inner lines of each cell. But labels B31 and B32 add a wall only to a cell which that has either a w1 or a w2 label and these shift to the outer line of the wall.

The sub shape that is generated in this stage has label z1 on the south-west corner cell, which stops the addition of walls and transmits the shape to the next stage (fig 7.4a & fig 7.4b).

7.3 Result and discussion:

The sub shapes generated by the A set rules in this stage are fixed. In this stage, the rules can only generate 3 sub shapes of three types. The first example represents a single dome mosque. In the second example, which has a verandah or corridor at the front (east side), a thick wall is also placed in between the main hall and the verandah. On the single aisle mosque that has a 3 bays, each bay is represented by labels to add openings in a later stage. The labels indicate the location of the towers, the *mehrabs*, and the openings. The number of openings is also varied in the single dome mosque and in the verandah mosque. The openings vary from one to three in these two types mosque.

But with the application of B set rules, the user can generate a number of new possible mosques in the corpus along with the mosques that are in the corpus. For instance, generation of three types of mosque - double aisles, multi aisles without vaulted nave, and multi aisles with vaulted nave have the walls and the labels for towers, *mehrabs*, and openings. The final stage is a nondeterministic stage and it depends on user decisions.

The grammar is generates two-dimensional ground plans of mosques, but due to limitations of the shape grammar interpreter it is not possible to show line weights or and differentiate cut and non cut surfaces of the plan. That is why the rules add dots inside the walls along with the labels to symbolize the cut surface of the plan. The outline of the grid remains in the plan to represent the dome above as it is not possible for the interpreter to draw a dotted line.

Chapter 08.

Stage 4: Locating the Corner Towers and the Openings on the Walls.

This is a nondeterministic stage. This stage will determine which type of mosque is going to be produced. Through this stage the finished mosque's plan will be generated with all details of the plan.

8.1 Concept:

As we know that the *qibla* wall of the prayer hall must be faced towards Mecca, in the Bengal region it is located on the west side wall. The wide *mehrab* is placed in the mid point of this wall and other small *mehrabs* are placed bilaterally on both sides of the central *mehrab*. In Bengal mosques, the number of *mehrabs* on the west wall depends on the number of the openings on the east wall. The forms of *mehrab* can take two shapes: it is either semicircular or half square in plan and it has either a semicircular arched top or a stagger flat roof on the top. As the grammar will only generate two dimensional plans of Sultanate mosques three dimensional features are omitted in the development of the grammar. Frequently the central *mehrab* is more decorated than the succeeding *mehrabs*. Normally, the main entrances are placed on the east wall. The openings on the north and south walls become windows or doorways or niches. In multi dome mosques, each bay is terminated with an entrance on the east wall and a *mehrab* on the west wall. And each aisle is terminated either with windows or doors or niches on the north and south walls. For single dome mosques the number of *mehrabs* varies from one to three on the west wall and so the number of openings also varies from one to three on the other three walls. The single dome mosque with verandah also has one or three *mehrabs* on the west wall and one to three openings on the other three walls. The number of openings in the wall in between the prayer hall and the verandah also depend

on the number of the *mehrabs*. Various combinations between the *mehrabs* and the openings can be found in the mosques of the corpus. These variations were taken into account in the development of the rules for this stage.

The corner towers are another feature common to all Sultanate mosques. Two types of corner towers are found at the four corner of the mosque – circular and octagonal. To make the grammar simpler I consider only an octagonal shape for the tower. The main constraints in this stage are:

- The central *mehrab* should be wider and more decorated than the other *mehrabs*.
- The number of entrances on east wall depends on the number of *mehrabs* on the west wall.
- Four octagonal towers are placed at the four corner of the mosque.

8.2 The algorithm:

The algorithm of this stage is very simple. For the Multi dome mosque, start from one bottom corner of the outer cell where label z1 stopped adding walls in stage 3, the detail *mehrab* is added to each of the cells on the west wall by moving upwards. And door, windows, and niches are added to the cells by moving counter-clockwise from north to south. Label points 'wo' 'no', 'eo' and 'so' help to add all the detail features to the wall of each cell by moving counter-clockwise around the grid. And this stage is terminated by erasing the labels on the south side of the shape there by forming a complete plan of the mosque. But for the single dome square shape mosque, the details are added on 'L' and a counter 'L' manner. Firstly the details on the west and south side walls are added together on shape fashion 'L' then the details for the north and east side walls are added together in a counter 'L' fashion. When all the details are added, all the labels are erased simultaneously. For the single dome square mosque with verandah, the details of the west wall are first added then the details of the east wall are added. Finally, the details of the south and north walls along with the verandah wall are added and all the labels are erased at the same time. The algorithm for the single aisle mosque is almost the same as for multi dome mosques. Each rule represents a detail of the wall.

Rules sets:

Both sets of rules are applicable at this stage.

- Rule set 'A' belongs to the single dome and single aisle mosques' plans;
- Rule set 'B' belongs to the multi aisles mosques' plans without vaulted nave and with vaulted nave.

Rules set A is applicable to the shape that is generated in stage 3 and rule set B is applicable to shapes that are generated in stage 3.

Rule set A: Rules A16 to A62 are applicable in this stage to generate the final plans of the mosques (fig 8.1 a,b,c,d). Rules A16 to A37 are applicable to single dome square mosque and to single aisle mosque. Rules A16, A18, A20, A21, A22, A23, A25, A27, A29, A31, A32, A34, and A36 are applicable to the 'L' formed by the west and south walls. *Mehrabs* are added on the west wall and openings or niches on the south wall. Two towers are placed at the south-west and south-east corner of the square. And rules A17, A19, A24, A26, A28, A30, A33, A35, and A37 are applicable to the counter 'L' formed by the north and east side walls. Main entrances are added on the east wall and openings or niches on the north wall. Two towers are placed at the north-west and north-east corner of the square. Although this is a single dome square mosque some of the mosques have three *mehrabs* on the west wall and three entrances on the other three sides of the mosque.

Rules A38 to A47 are applicable to single aisle mosque from. Rules A38, A39, and A40 are applicable to the cell that has the labels w and o on the west side of the wall. Then rules A41, A42, and A43 are applicable to the cell that has labels w1 and o in the middle of the west wall. Rules A44, A45, A46 and A47 are applicable to the cell that has only labels e and o on the east wall.

Rules A48 to A62 are applicable to the single dome square mosque with verandah. Rules A48 to A54 are applicable to the west wall of the shape and it adds *mehrabs* and two towers on the south-west corner and on the north-west corner. Rule A55 and rule A56 place the two towers on the south-east and on the north-east corner and entrances on the east wall.

Rules A57 to A62 add openings or windows or niches on north and south walls and also on the middle wall of the verandah. Finally, the complete plans of

the mosques are generated without any labels and small points are placed inside the wall to symbolize the cut surface of the plan (fig 8.3).

Rule set B: Rules B33 to B115 are applicable at this stage to the shapes generated in stage 3. Rules B67 to B70 are applicable to the wider cell that contains label w2 and rule B98 is applicable to the wider cell that contains label e1 (fig 8.2 a,b,c,d,e).

Rules B33 to B42 are applicable to the south-west corner cell that contains label z1. This label stops adding walls in the last stage and is replaced by the label wo to add the details to this corner cell. This cell contains labels w, o on the west, and s, and o on the south, and tw on the south-west corner. A tower is placed along with the *mehrab* on west wall and openings or niches on the south wall by the application of these rules.

Rules B43 to B52 replace labels w and o with a *mehrab* in the cells on west side. Rules B53 to B66 are applicable to the middle cell that has labels w1 and o and these labels are replaced by a bigger *mehrab* and then by the succeeding *mehrabs*. Rules B67 to B70 are applied to the wider cell with label w2.

Rules B71 to rule B80 are applied to the north-west corner cell that has label tn on the north-west corner and labels w, and o on the west and labels n, and o on the north side of the cell. These labels are replaced by the *mehrab* on the west side and openings or niches on the north side of the cell and a tower is placed at the label point tn. At this phase of the generation, the label 'wo' is changed to label 'no' to add the details for this side.

Rules B81 to B86 are applicable to the cell that has label n and o on the north side. These labels are then replaced either by doors or widows or niches.

Rules B87 to B96 are applied to the north-east corner cell that has label te on the north-east corner and labels e, and o on the east and labels n, and o on the north side. These labels are replaced by the entrances on the eastside and openings or niches on the north side of the cell and a tower is placed at the label point te. At this point of the generation label 'no' is changed to label 'eo' to add the details for this side

Rule B97 is applied to the cells that have labels e and o. Both the labels are replaced by the entrances on this side of the cell. Rule B98 is applied to the

wider cell that has labels e1 and o. Both labels are replaced by the wider entrances on this side of the cell.

Rules B99 to B108 are applied to the south-east corner cell that has label ts on the north-east corner and labels e, and o on the east and labels s, and o on the south side. These labels are replaced by the entrances on the east side and openings or niches on the north side of the cell and a tower is placed at the label point ts. At this point of the generation label 'eo' is changed to label 'so' to add the details to this side.

Rules B109 to B114 are applicable to the cell that has labels s and o on the south side. These labels are replaced either by doors or widows or niches on this side. At this point the grid of a mosque turns into a complete plan of a mosque with the all details. Finally, rule B115 is applied to erase label 'so' and small points are placed inside the wall to symbolize the cut surface of the plan (fig 8.4a & fig 8.4b).

8.3 Result and discussion:

The sub shapes generated by the A set rules in this stage are fixed. In this stage the rules generate 3 final shapes of three types. The first example represents a single dome mosque. In the second example which has a verandah or corridor at the front (east side), a thick wall is also placed in between the main hall and the verandah. In the single aisle mosque which has 3 bays, each bay is represented by labels to add openings in a later stage. The labels indicate the location of towers, *mehrabs,* and the openings. Through the application of the rules in this stage it is possible to generate not only all the mosques in the corpus but also new ones not in the original corpus.

With the application of B set rules the user can generate a number of new possible mosques in the corpus along with existing mosques. For instance, generation of three types of mosque - double aisles, multi aisles without a vaulted nave and multi aisles with a vaulted nave have the walls and the labels for towers, *mehrabs*, and openings. As the final stage totally depends on the user decisions it is possible to generate 18 different types of mosques in each category through the application of B set rules (fig 8.5 is showing 18 types of six

domes mosques). The evaluation of these mosques is described in the last chapter.

The grammar generates two-dimensional ground plans of the mosques but due to limitations of the shape grammar interpreter it is not possible to show line weights or differentiate the cut from non cut surfaces of the plan. That is why the rules add dots inside the walls along with the labels that symbolize the cut surfaces of the plan. And the outlines of the cells represent the domes on the roof as it is not possible to draw dotted lines with the interpreter.

Chapter 09.

The Language of Designs

In this thesis, I have proposed a non parametric shape grammar that generates the language of designs of Sultanate style mosques of Bengal. This grammar gives a framework not only for predicting and testing the language but also for understanding the style. According to Stiny and Mitchell's description, to create an analytical shape grammar for a given design style, at first we have to examine the corpus, and then to write the grammar to generate the designs, and finally to test the design in terms of criteria formulated after examination of the corpus. In the starting point development of the grammar for Sultanate mosques is to choose of the plan type by making 'T'. The set of rules, specified in the previous chapter, has been applied to allocate the functions in each cell after choosing the plan type. And the last stage will define the complete plan. Through the application of different combinations of two sets of rules, various plans can be generated. These sets of rules not only generate all the seventy mosques in the corpus but also 18 variations of each mosque of each type, as well as new designs in the language (fig 9.1). By looking at the chart one can observe that (fig 3.17b) it is possible for the grammar to generate the mosques in the corpus (D), which are represented by the medium grey color. It is also possible to generate new mosques (D') that do not fully comply with the conditions observed in the corpus, which represented by light grey color without a star sign. This is the case, for instance, of mosque with 4 aisles and 3 bays; of 6 aisles and 5 bays which are new in the language (fig 9.2). Finally it can generate new mosques (D"), that fulfill all the criteria and as acceptable, which are represented by light grey color with a star sign. 9 types of new mosques can be generated in the language. Stiny & Mitchell, in their paper, also offer three criteria that a grammar should comply with. I have already mentioned these three criteria in the 'Introduction' chapter. Briefly the three criteria are: the grammar should be able to generate a new example in the style, it should provide the criteria for

testing whether a design not in the corpus is in the same style, and it should give the means for explaining the basic compositional features of designing the style.

According to the first criterion the grammar should able to generate a new design which is not in the corpus. New designs have been generated by this grammar that is not any of the seventy designs in the corpus. The new designs are the variations of these seventy designs. The new designs that have been produced by the grammar are examples of the Sultanate mosque's style.

If we consider the characteristics of the various types of mosques then we can see that the new plans generated by the grammar have some resemblance with the original plans of the style (fig 9.2). For instance, the new mosque's plans without vaulted nave, that have four aisles and five bays (4X5) (fig 9.2 e), and six aisles and nine bays (6X9) (fig 9.2 f), are new in the sense that there are no mosques with the combination of these numbers of aisles and bays in the corpus. However, proportionately the mosques satisfy the proportions of the mosques in the corpus. The central *mehrab* is also more decorated than the succeeding *mehrabs*. As the grammar was developed by examining the characteristics of the mosques in the corpus, so the new designs that are generated by the grammar have the same characteristics.

According to the third criterion, the new designs that are generated by the grammar should explain the basic features of the style. In the proposed grammar this is accomplished because the variation of the designs depends on the application of the rules of stage one and stage four. During the generation process I applied the rules in stage one to create the shape underlying the plan 'T' and fix the numbers of aisles and bays and in stage four I applied the rules to add details on the cells to complete the plan of the mosque. And this complete plan has the same features of the style.

As we fix the value of X and Y (chart 3.17b) to make the grammar easy the numbers of designs generated by the grammar belong in between the value of X and Y. But the grammar is able to produce more beyond this limit. The language defined by this grammar contains designs of all types of mosques' plans. There are normally 8 types of plans which this grammar can produce. Derivation demonstrates how this grammar is used to generate an instance of each type. Three sets of mosques plans are generated by the grammar:

D set of mosques' plans: This set of mosques is already in the corpus and the mosques in the corpus are categorized into 8 types (fig3.3). The grammar not only generates all of them but it also generates 18 variations of these 8 types of mosques. And this contains a total at 214 (144+70) distinct plans of all types (fig9.1 is showing part of them). These mosques should be tested through the above mentioned conditions. Though these mosques are already in the corpus and other 144 possible mosques are variations of those mosques, so these mosques belong to the original style.

D' set of mosques' plans: This set of mosques is possible which means that they fulfill the criteria to some extent and so are still instances of the style. For instance 4 aisles and 3 bays (4X3); 5 aisles and 3 bays (5X3); 6 aisles and 5 bays (6X5); 7 aisles and 5bays (7X5); these four types of mosques are new in the language (fig 9.2 a,b,c,d). And the grammar generates 18 variations of these 4 types of mosques. If we compare the plans with the condition, all the plans have odd numbers of cells in the north-south direction and even numbers of cells in east-west direction. The central *mehrab* is more decorated than the others and the numbers of the openings in the east wall are exactly the same numbers as the *mehrabs* in the west wall. The proportions of these mosques vary from 1.2 to 1.67. So those are still within the limits. If we compare these with the criteria mentioned in chapter 3 we can find that these mosques do not fulfill this condition as they are elongated towards the east direction. But proportionately these mosques are acceptable to do the prayer in one line facing the *qibla* wall. Therefore these 72 possible mosques' plans also belong to the style.

D" set of mosques' plans: The new mosques (D") fulfill all the criteria and are legal. 9 types of new mosques can be generated in this set, namely, mosque with 4 aisles and 5 bays (4X5); 3 aisles and 7 bays (3X7); 6 aisles and 7 bays (6X7); 4 aisles and 9 bays (4X9); 5 aisles and 9 bays (5X9); 6 aisles and 9 bays (6X9); 7 aisles and 6 bays (7X6); 5 aisles and 11 bays (5X11); 6 aisles and 11 bays (6X11). These 9 types of mosques are new in the language (fig 9.1). And the grammar generates 18 variations of these 9 types of mosques. They are new in the language because there are no mosques with these aisles and bays combinations and all these 162 plans of the mosques satisfy the above mentioned conditions.

In the case of the large mosque's plan with vaulted, the grammar also generates 18 variations of each type of mosque.

The grammar is a hypothesis based on a corpus and it generates new designs in the language that can be tested against the characteristics of the mosques in the corpus. The grammar can be revised if the predictions or the generated new designs are not stylistically correct. The author of a grammar tests the predictions against the criteria that define what is stylistically correct. Or the author can ask a historian of the style or an expert of the style to do the test. If no such expert exists then the author of the grammar could do the test based on his or her knowledge. Actually this knowledge helps the author to write the grammar at the beginning. But the question is how the author does such a test? The underlying response to this question may be that, the grammar has been written by the author who has already gained some understanding of the style. While writing the grammar different people have different opinions about a style for which the stylistically correctness of a style also may vary. If the predictions of a grammar are tested by different experts and give different opinions this does not mean that the grammar needs to be revised as long as the predictions are stylistically correct. If not then the grammar should be revised. For this thesis I have tried to understand the style of Sultanate mosques in Bengal and develop the grammar accordingly, and so the grammar generates the plans of mosques in the corpus and also new plans that are not in the corpus. But whether the mosques are stylistically correct or not should be judged by a historian or by the experts in mosque design.

Conclusion

Shape grammar is formal and generative and a rule based methodology. Shape grammars generate a language of design and provide a framework to understand a style. A grammar generates new designs in the style, tests the designs and explains the formal structure of designs by setting a framework for understanding the style. The creation of a grammar is not separated from traditional design. The procedure for developing a grammar derives from traditional design procedure.

The aim of this research firstly is to develop a grammar for generating new designs in the style and all the designs that already exists in the style and was never built during Sultanate period. This mosque's grammar not only gives a framework to understand the Sultanate style in Bengal but also embodies Islamic principles. Secondly is to use of a grammar interpreter to develop the grammar. To develop and to run the grammar this interpreter has been successfully used in this research.

Traditionally architectural historians try to classify and differentiate the features of Islamic architecture on the basis of climatic, geographic and cultural conditions of Bengal and to analyze mosque architecture in terms of their design elements or features. But this type of analysis only describes features separately. By using shape grammar methodology it is expected to identify and to relate these features with each other and to develop a framework to understand the style.

By developing a non parametric shape grammar for Sultanate mosque style in Bengal, it is expressed how a rule based methodology can be used to generate a geometric plan of mosques in this style. The use of the shape grammar method described here gives a new and alternative approach for studying and analyzing this traditional mosques architecture with an emphasis not on building style or type but on the creation of a framework to understand design complexity. The functional and formal features of the mosques have been analyzed to formulate the rules. These rules have been applied to generate the compositional forms of the mosques in a bottom-up approach. The grammar generates different types of layouts through application of different combinations of rules. Thus, it explains the design process of the Sultanate mosque style. As

the language of Sultanate mosques has the same vocabulary elements, different types of new designs have similar formal characteristics. The grammar condenses knowledge gathered from the analysis of the compositional features of the plan elements of the style and from the interpretation of the style and the knowledge can be used to generate a new design in the style.

If we look at the chart 3.17b we can see that the grammar is able to generate the designs those are represented by dark grey color (5x5 or 7x7 domes mosques). But those are not acceptable according to the criteria described in chapter 3. On the other hand those can be new examples in the style and can be new issues for the historians to do further research on mosque architecture. For instance 5X5, or 7X7 domes mosques can not be found in the corpus depending on the source but grammar is able to generate these two types of mosques. So in further research it will help to think the historians or researchers to find out the evidence for these mosques. The grammar gives the hypothesis that these two mosques satisfy the characteristics of the style accept the size but according to the field report they were never built.

In this research, the process of writing the grammar and generating designs was carried out using a shape grammar interpreter-Grammar Environment. There are some technical limitations in developing the grammar as the interpreter software is still at an early stage. The grammar starts by generating 'T' shaped plans like in the Palladian and in the *Yingzao fashi* grammars but the interpreter not able to generate the grid parametrically like in these two grammars. Therefore, the rules in stage 2 develop the grid in such a way that each rule adds a cell on one side of the 'T' instead of adding cells bilaterally on both sides of the 'T'. For adding walls in stage 3 it is also not possible to give the line weights to the two dimensional plans of these mosques by the interpreter. I add a small dot in the cut surfaces of the plan so that finally I can apply a hatch on these surfaces. Sometimes, the interpreter also takes time to generate the shape if the shapes contain too many lines. Despite these small limitations, writing the grammar and generating examples using Grammar Environment is very helpful as it permits to easily test the grammar in every stage.

The Sultanate period has ended. A great deal of changes in mosque designs in the region has occurred from the end of the Mughal period till the

present time. In future research this grammar will be extended to generate the designs that incorporate such transformations so that it helps to fully understand the style of Islamic architecture in this region. The rule sets of this grammar have been applied to generate two dimensional plans layouts. In future research the grammar also will be extended to a three dimensional grammar.

References:

Ahmed, S & Chase, SC: 2004, Design generation of the central Asian Caravanserai. Paper presented at 1st ASCAAD International Conference on e-Design in Architecture at KFUPM, Dhahran, Saudi Arabia. Archnet Islamic Architecture Community. http://www.archnet.org/linrary/places.

Buelinckx, H: 1993, Wren's language of city church designs: a formal generative classification, *Environment and planning B: planning & design* 20: 645–676.

Cagdas, G. (1996). A shape grammar: the language of traditional Turkish houses. *Environment and planning B: planning and design,* 23. 443-464.

Downing F, Flemming, U: 1981, The Bungalows of Buffalo. *Environment and planning B: planning & design* 8: 269-293

Duarte, JP: 2001, Customizing mass housing: a discursive grammar for Siza's Malagueira houses, Ph.D. dissertation, Department of Architecture, Massachusetts Institute of Technology, Cambridge, Mass.

Eaton, Richard M: 1993, *The Rise of Islam and the Bengal Frontier, 1204-1760.* Berkeley: University of California Press. From http://ark.cdlib.org/ark:/13030/ft067n99v9/

Flemming, U: 1981, The secret of the Casa Giuliani Frigerio. *Environment and planning B: planning & design* 8: 57–96.

———. 1987. More than the sum of parts: the grammar of Queen Anne houses. *Environment and planning B: planning & design* 14: 323–350.

Fisherman, M & Khan, H.U: 1994, *THE MOSQUE: History, Architecture, Development & Regional Diversity*, London. Thames & Hudson Ltd.

Hassan, P: 1989, Sultanate Mosques and Continuity in Bengal Author(s), *Muqarnas,* 6.58-74 From http://www.jstor.org/stable/1602281

———. 2007, *The Early Muslim Architecture in Bangladesh: Sultans and Mosques,* London. New York: I.B. Tauris.

Hoag, J.D: 1975, *Islamic Architecture,* Milan, Elacta Editrice.

Kirsch, J.L. & Kirsch, R.A.: 1986, The structure of Paintings: Formal Grammar and Design, *Environment and Planning B: Planning and Design,* 13, 163-176.

Knight, TW: 1981, The forty-one steps, *Environment and planning B: planning & design* 8: 97–114.

———. 1994. *Transformations in design: a formal approach to stylistic change and innovation in the visual arts.* Cambridge, England: Cambridge University Press.

———.2000, Shape *Grammars in Education and Practice: history and prospects:* Department of Architecture, MIT. From http://www.mit.edu/~tknight/IJDC

Koning, H & Eizenberg, J: 1981, The language of the prairie: Frank Lloyd Wright's prairie houses. *Environment and Planning B: Planning and Design,* 8. 295 -323.

Li, AI: 2001, A shape grammar for teaching the architectural style of the *Yingzao fashi,* Ph.D. dissertation Department of Architecture, Massachusetts Institute of Technology,Cambridge, Mass.

———. 2003. The *Yingzao fashi* in the information age, paper read at The Beaux-Arts, Paul-Philippe Cret, and 20th-century architecture in China, at University of Pennsylvania.

———. 2004. Styles, grammars, authors, and users. Paper presented at Design computing and cognition '04, at Cambridge, Mass.

Li, AI & Lau, MK: 2004, A set –based shape grammar interpreter, with thoughts on emergence. Paper read at Workshop 3, Implementation issues in generative design systems, First international conference on design computing and cognition, at Massachusetts Institute of Technology.

Li, AI, Chau, H.H, Liang, C & Yang,W: 2009, A prototype system for developing two-and three-dimensional shape grammars. Paper presented at CAADRIA'09, at Taiwan.

Meinecke, M: 1996, *Pattern of Stylistic Changes in Islamic Architecture,* New York & London: NewYork University Press

McGill, M.C: 2002, Shaper2D: Visual software for learning shape grammars, in K.Koszewski and S. Wrona (eds.), *Design e-ducation: connecting the real and the virtual, Proceedings of the 20th Conference on Education in Computer Aided Architectural Design in Europe,* eCAADe, Warsaw.

Michell, G: 1984, *The Islamic Heritage of Bengal*, Belgium: Unesco. Persian muslim elements in the history of Bengal. From http://www.iranica.com/newsite/articles/v4f2/v4f2a022.html

Mitchell, W J, Liggett R, Pollalis S, Tan M: (1991) Integrating shape grammars and design analysis, in *CAAD* Futures, 91 Ed. G Scmitt. 19-32.

Naqi, A: 2002, The architecture of the Khan-e-Jahan style: Context and influence, Master of architecture dissertation, Department of Architecture, Bangladesh University of Engineering and Technology, Dhaka.

Nath, R: 1978, *History of Sultanate Architecture,* New Delhi: Abhinav Publications.

Petruccioli, A & Pirani, K.K: 2002, *Understanding Islamic Architecture 27-29,* London: RoutledgeCurzon.

Richmond, E.T: 1926, *Moslem Architecture*, London: The Royal Asiatic Society.

Roy, A: 1997, *Primitive Bangali Anthropological and Sociological Analysis*, Dhaka: Bangla Academy.

Sass, L: 2007, A Palladian construction grammar: design reasoning with shape grammars and rapid prototyping. *Environment and Planning B: Planning and Design, 34. 87-106.*

Stiny, G: 1977, Ice-ray: a note on the generation of Chinese lattice designs. *Environment and planning B: planning & design* 4: 89–98.

———. 1980a. Introduction to shape and shape grammars. *Environment and planning B: planning & design* 7: 343–351

———. 1980b. Kindergarten grammars: designing with froebel's building gifts. *Environment and planning B: planning & design* 7: 409-462

———. 1981. A note on the description of designs. *Environment and planning B: planning & design* 8: 257–267.

———. 1990. What is a design? *Environment and planning B: planning & design* 17: 97–103.

———. 1992. Weights. *Environment and planning B: planning & design* 19: 413–430.

Stiny, G & Gips, J: 1972, Shape grammars and the generative specification of painting and sculpture, in *Information Processing 71* (North Holland, Amsterdam): 1460-1465.

Stiny, G & William J.M: 1978, The Palladian grammar. *Environment and planning B: planning & design* 5: 5–18.

———. 1978. Counting Palladian plans. *Environment and planning B: planning & design* 5: 189-198

———. 1980. The grammar of paradise: on the generation of Mughul gardens. *Environment and planning B: planning & design* 7: 209–226.

Appendix

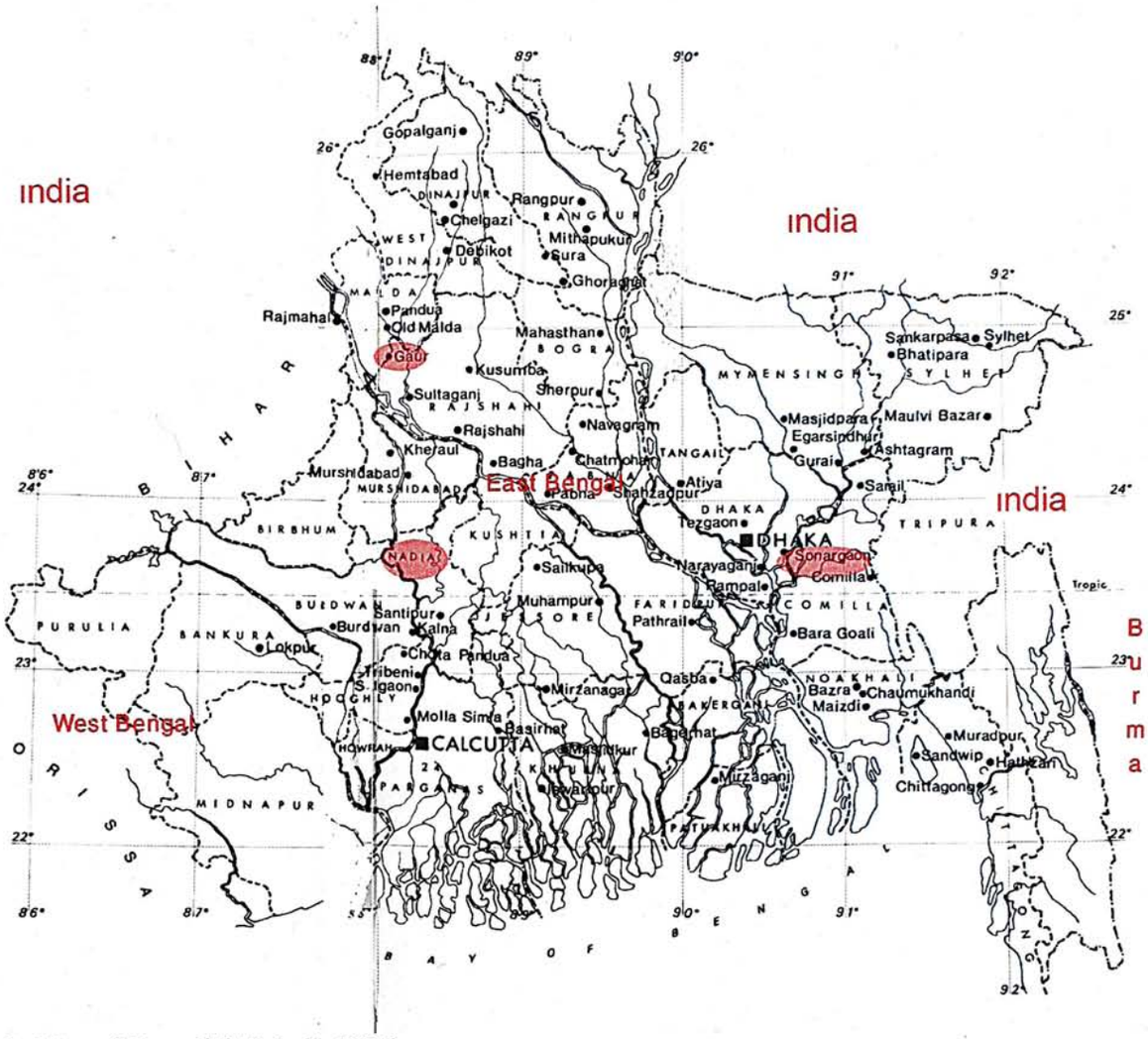


Figure1.1- Map of Bengal (Michell, 1984).

Figure1.2- Village hut of Bengal (Hassan, 2007)

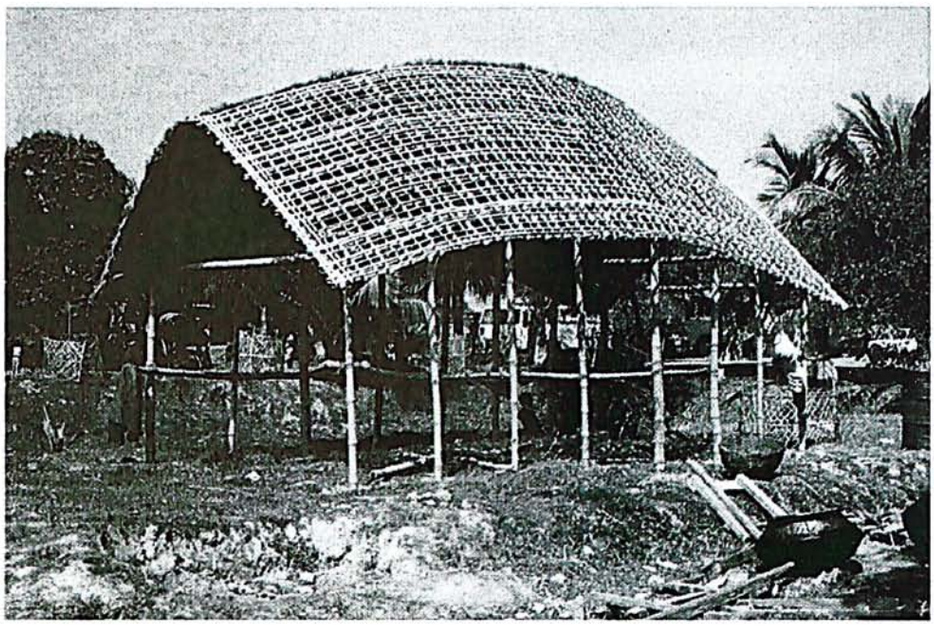


Figure1.3- The frame of a village hut (Hassan, 2007)

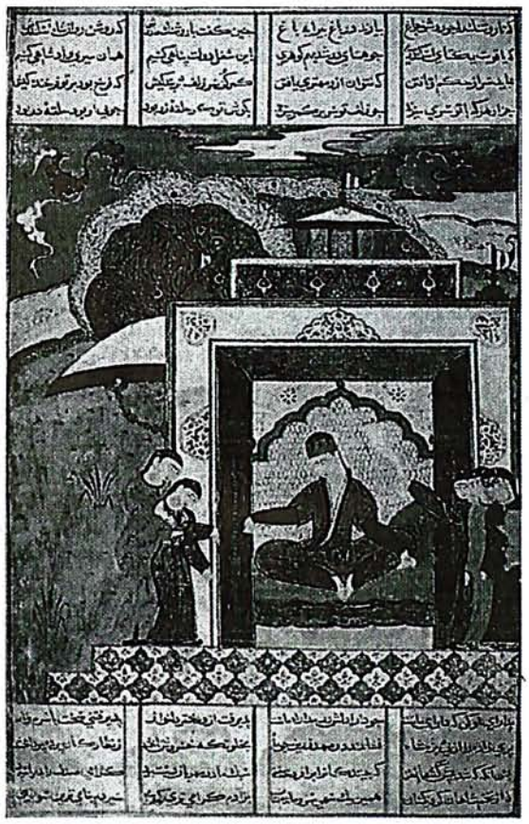


Figure1.4- Painting that shows the small *chala* roof pavilion on a square building (Hassan, 2007)

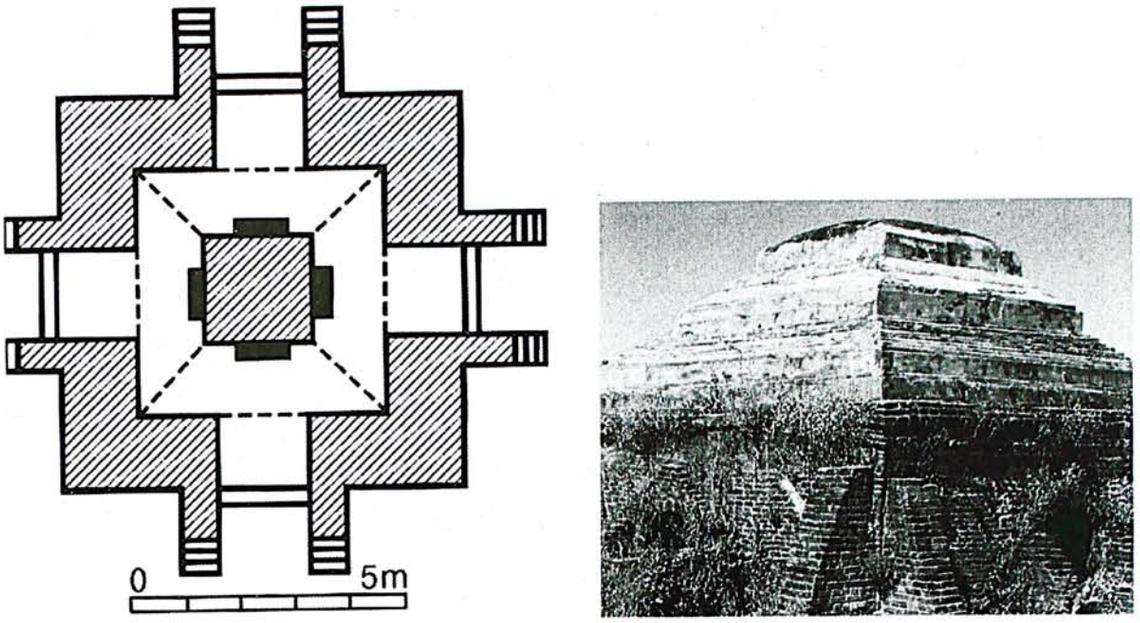


Figure1.5- The ancient Hindu temple's plan and the roof of the temple (Hassan, 2007)

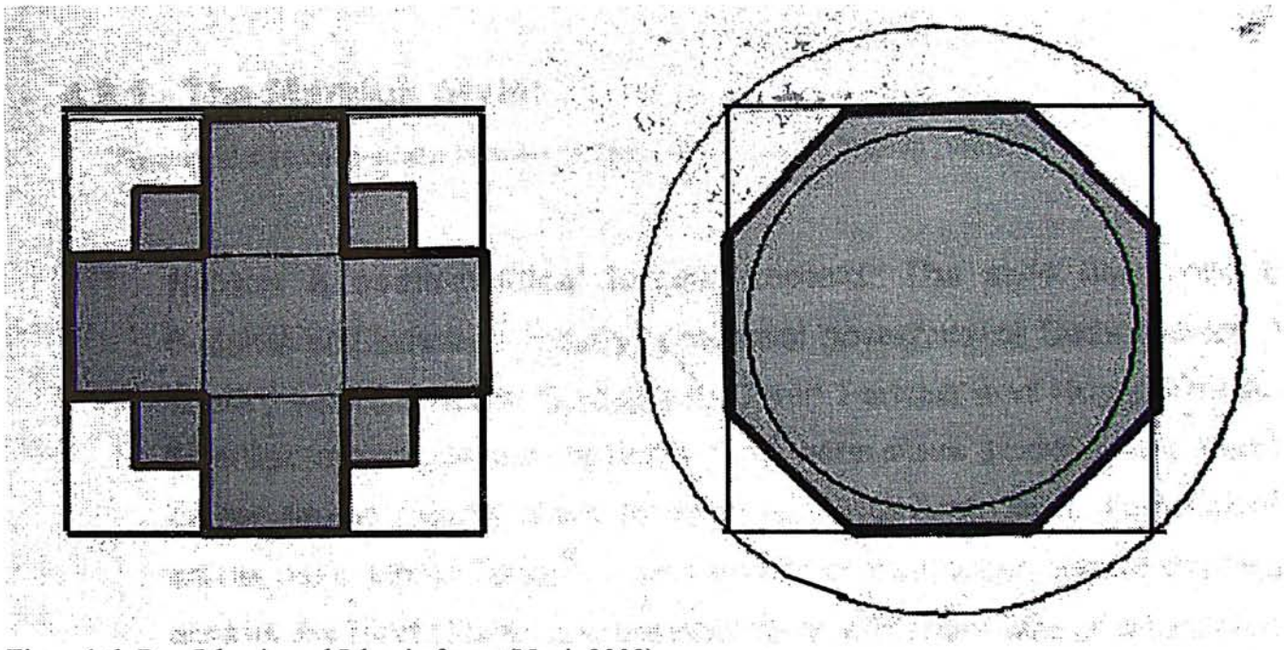


Figure1.6- Pre- Islamic and Islamic form. (Naqi, 2002)

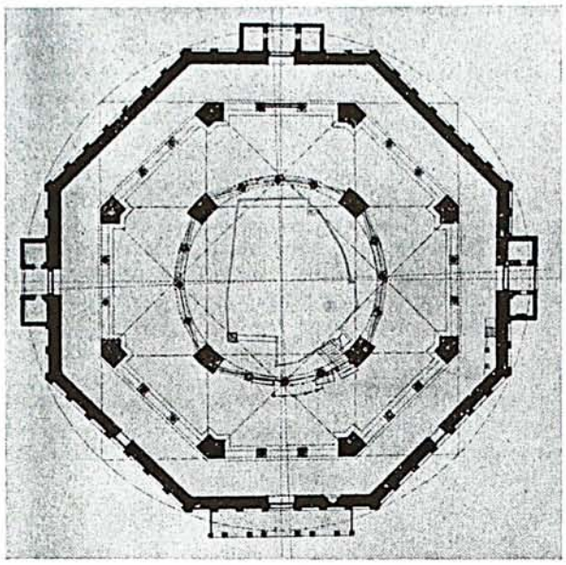


FIG. 5.—PLAN OF THE DOME OF THE ROCK.

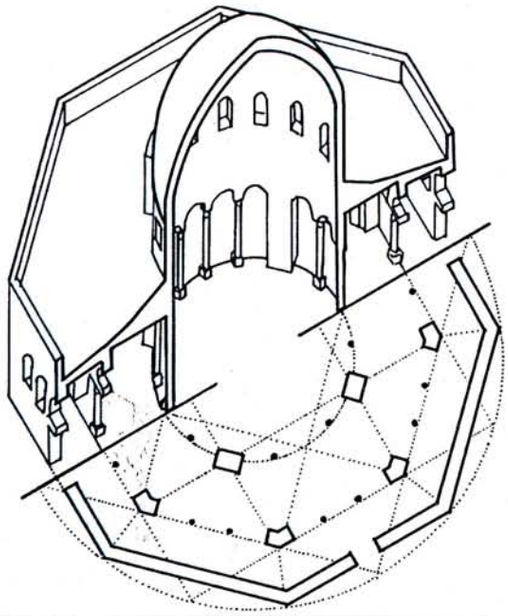


Figure1.7- The plan of the Dome of the Rock and the axonometric view of the Dome. (Hoag, 1975)

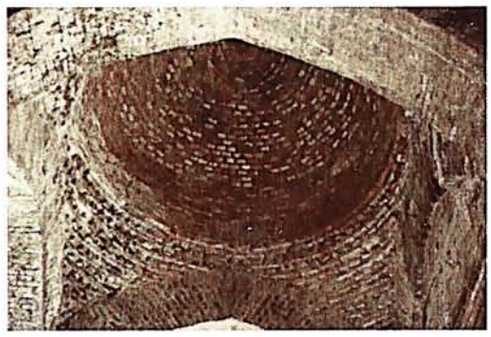


Figure1.8- Representation of the *Chala* Roof and Brick construction.

(www.archnet.org/library/places/places)

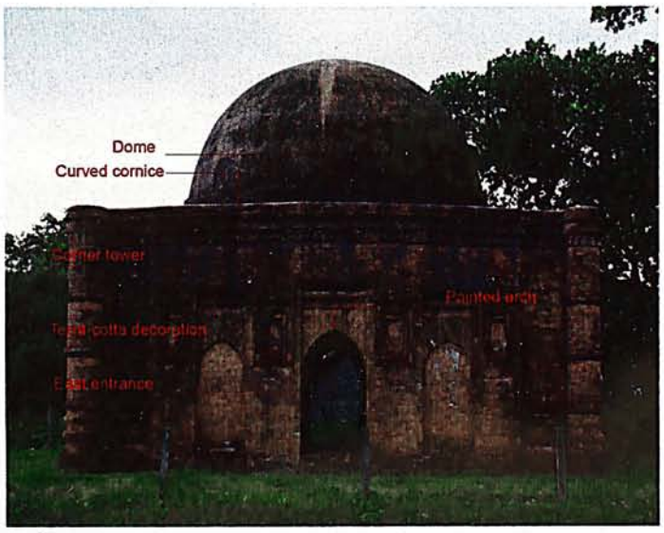


Figure1.9- A single Dome Mosque with its features. (www.archnet.org/library/places/places)

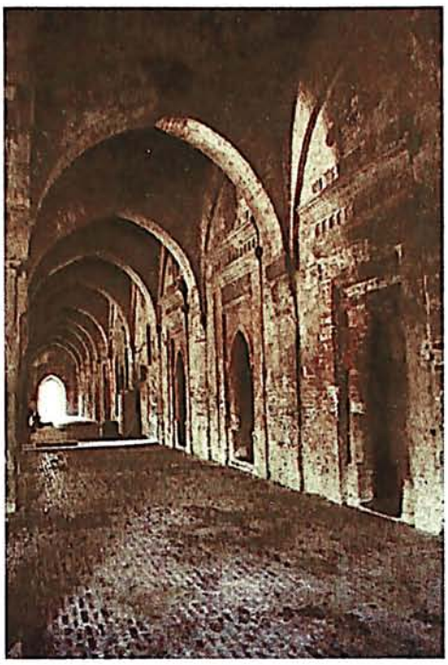


Figure1.10- *Mihrabs* on the *Qibla* wall and the central entrance on the east wall.
(www.archnet.org/library/places/places)

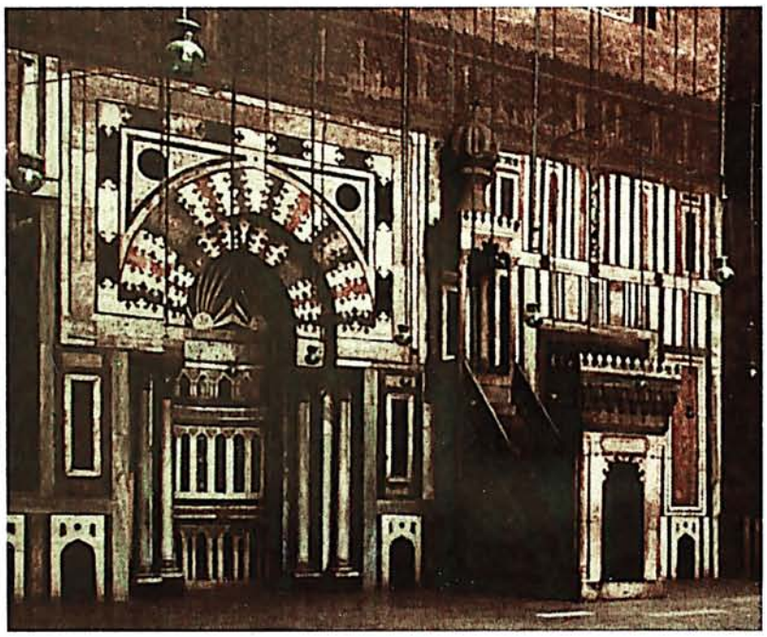


Figure 1.11- *Mehrab & Minbar* .

Figure 1.12- Terra-cotta decoration.

(www.archnet.org/library/places/places)

Figure 1.13- Pond near a mosque.

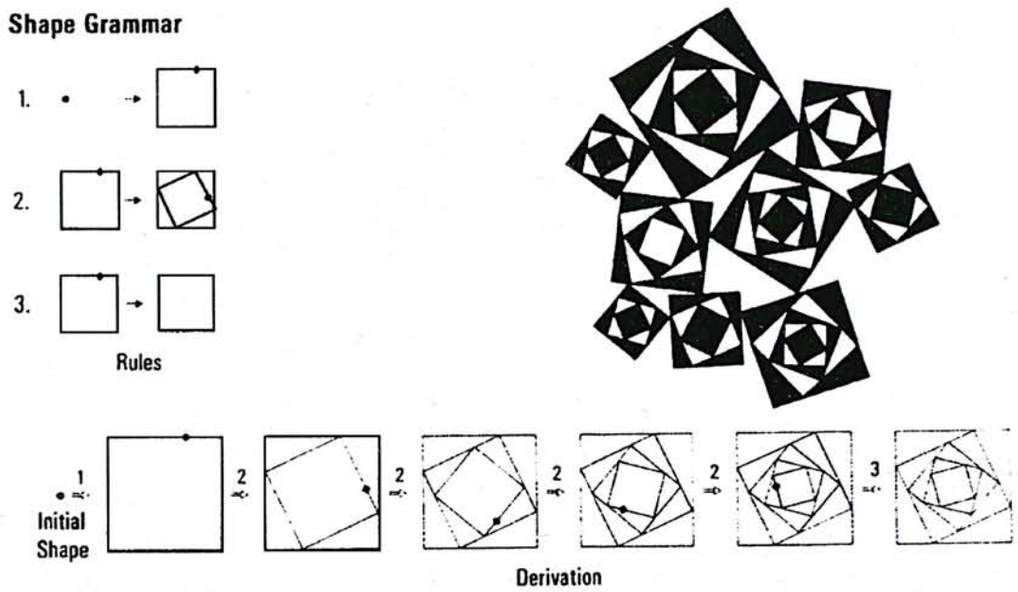


Figure 2.1- (a) Rules for a Standard Shape Grammar (b) A derivation of the designs are derived (c) A result generated by applying the rules repeatedly. (Stiny, 1985)

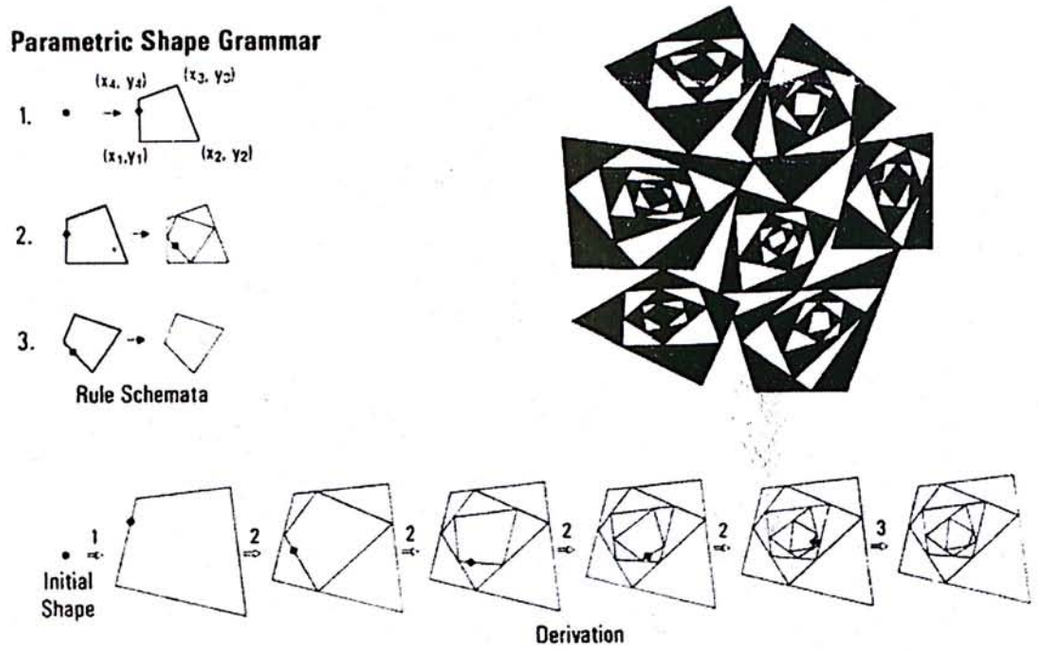


Figure 2.2- (a) Rules for a Parametric Shape Grammar (b) A derivation of the rules (c) A result shapes generated by applying the rules. (Stiny, 1985).

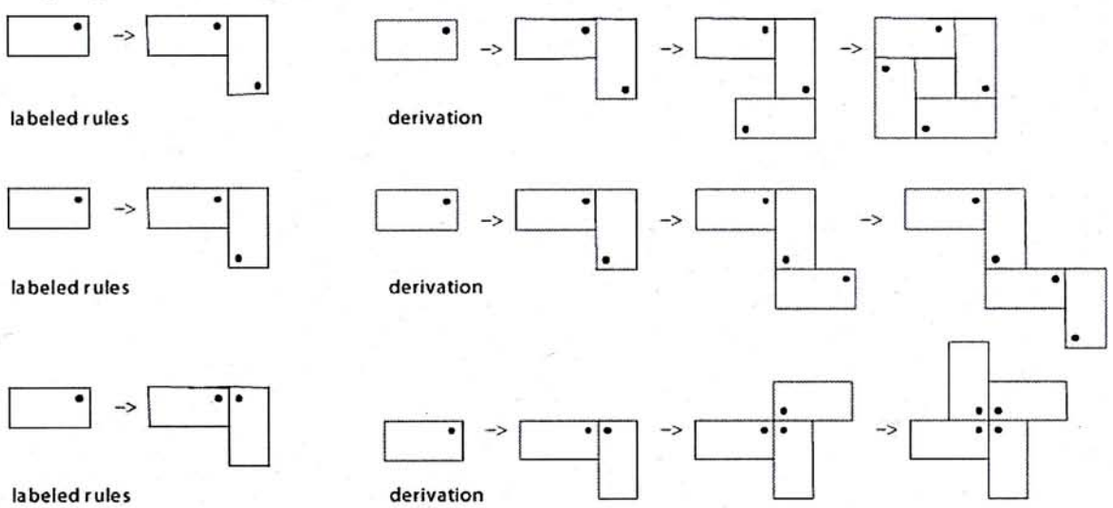


Figure 2.3- Various 2D labeled rules for standard shape grammar and their derivations. (Knight, 1994).

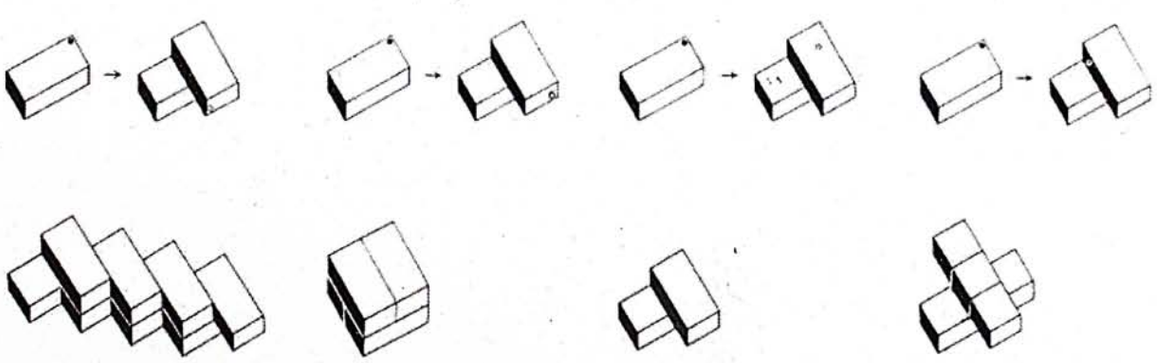


Figure 2.4- Various 3D labeled rules for standard shape grammar and their derivations. (Knight, 1994).

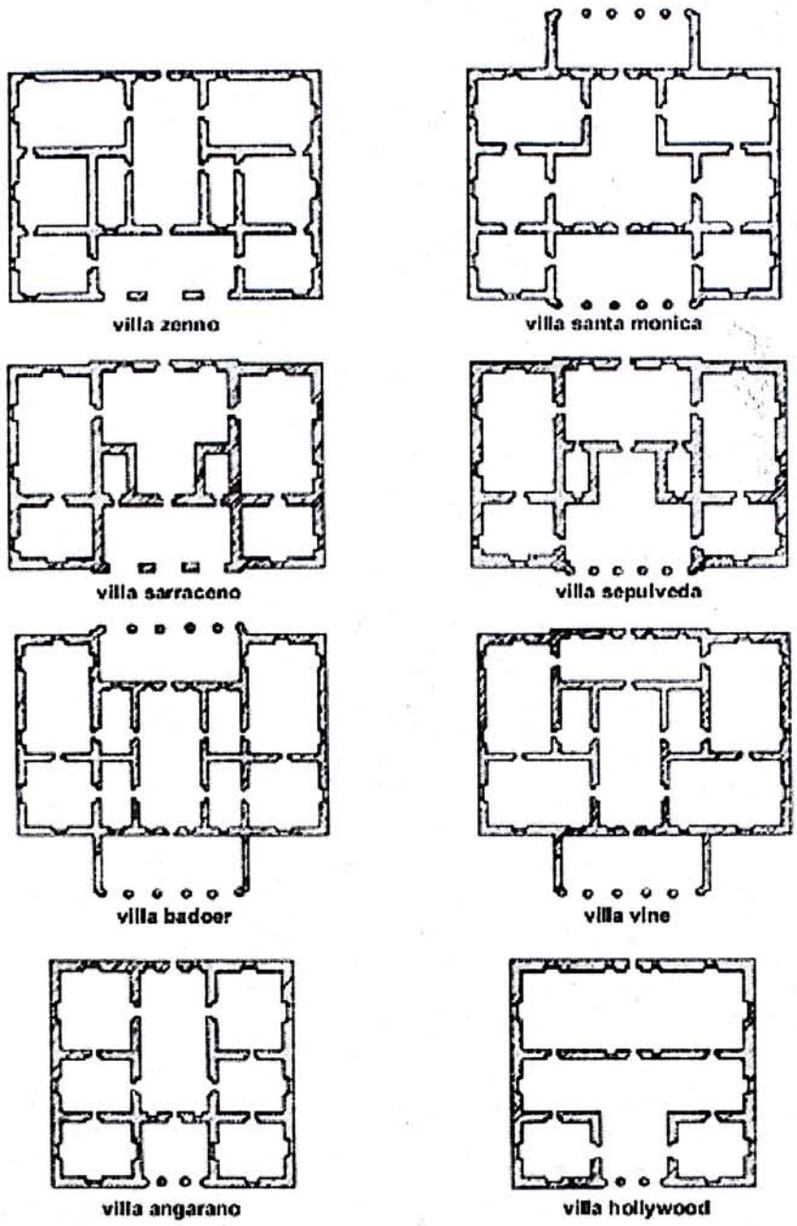


Figure 2.5- Possible Palladian villa plans after the Palladian villas grammar. (Stiny and Mitchell, 1978)

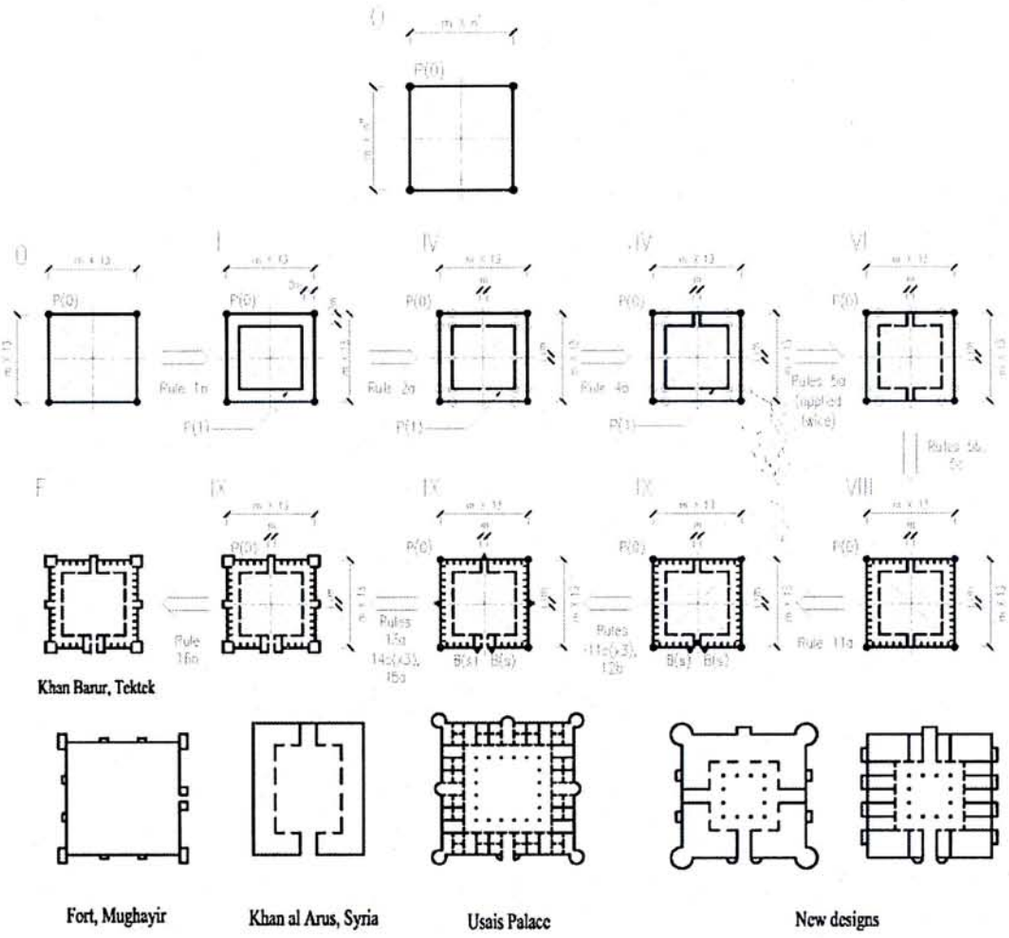


Figure 2.6- The initial shape of the caravanserai grammar, a derivation according to the grammar and sample of the language generated by the grammar (Ahmad and Chase, 2004).

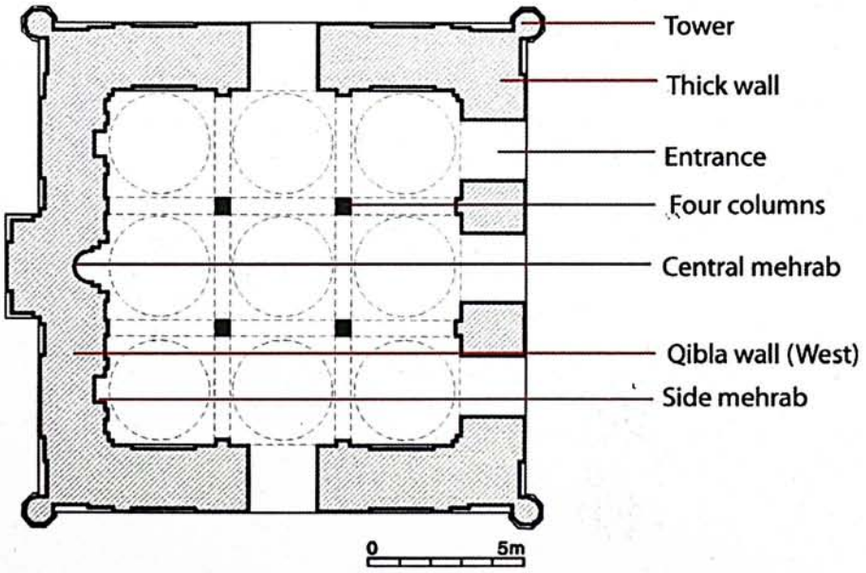


Figure3.1- Nine dome mosque, four columns holding a dome above (Hassan, 2007).

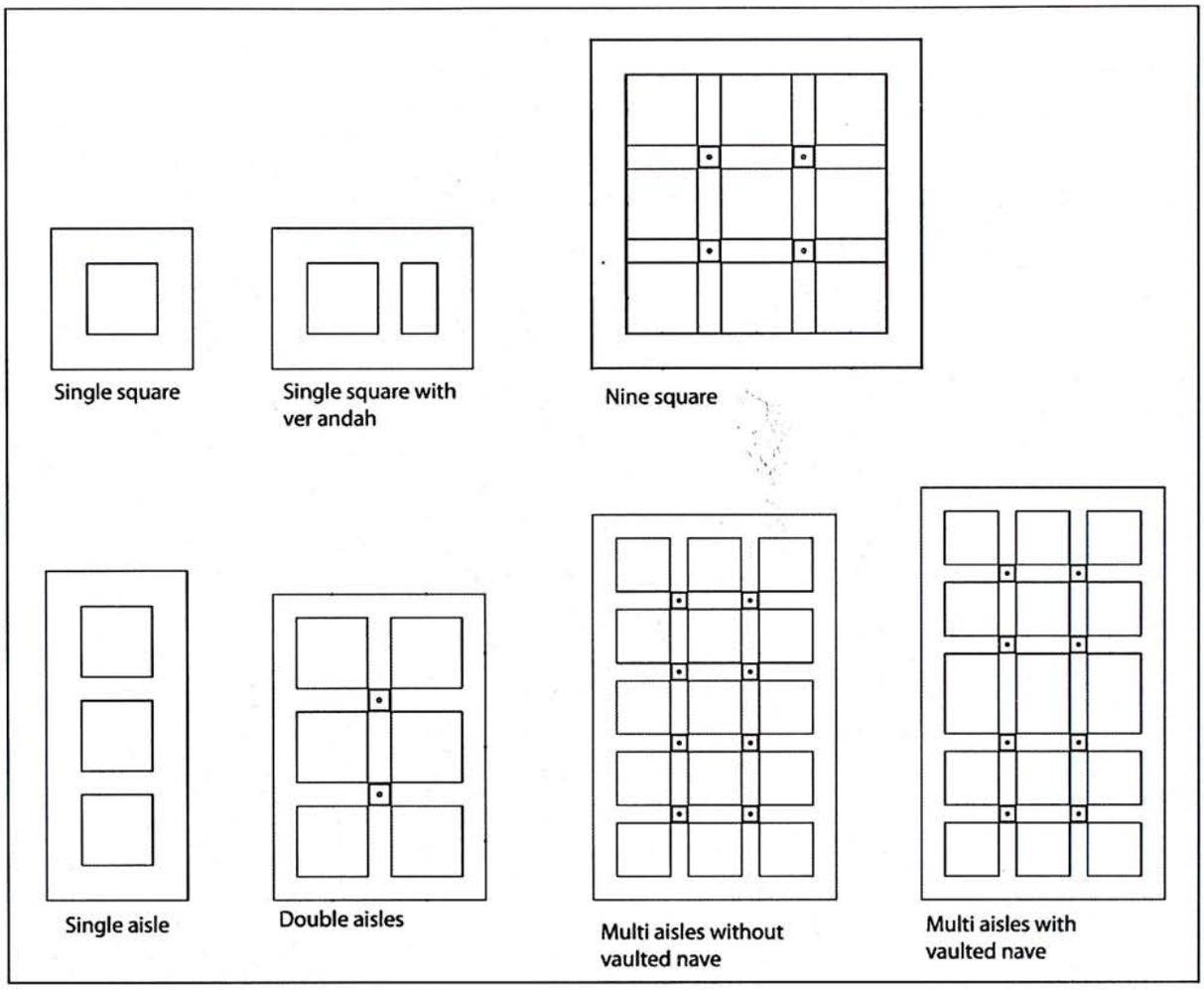


Figure3.2- Different types of plans.

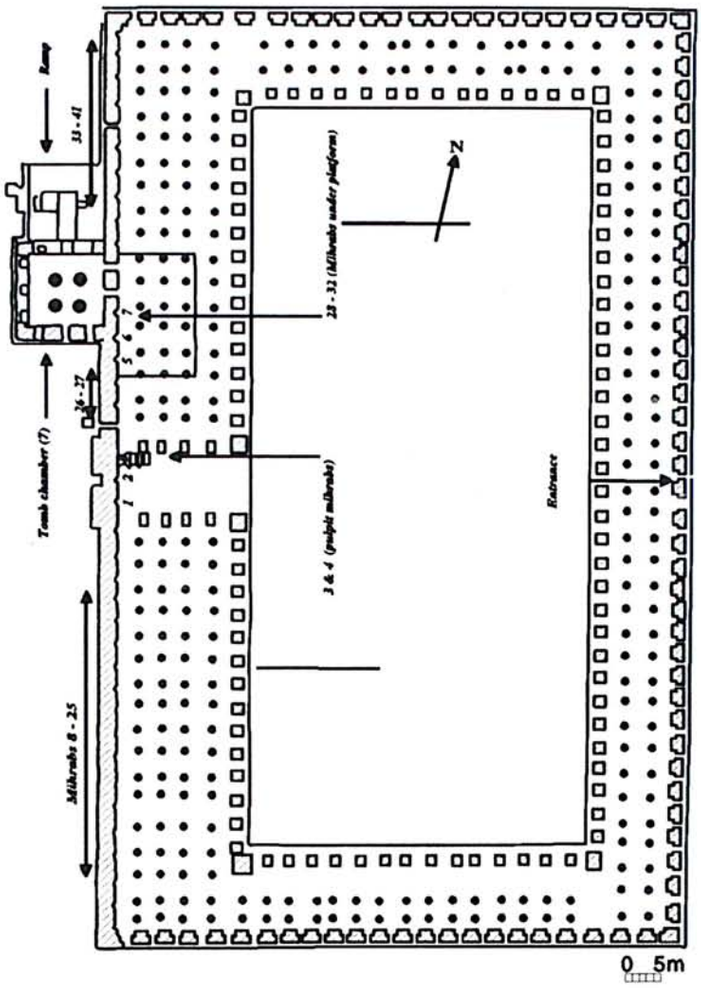


Figure 3.4- Adina mosques, West Bengal 1375 (Hassan, 2007).

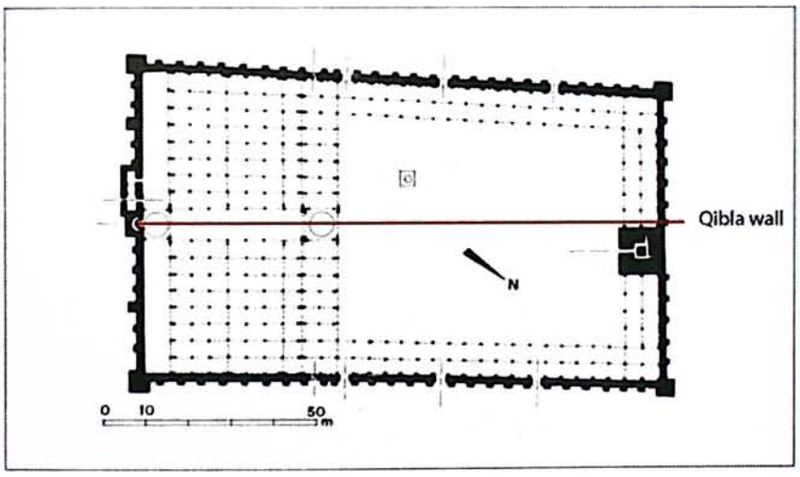


Figure 3.5- Kairouan mosque plan (Hoag, 1975, p.32)

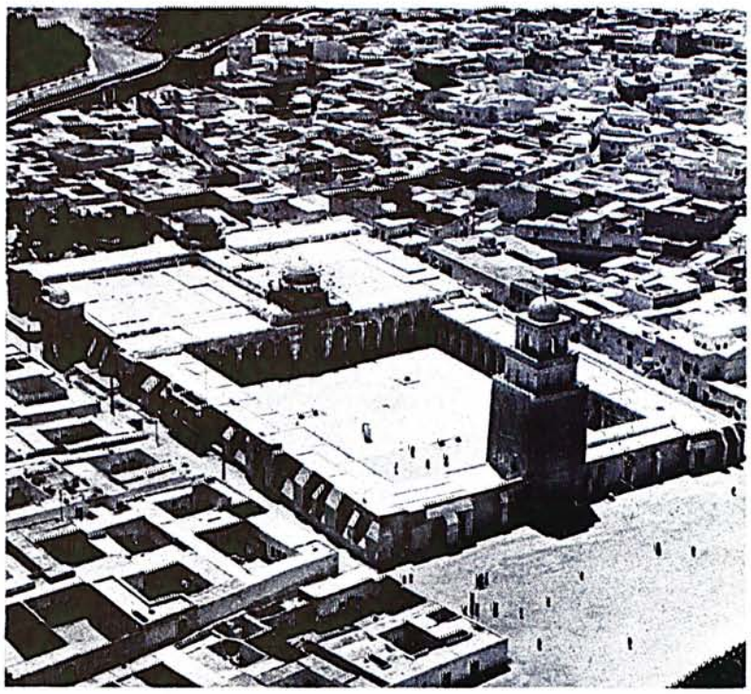


Figure 3.6- The view of the Kairouan mosque (Hoag, 1975, p.33)

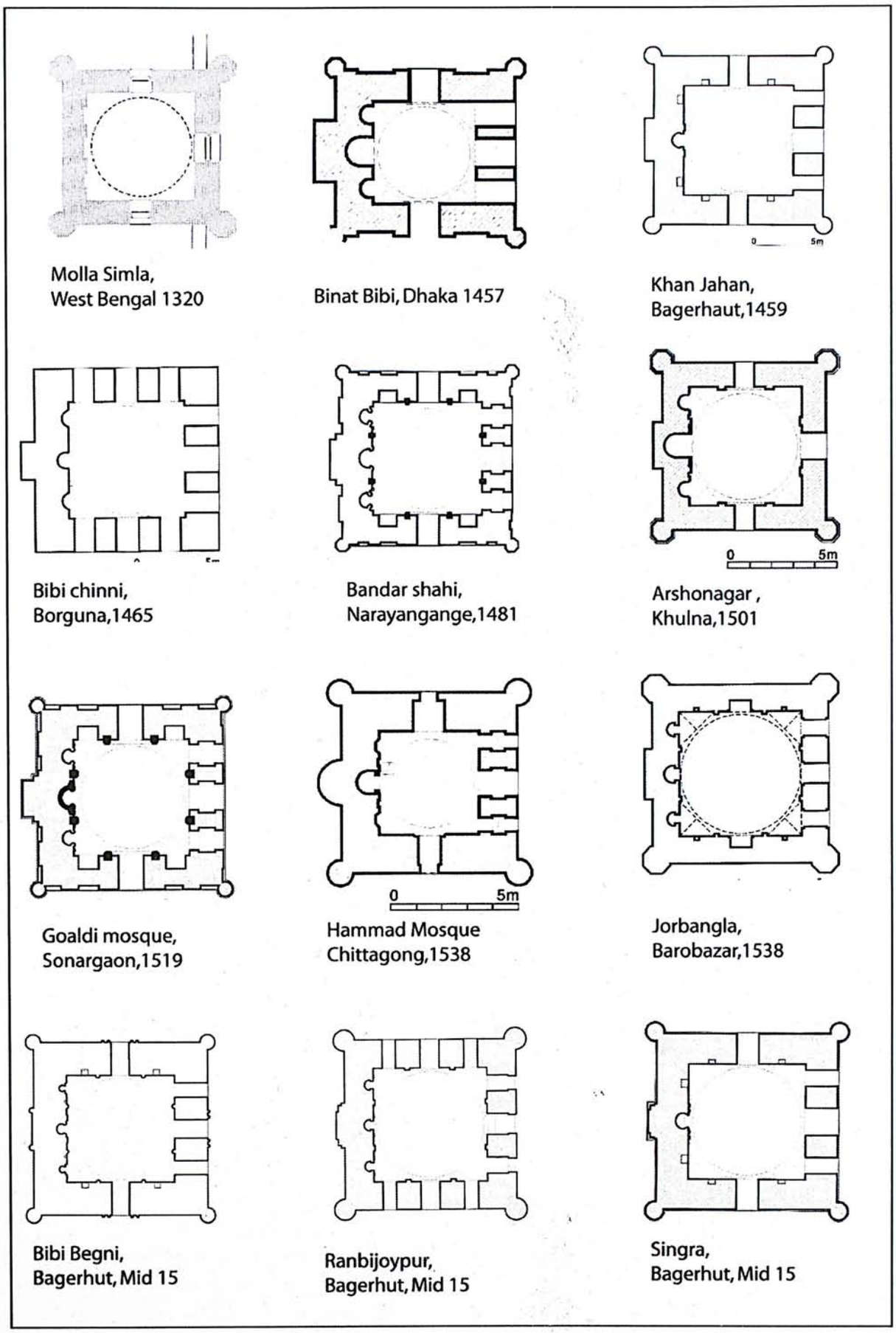


Figure 3.7a- Single dome square mosques in the corpus (Hassan, 2007).

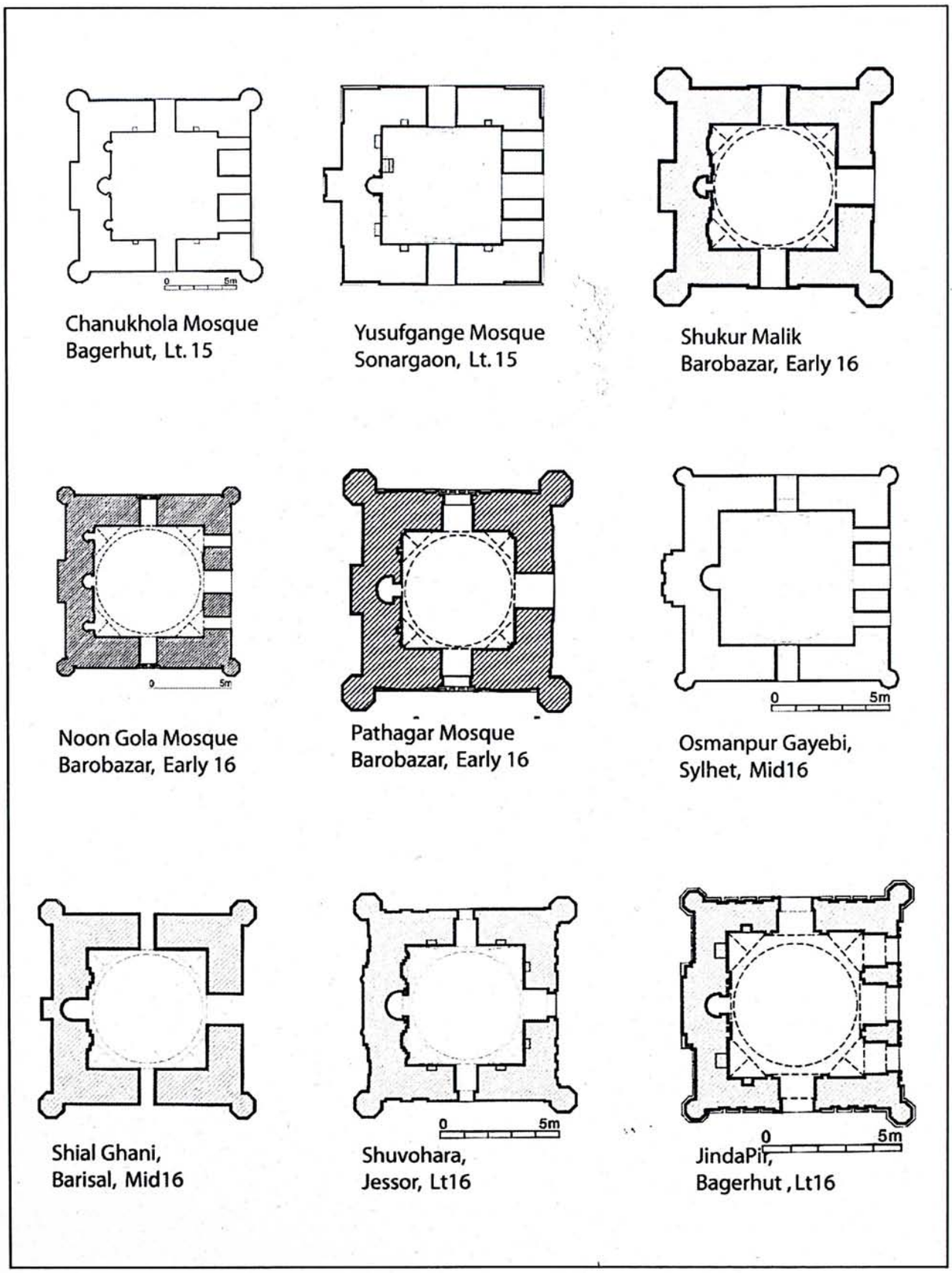


Figure 3.7b- Single dome square mosques in the corpus (Hassan, 2007).

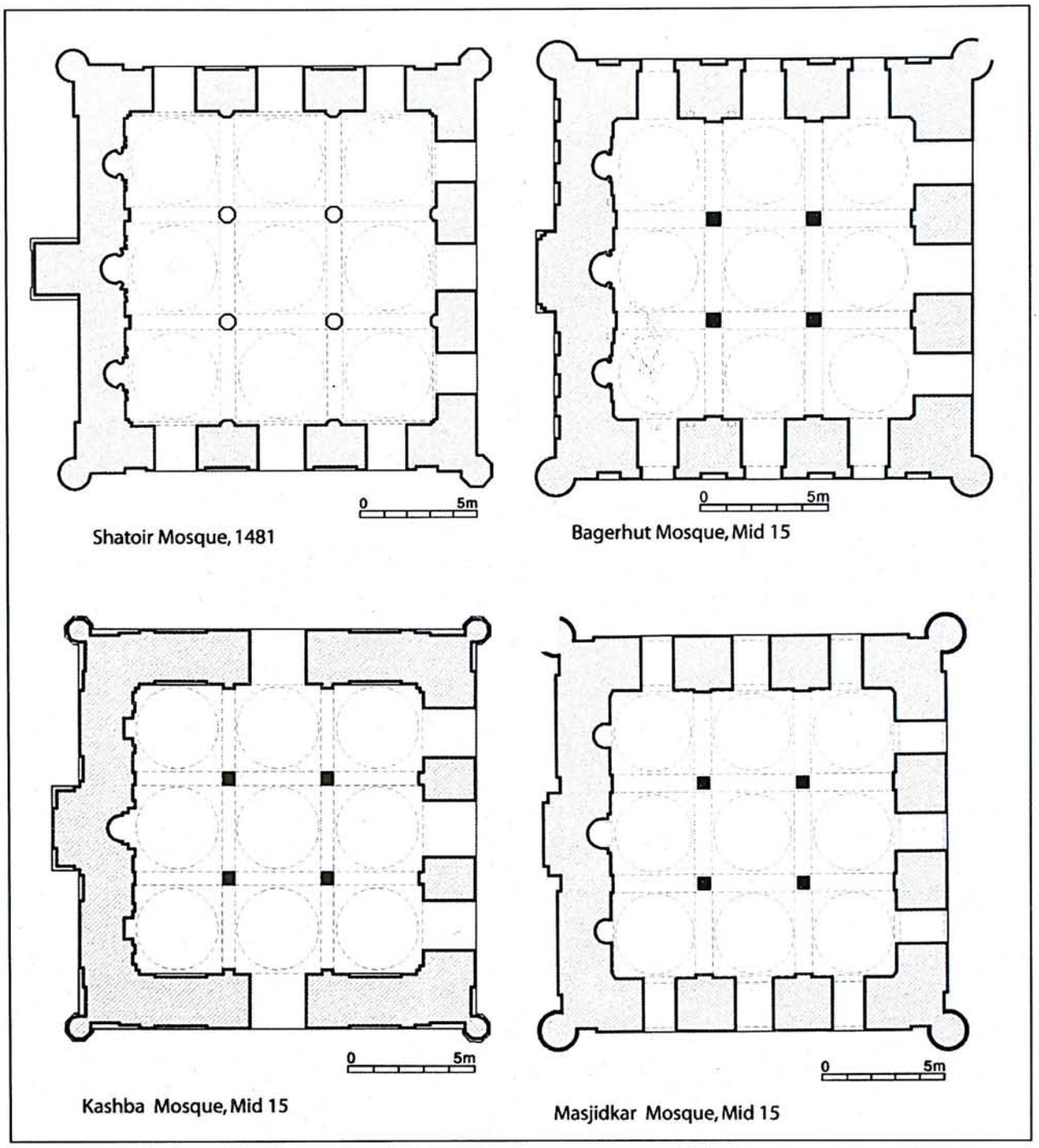


Figure 3.8- 4 Nine square mosques in the corpus (Hassan, 2007).

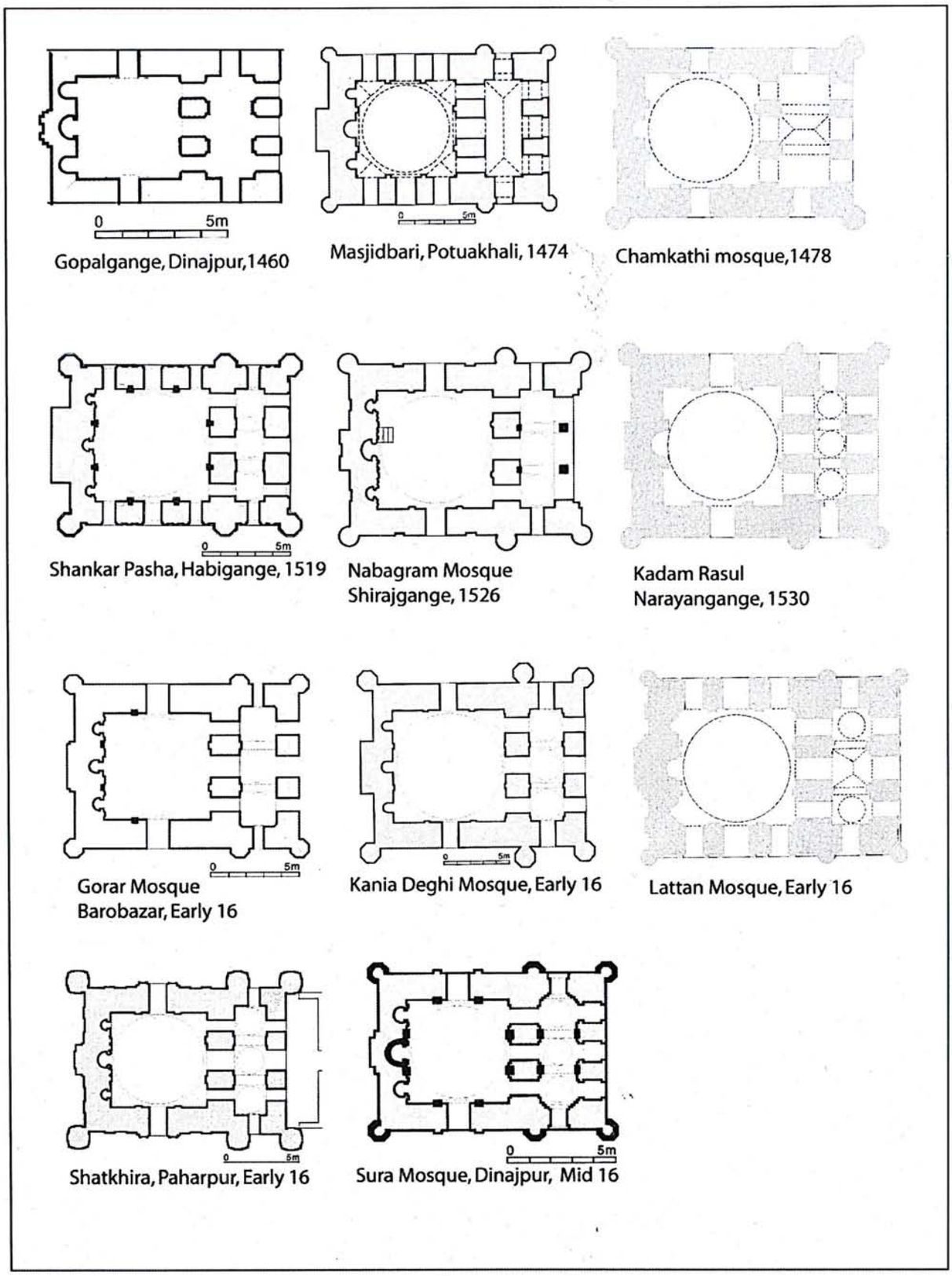


Figure 3.9- 11square mosques with corridor in the corpus (Hassan, 2007).

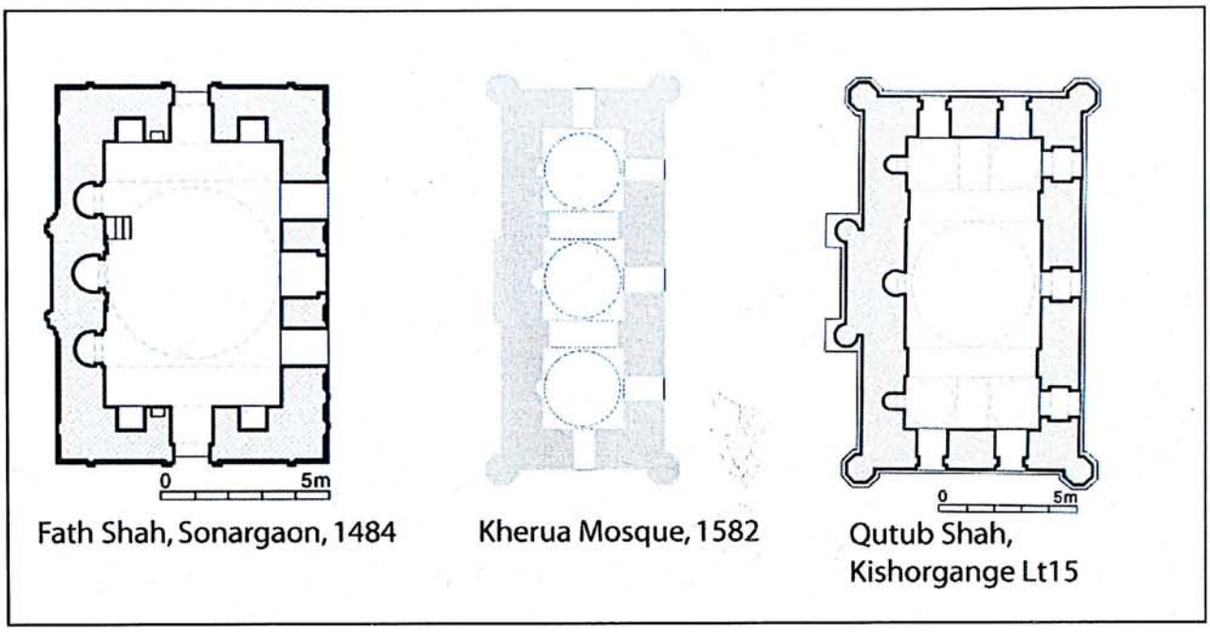


Figure 3.10- 3 one aisle mosques in the corpus (Hassan, 2007).

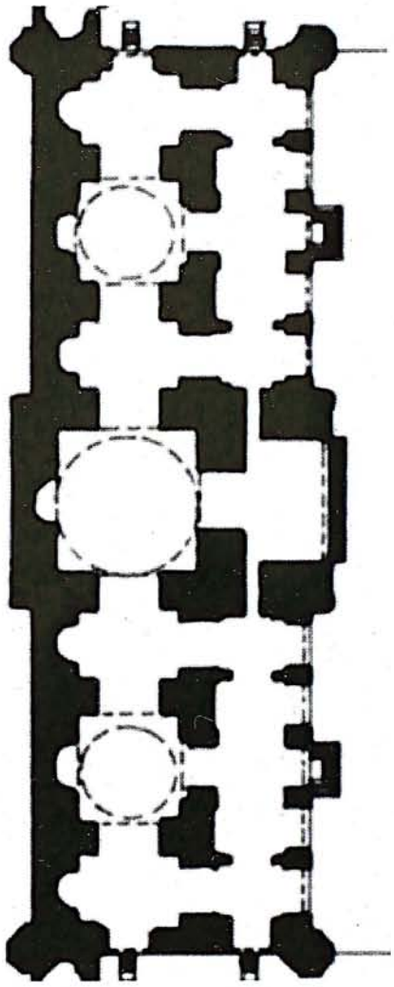


Figure 3.11- Badshai Mosque Lahor 5bays, 1974 (Fisherman & Khan, 1994)

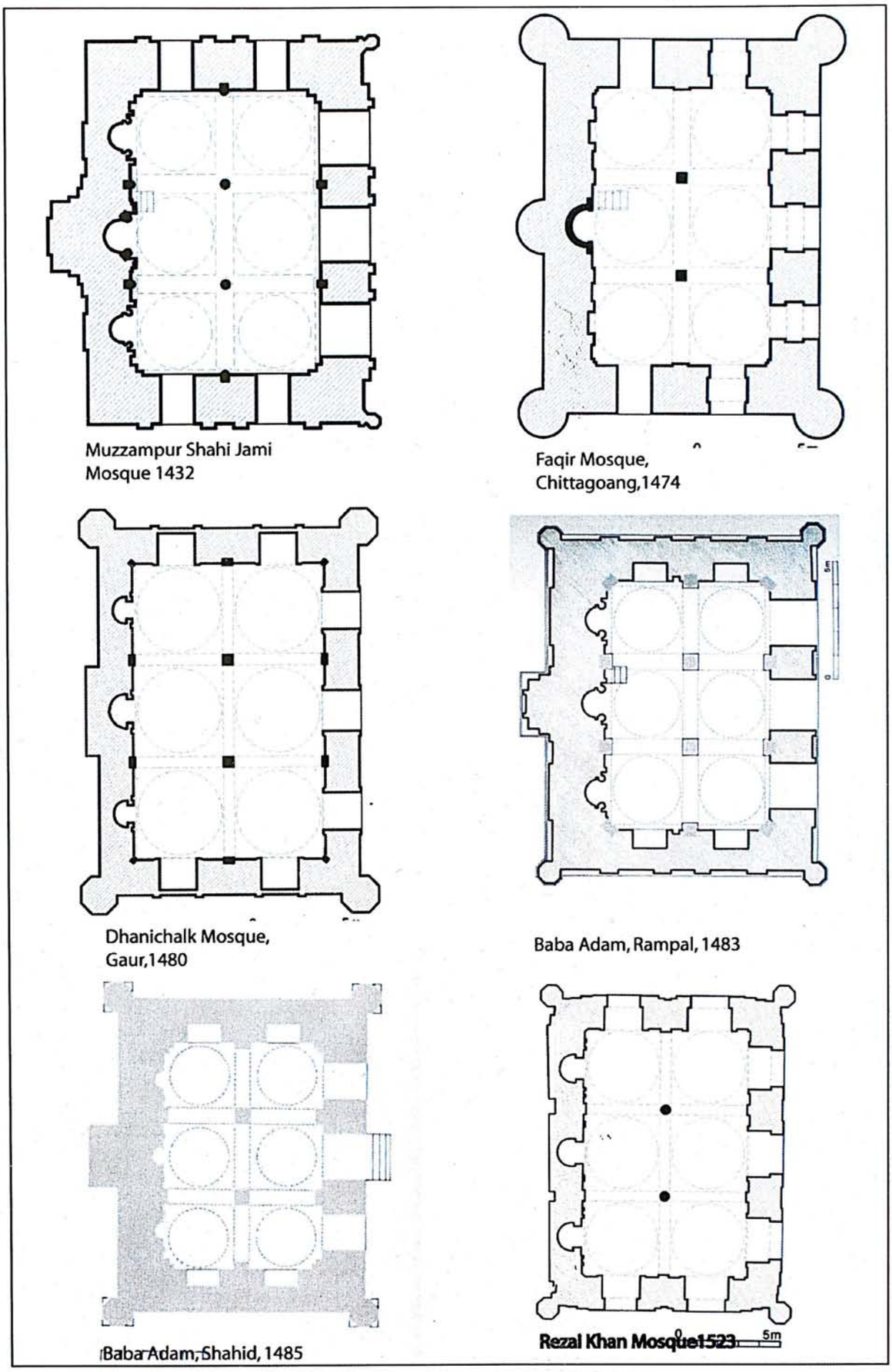


Figure 3.12a- 6 Double aisle mosques (6domes) in the corpus (Hassan, 2007).

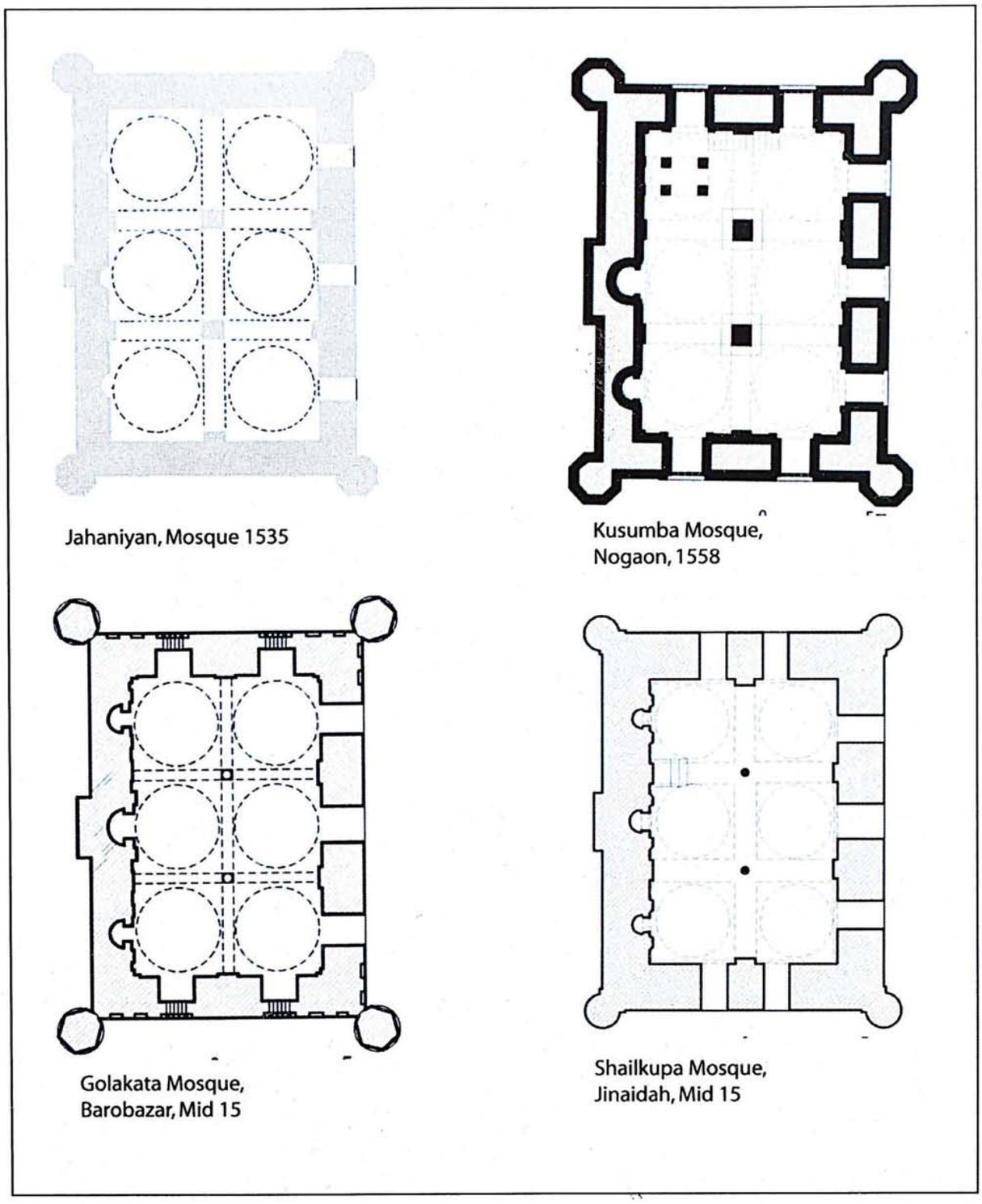


Figure 3.12b- 4 Double aisle mosques (6domes) in the corpus (Hassan, 2007).

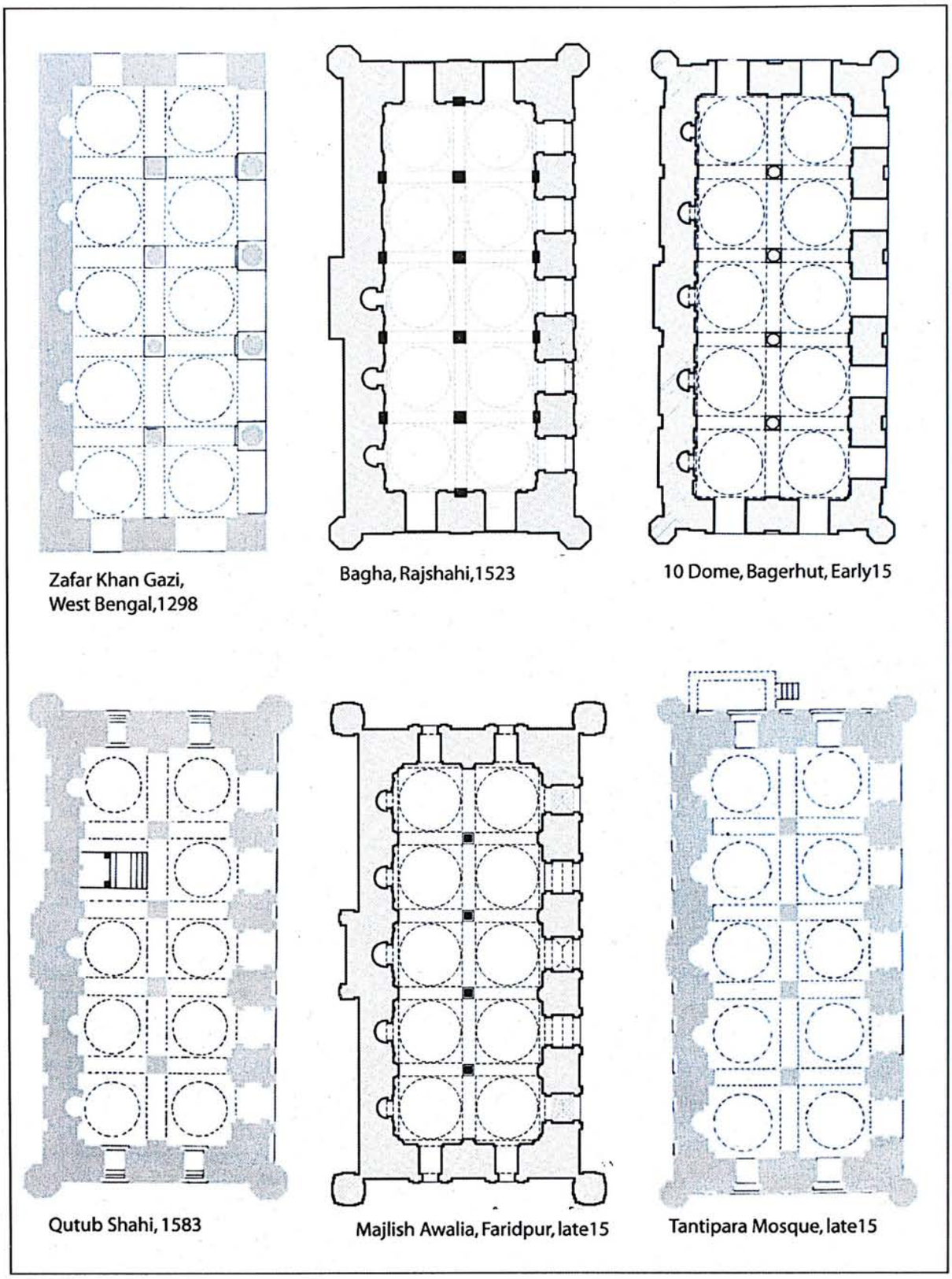


Figure 3.13- 6 Double aisle mosques (10 domes) in the corpus (Hassan, 2007).

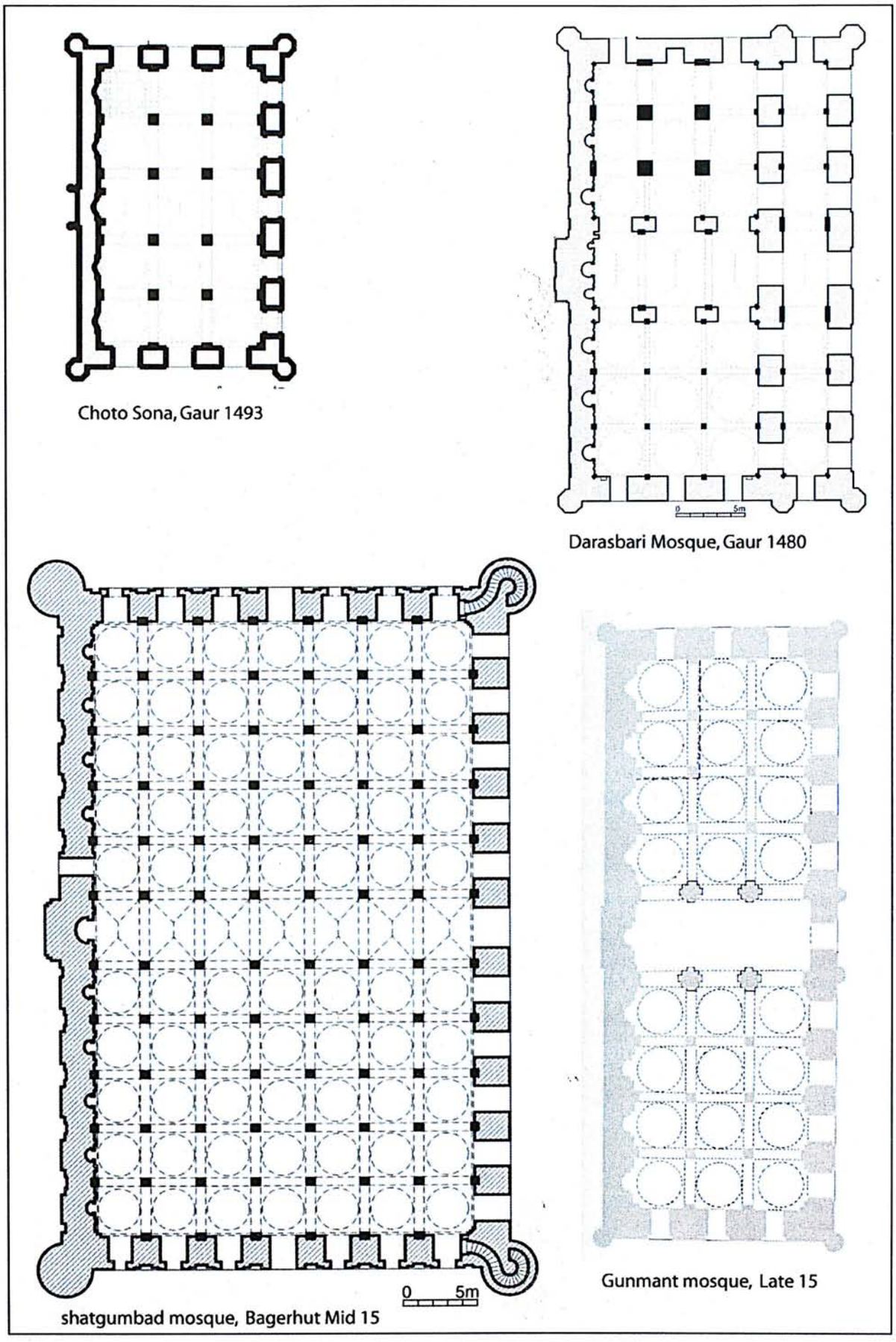


Figure 3.14- 4 Multi aisle mosques with vault in the corpus (Hassan, 2007).

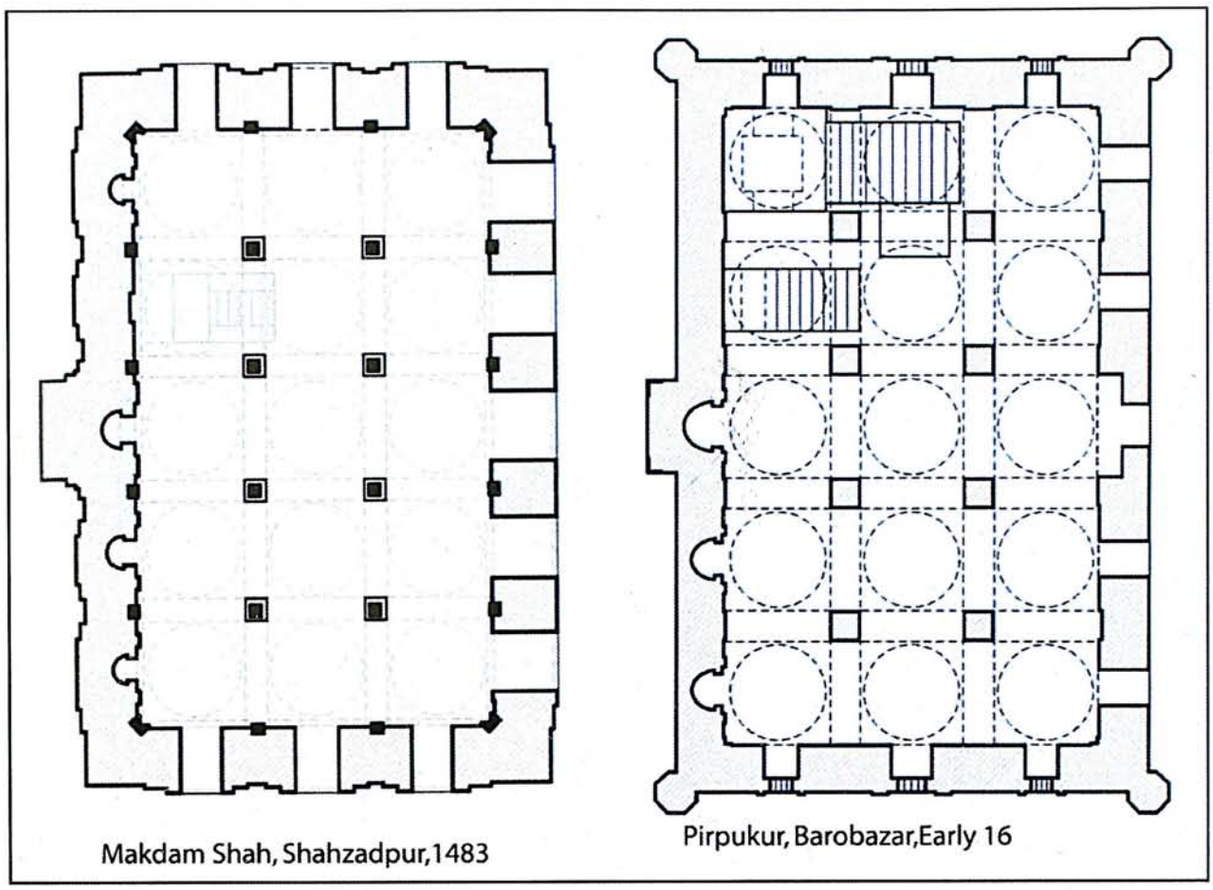


Figure 3.15a- 2 Multi aisle mosques without vault (15 domes) in the corpus (Hassan, 2007).

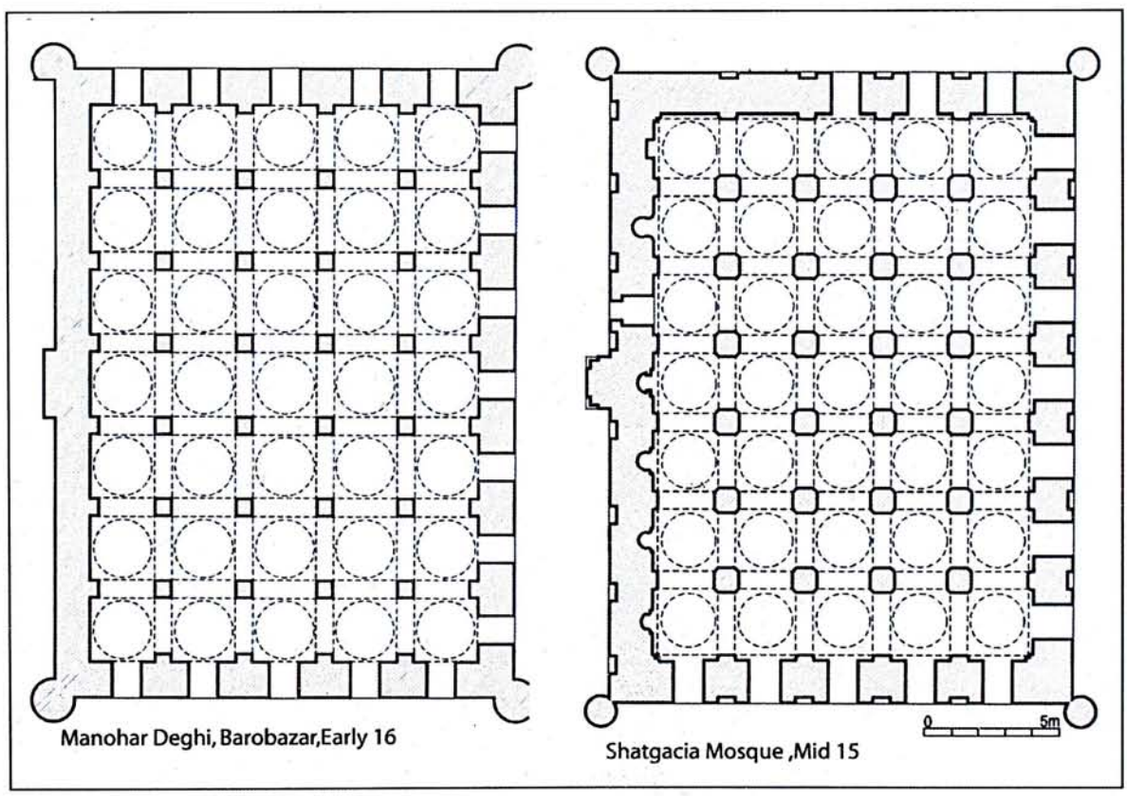
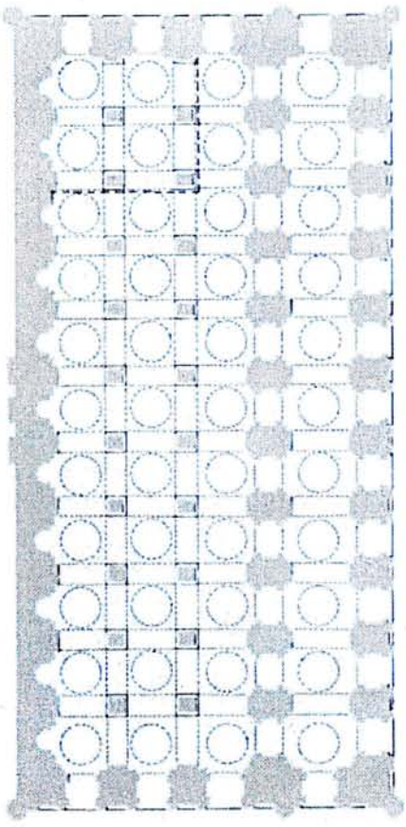
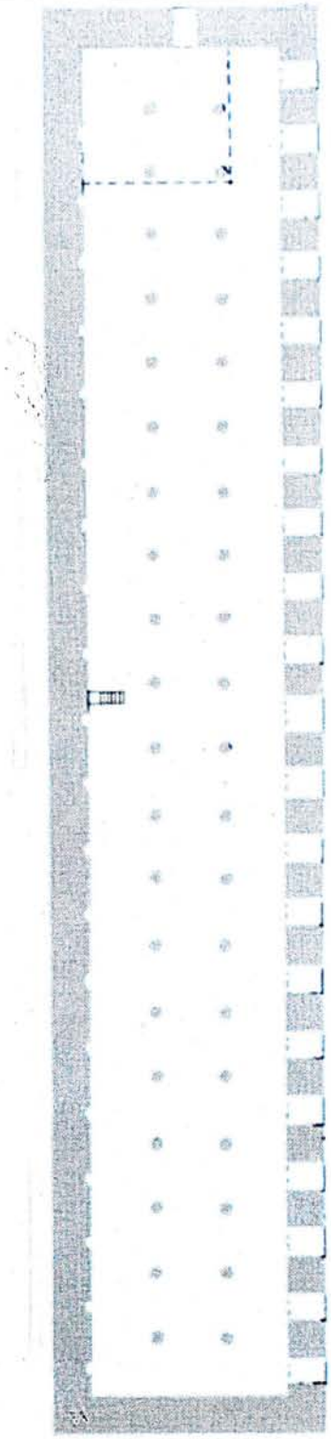


Figure 3.15b- 2 Multi aisle mosques without vault (35 domes) in the corpus (Hassan, 2007).



Barosona Mosque, 1526



Choto Pandua, West Bengal
Early 14

Figure 3.15c- 2 Multi aisle mosques without vault (44 and 63 domes) in the corpus (Hassan, 2007).

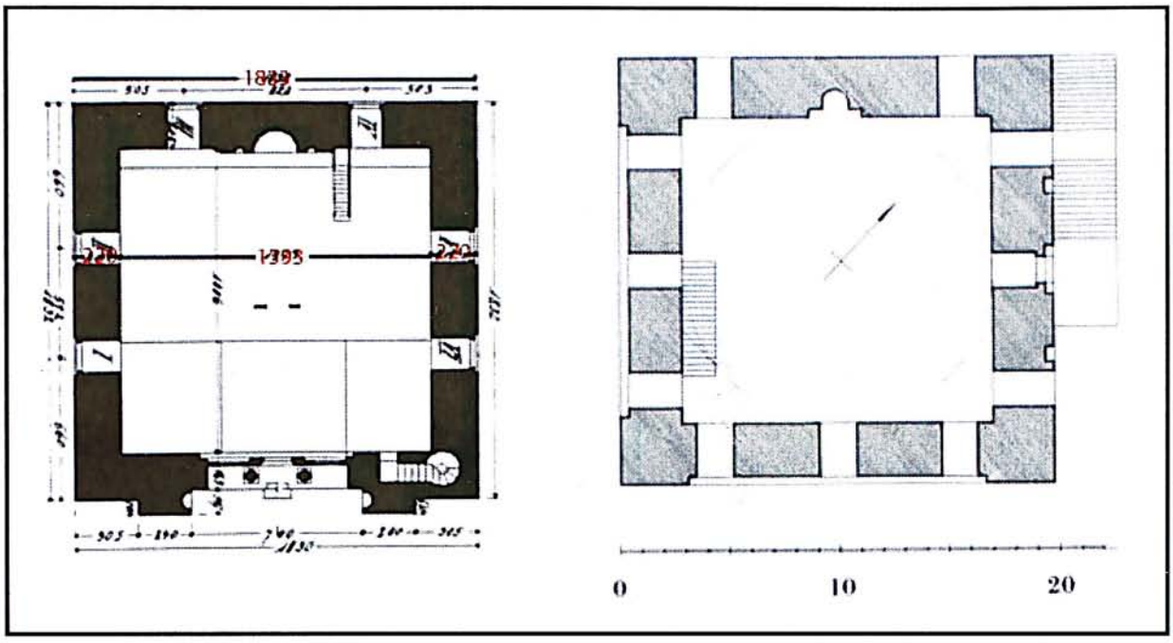


Figure 3.16a- Wall thickness showing of the mosque Balat from Islamic world, (Meinecke, 1996).

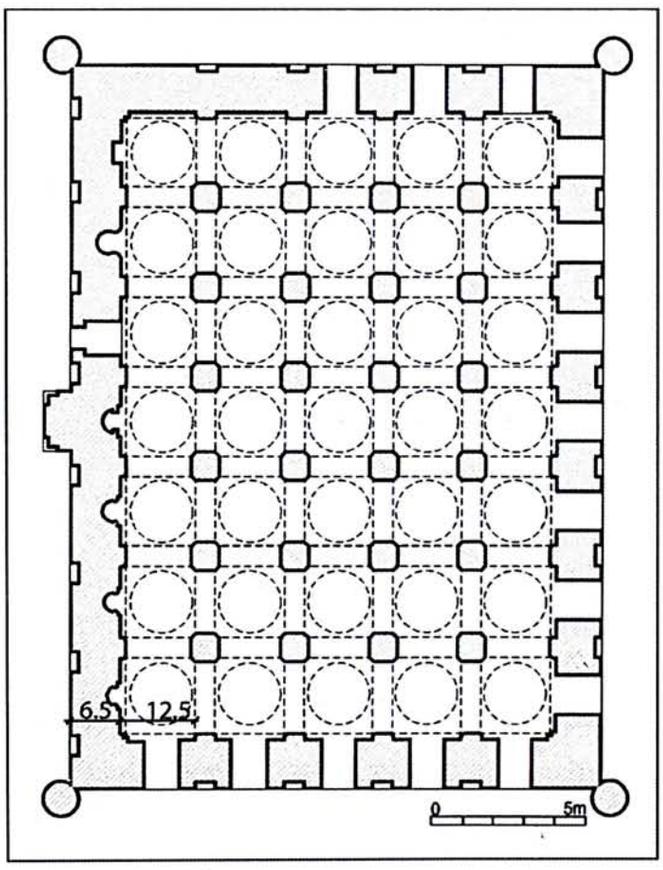


Figure 3.16b- Wall thickness of multi dome mosque in Bengal (Hassan, 2007).

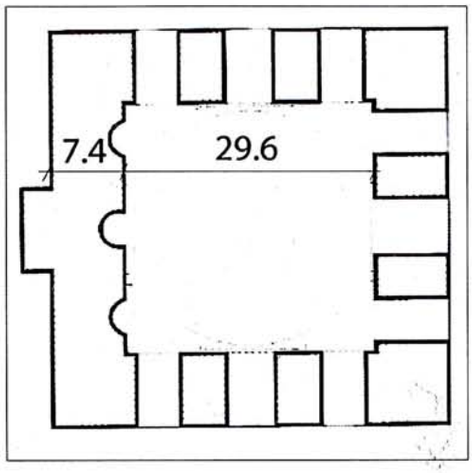
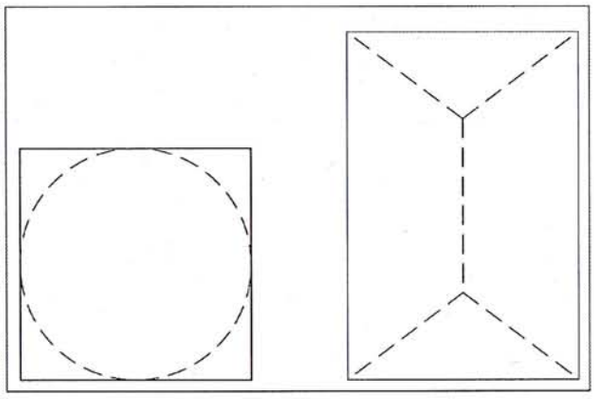


Figure 3.16c- Wall thickness of single domed mosque in Bengal, (Hassan, 2007).



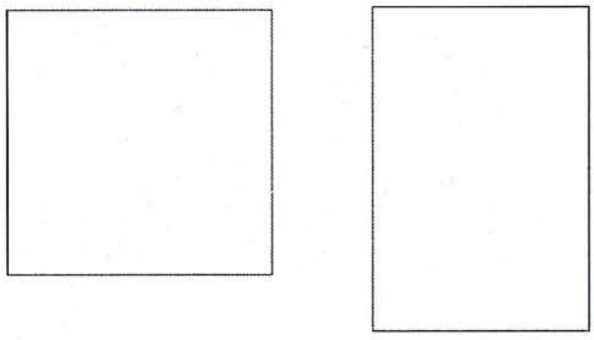


Figure 4.1- The two basic shapes with roof outline. Figure 4.2- The two initial shapes.

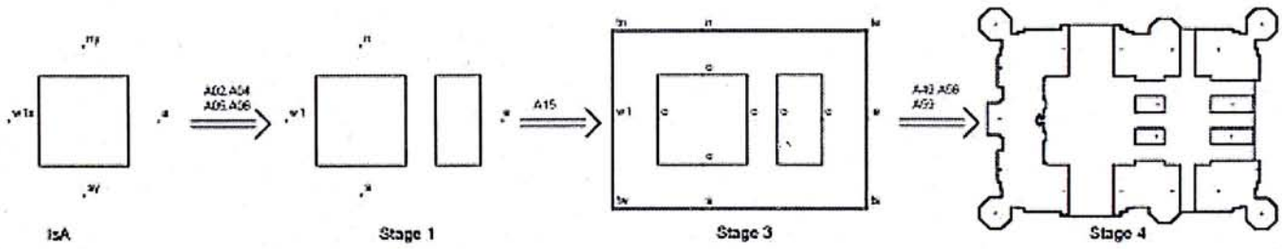


Figure 4.3- Derivation stages developed by applying the A set rules to the initial shape A.

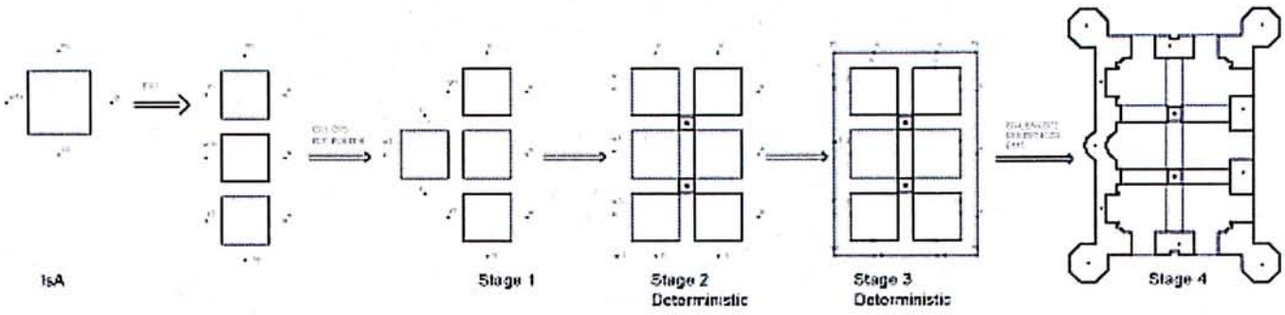


Figure 4.4-. Derivation stages developed by applying the B set rules to the initial shape A

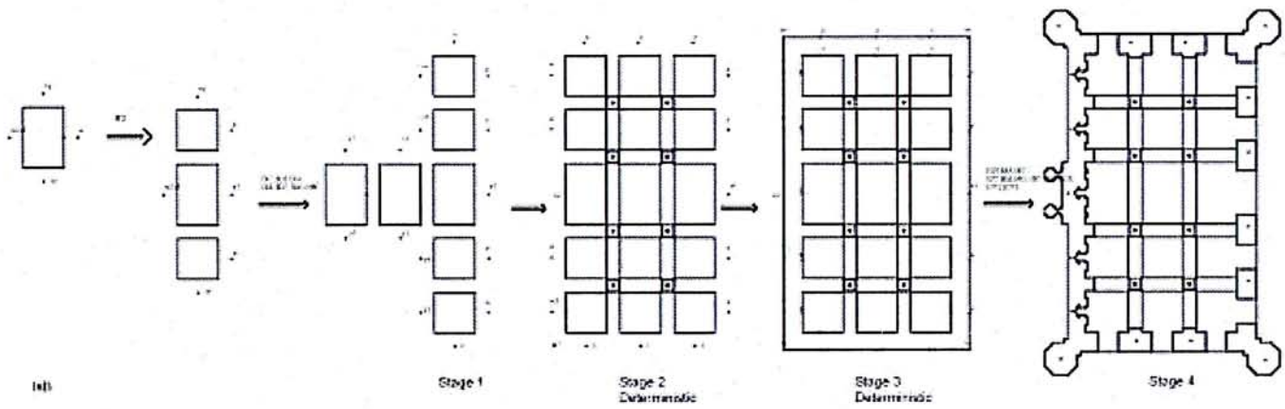


Figure 4.5- Derivation stages developed by applying the B set rules to the initial shape B

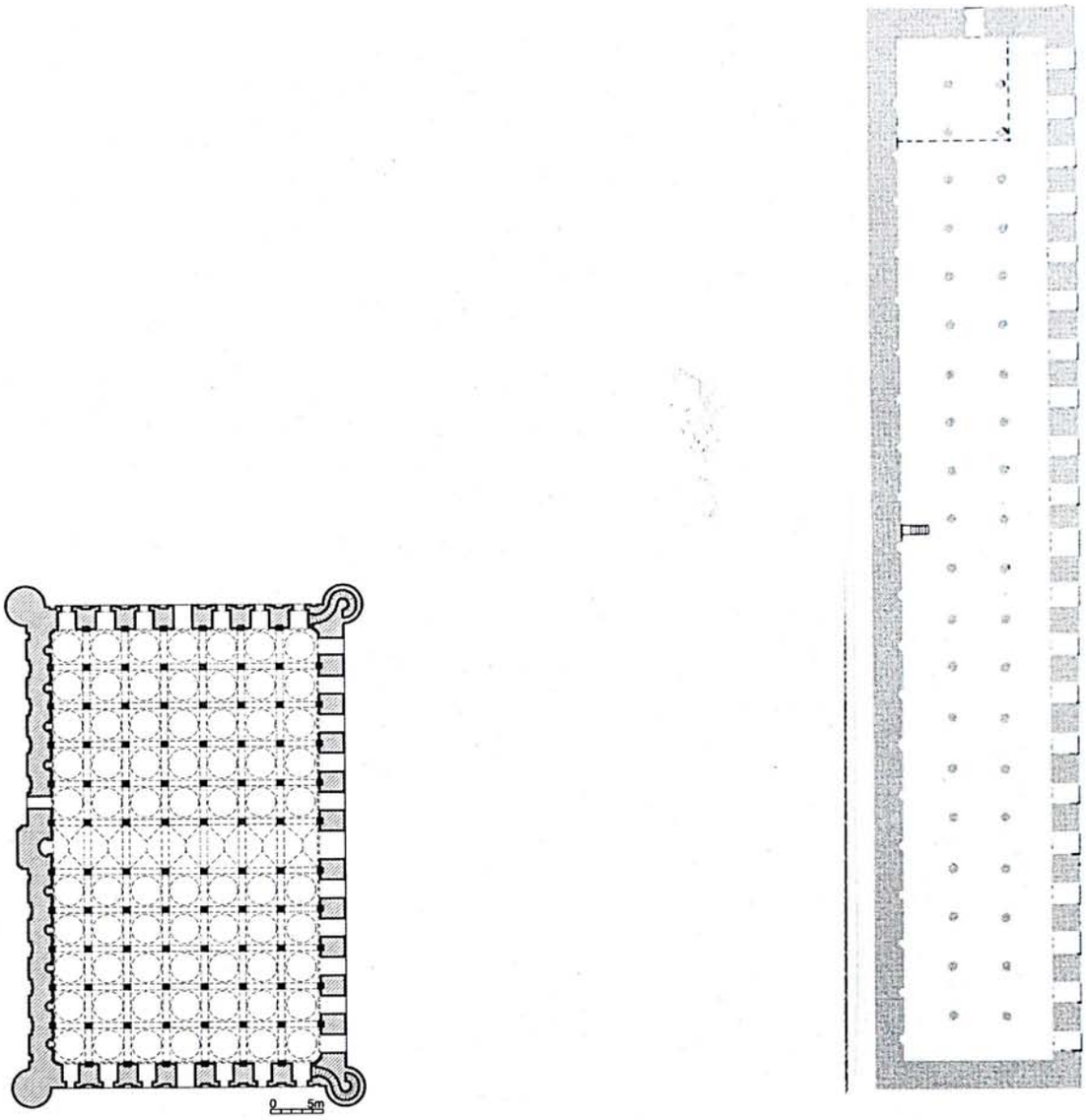


Figure 5.1- The widest (7 aisles) and the longest (21 bays) mosques in the corpus of Sultanate mosque in Bengal (Hassan, 2007).

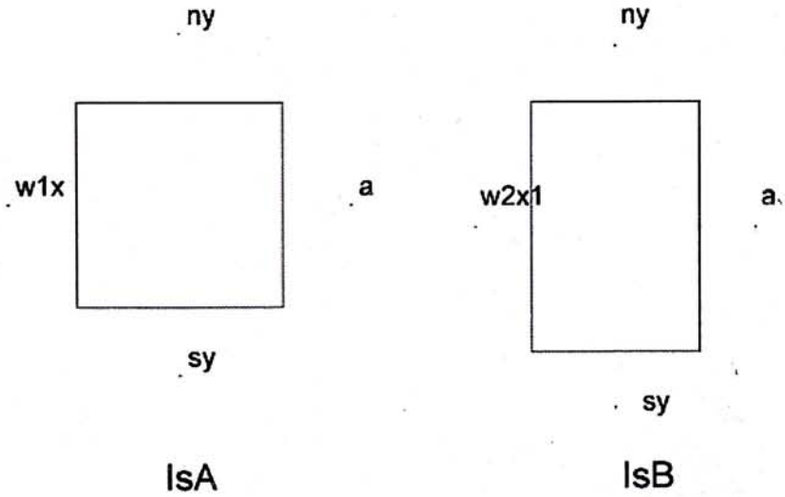


Figure 5.2- The two initial shapes.

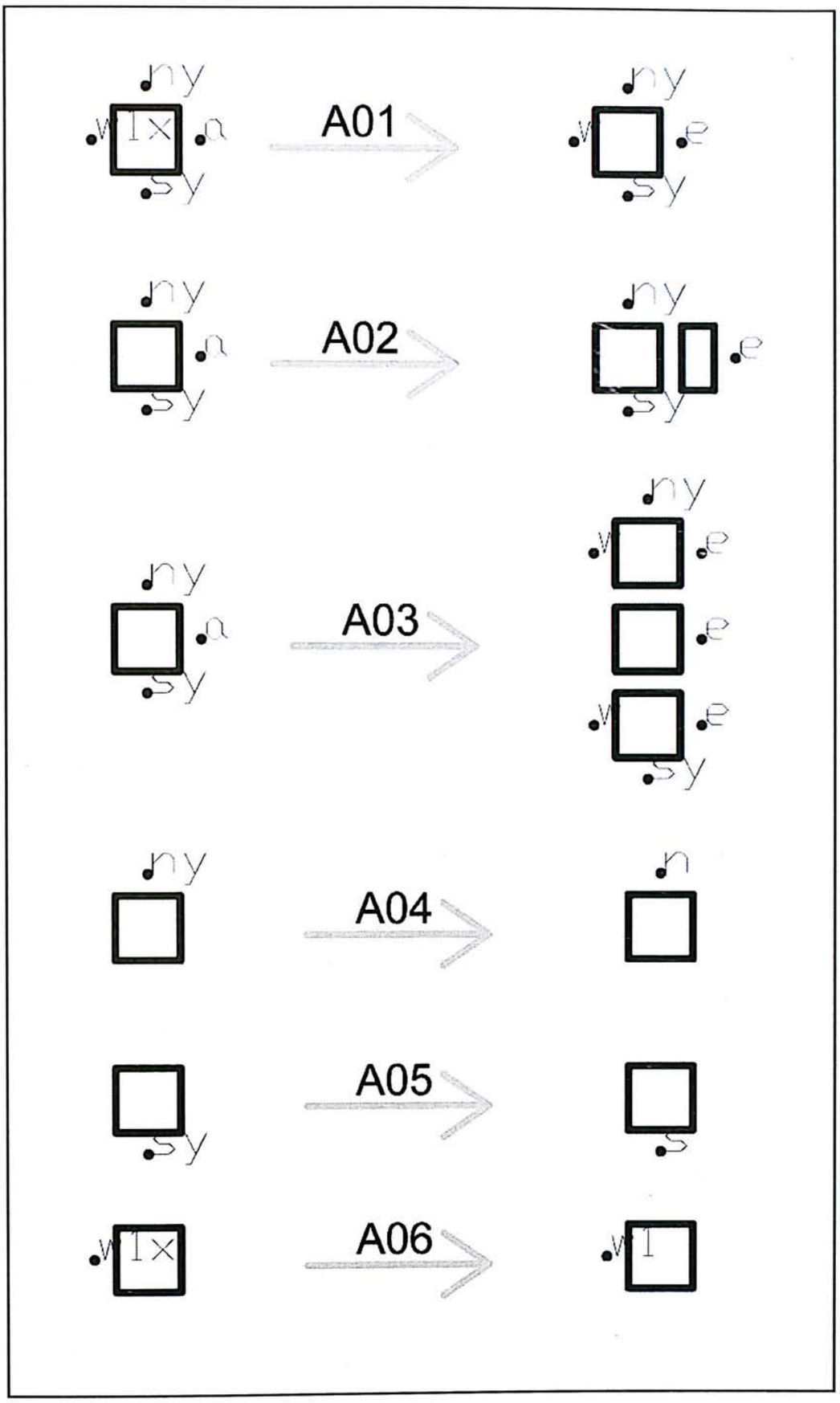


Figure 5.3a - The A rule set.

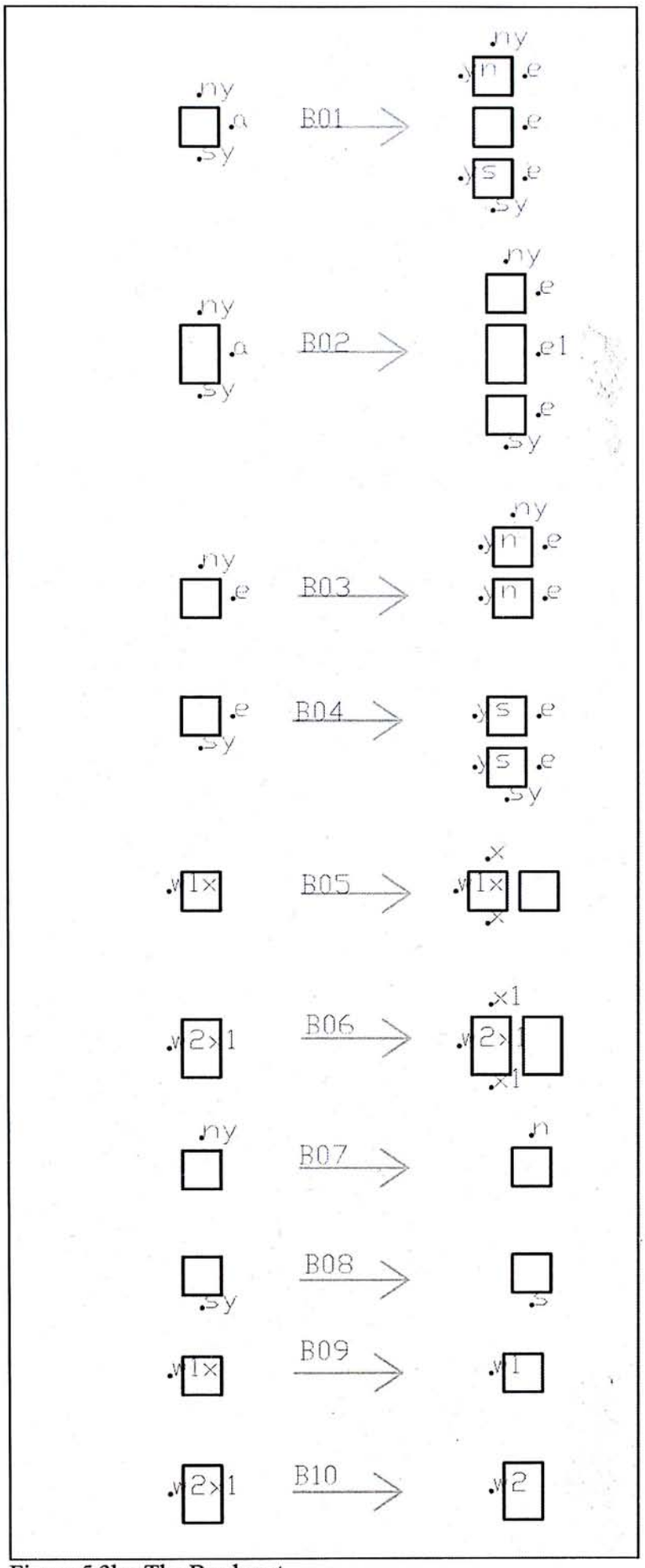


Figure 5.3b - The B rule set.

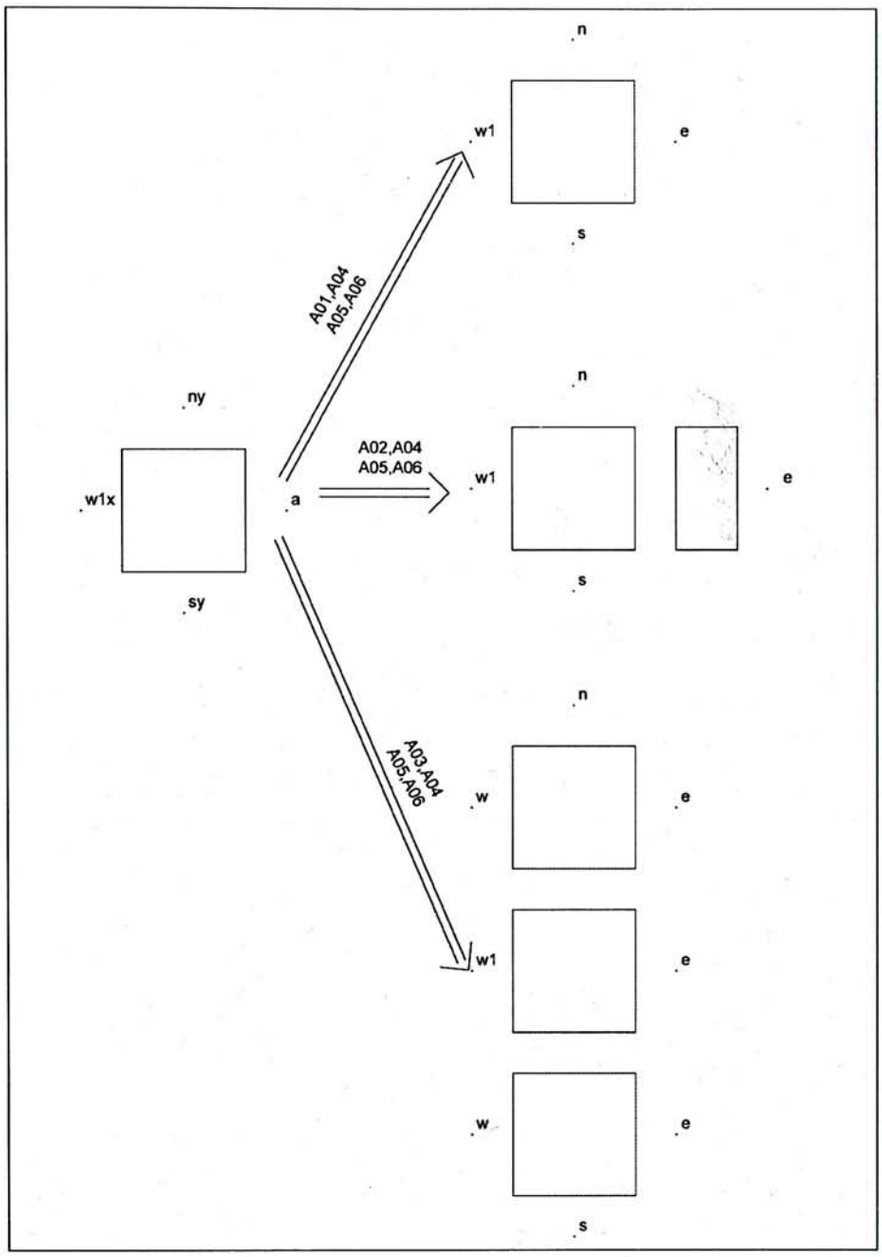


Figure 5.4- Derivation in Stage 1 by applying the A rule set.

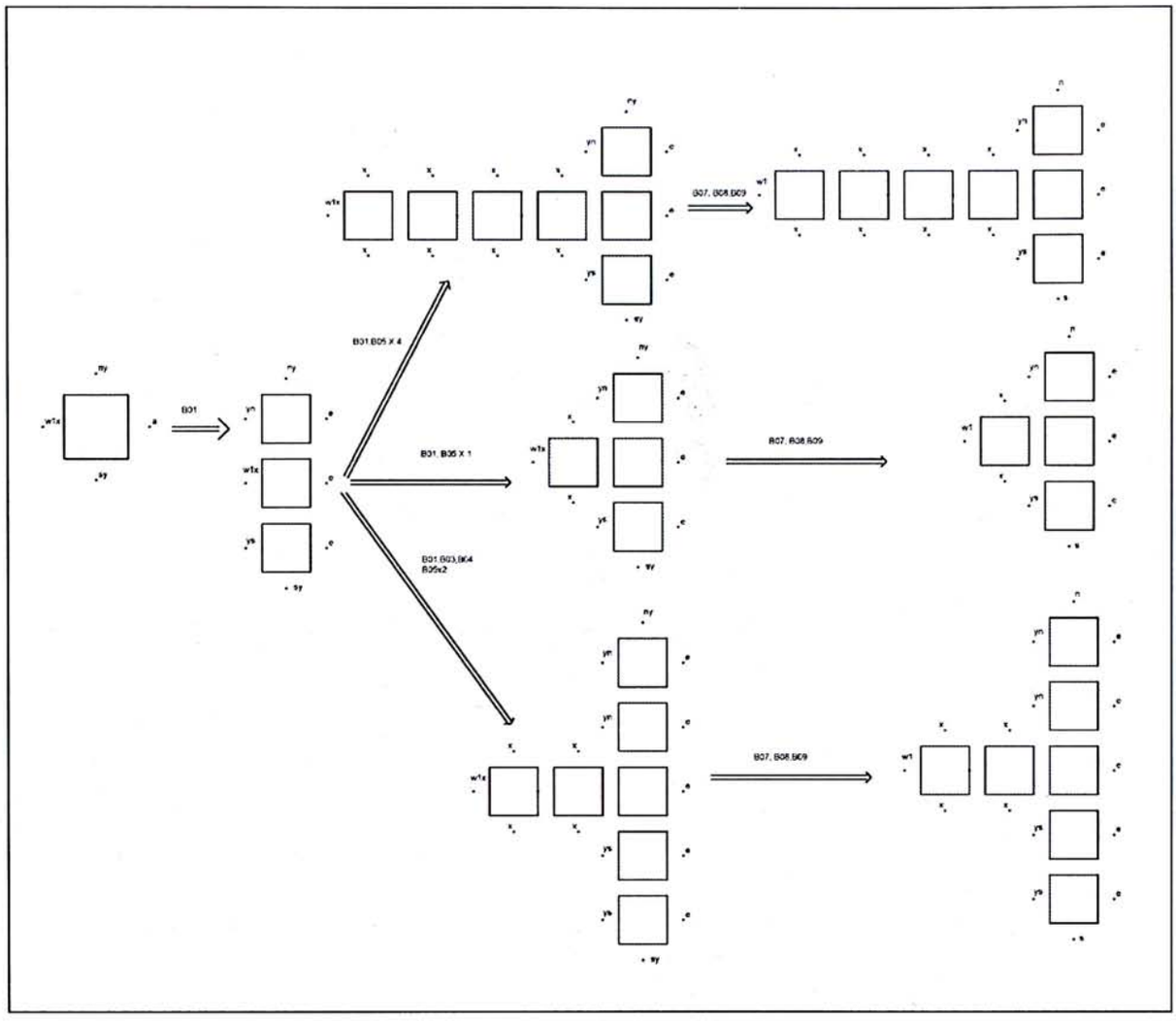


Figure 5.5a- Derivation in Stage 1 by applying the B rule set .

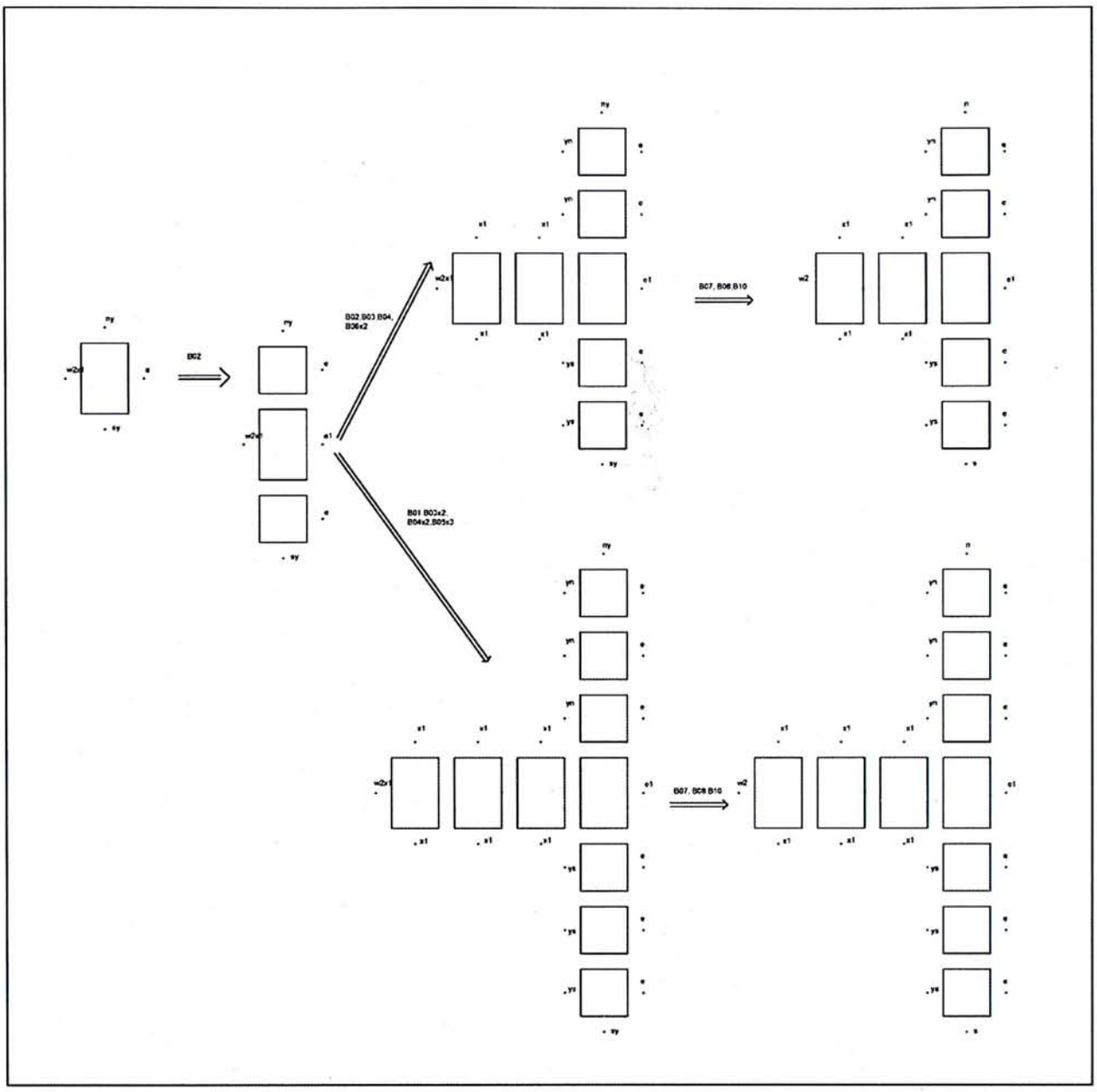


Figure 5.5b- Derivation in Stage 1 by applying the B rule set.

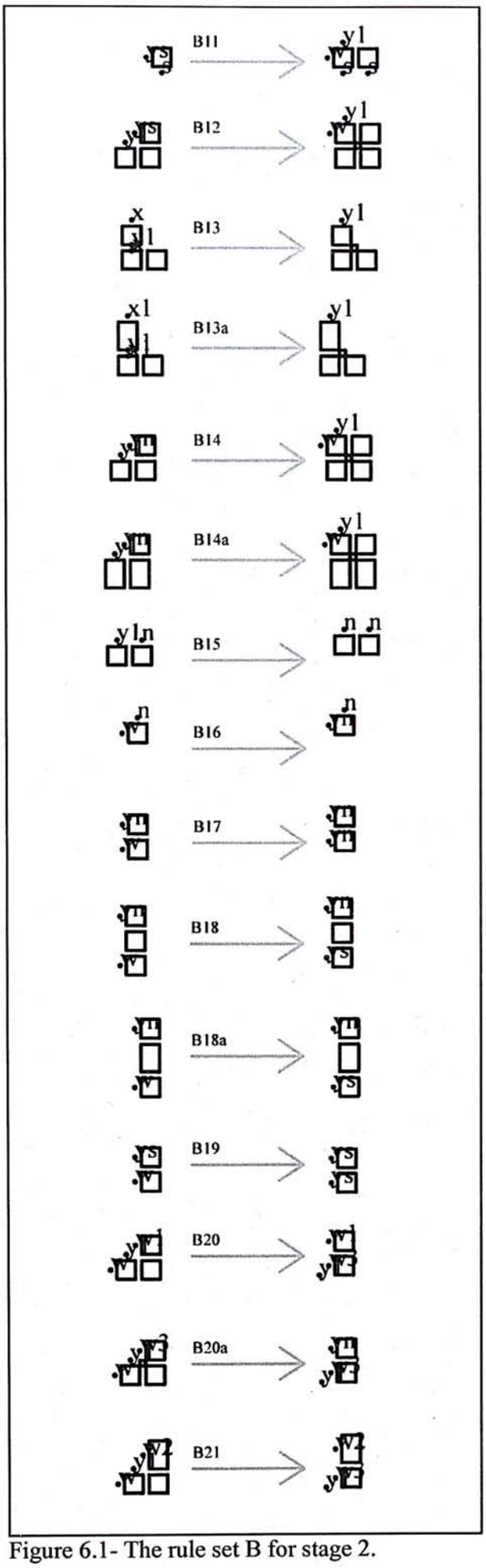


Figure 6.1- The rule set B for stage 2.

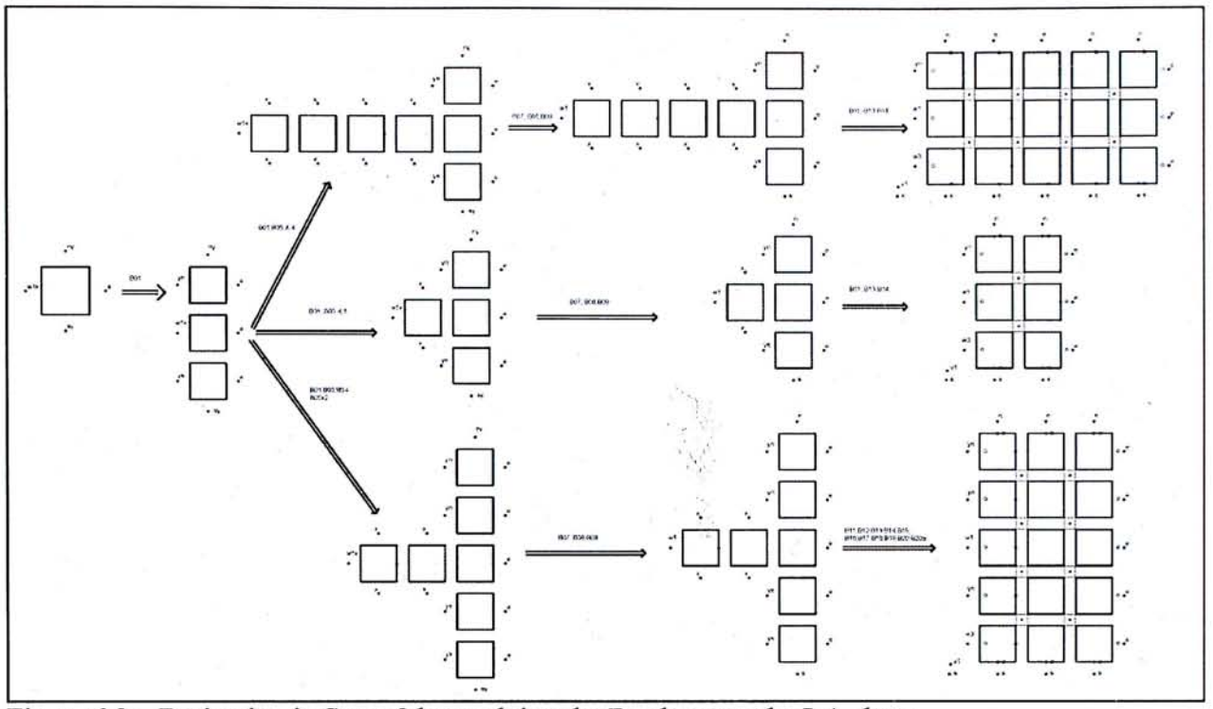


Figure 6.2a- Derivation in Stage 2 by applying the B rule set to the IsA shape.

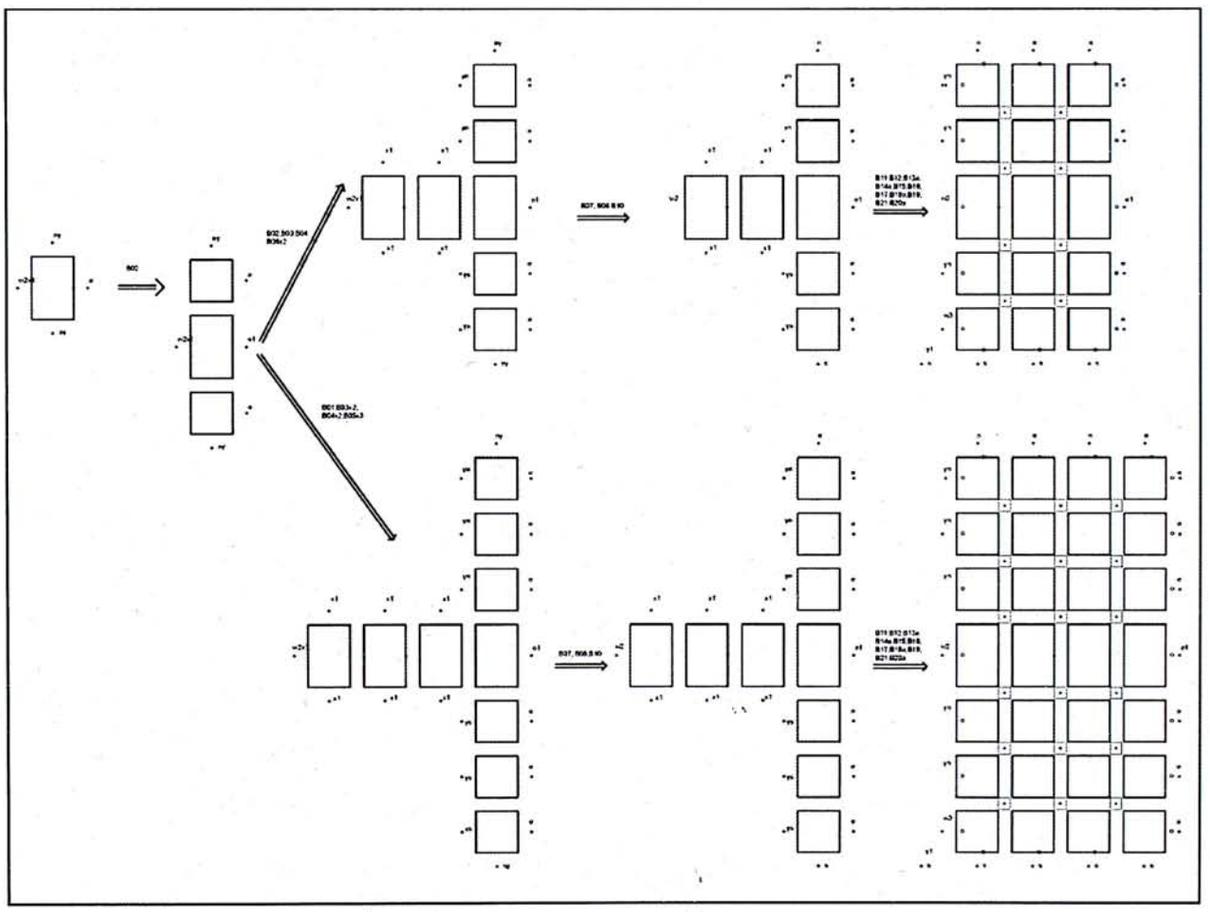


Figure 6.2b- Derivation in Stage 2 by applying the B rule set to the IsB shape.

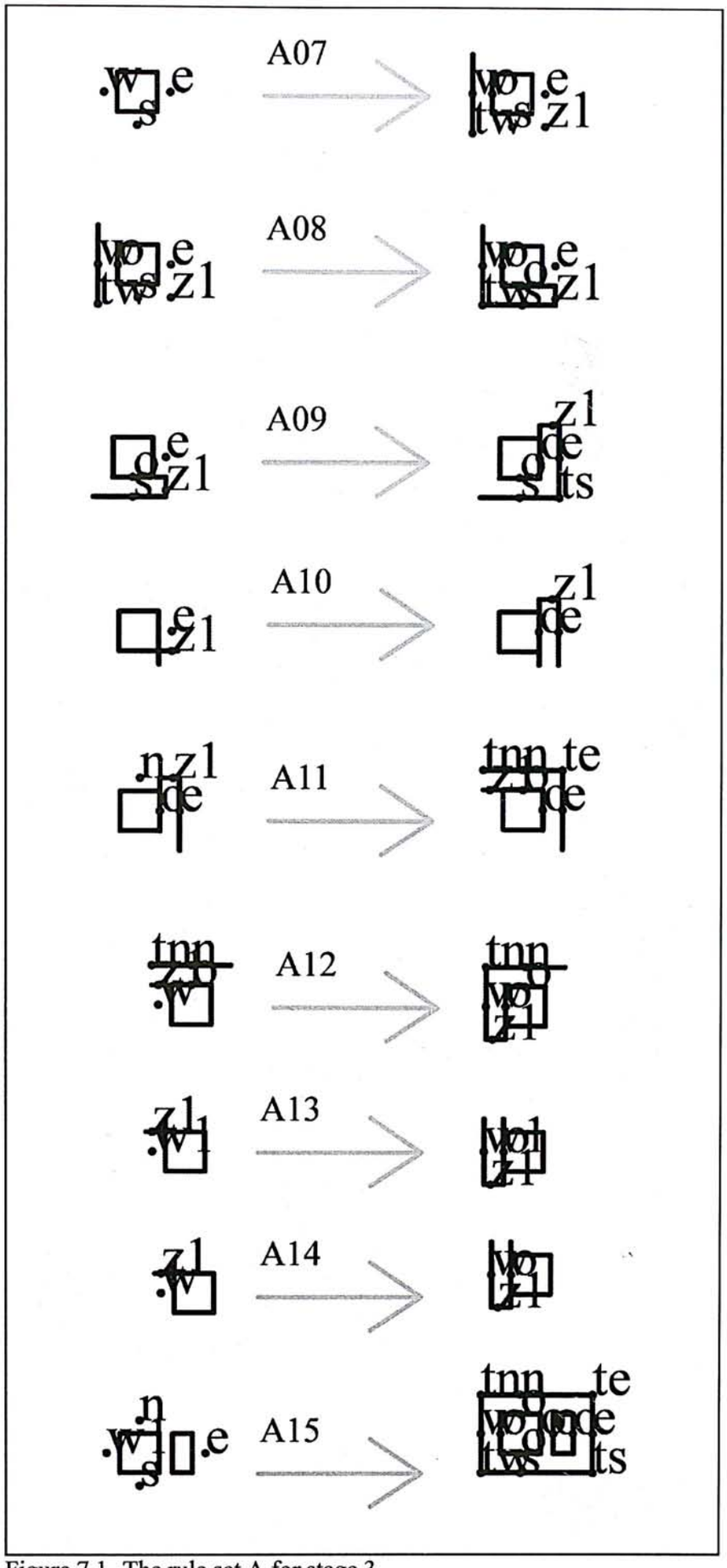


Figure 7.1- The rule set A for stage 3.

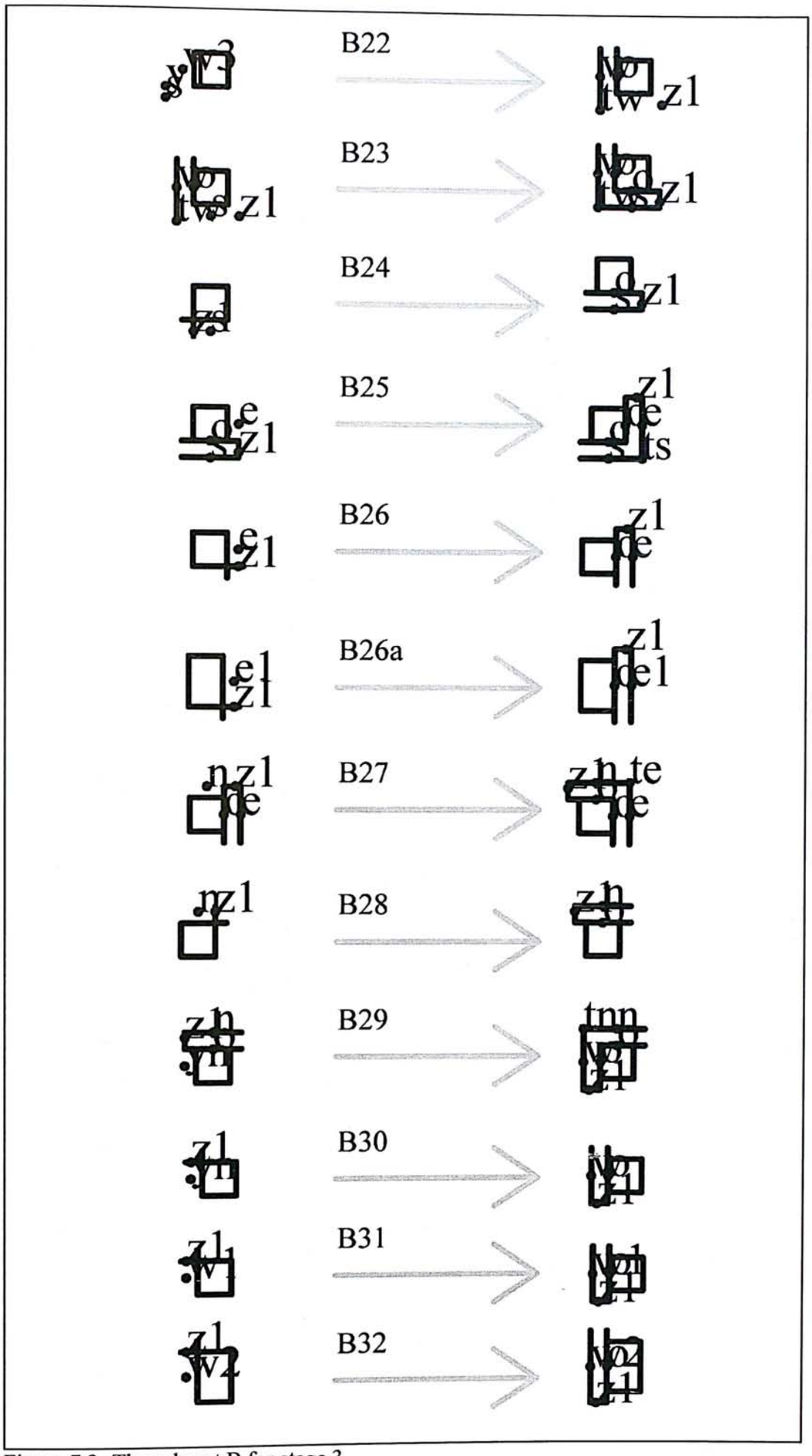


Figure 7.2- The rule set B for stage 3.

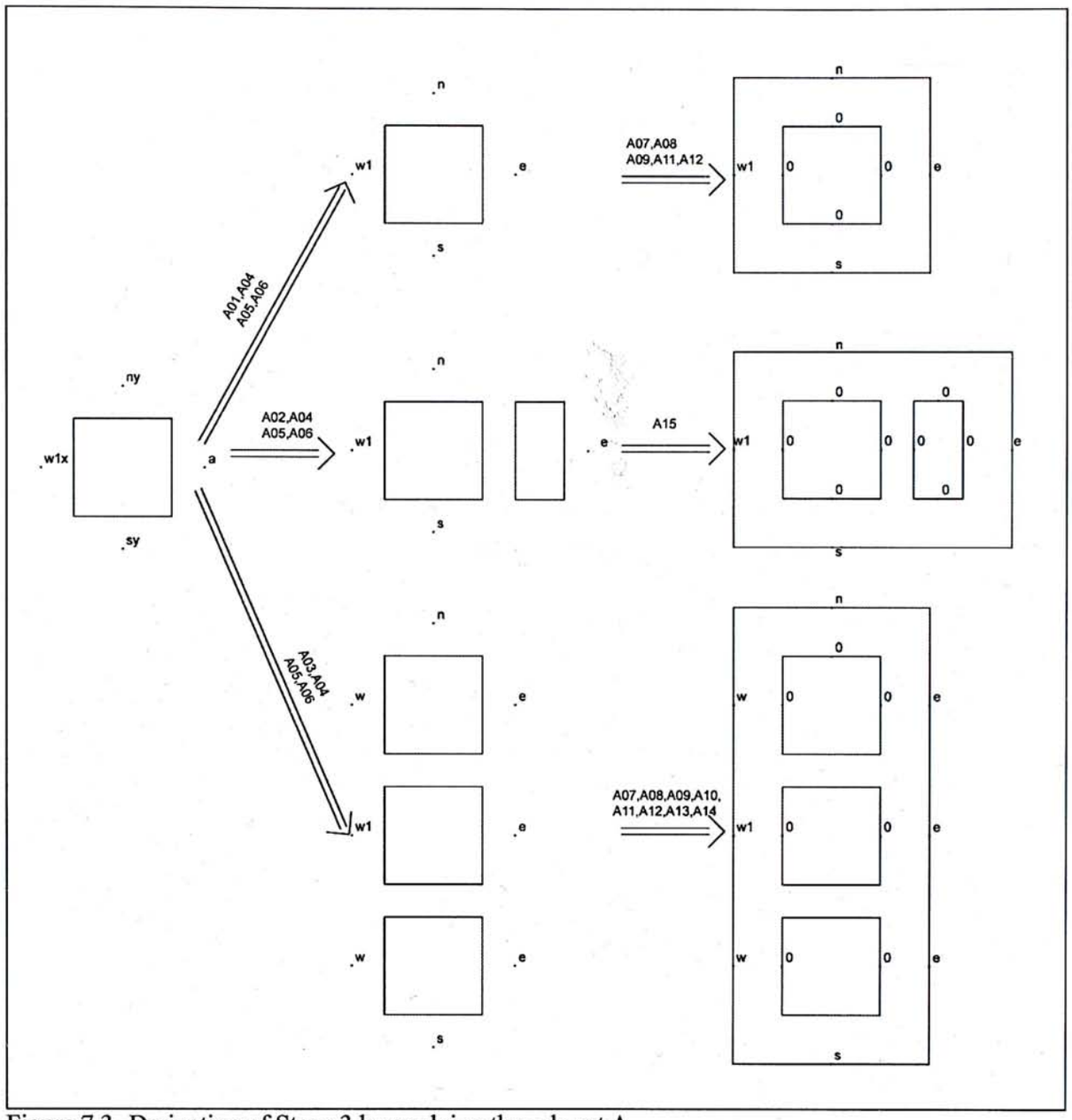


Figure 7.3- Derivation of Stage 3 by applying the rule set A.

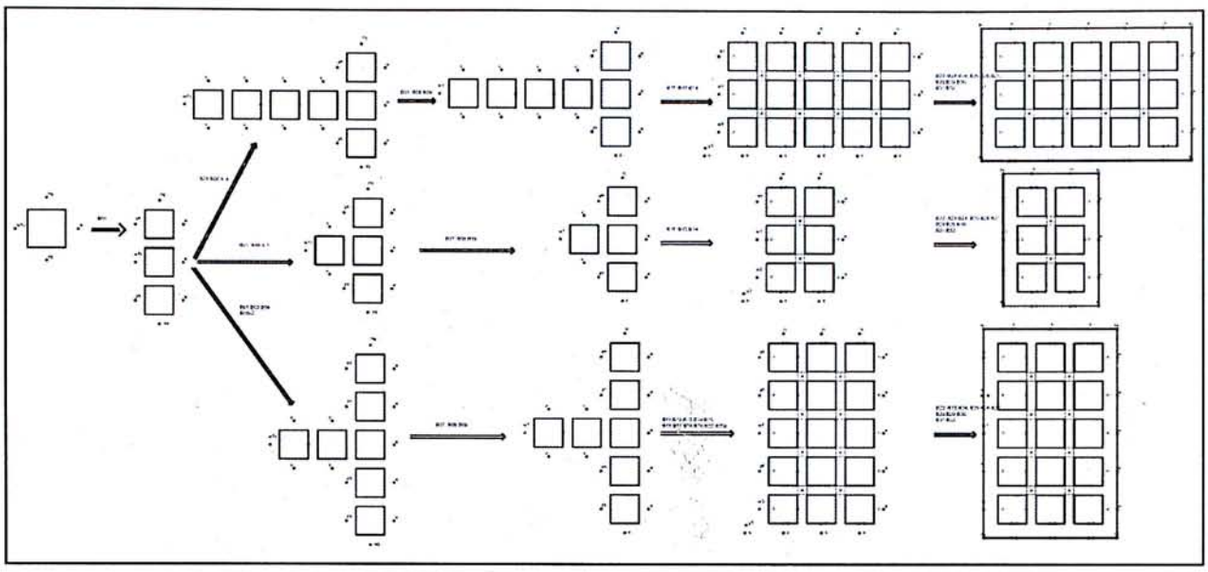


Figure 7.4a- Derivation in Stage 3 by applying the B rule set to the IsA shape.

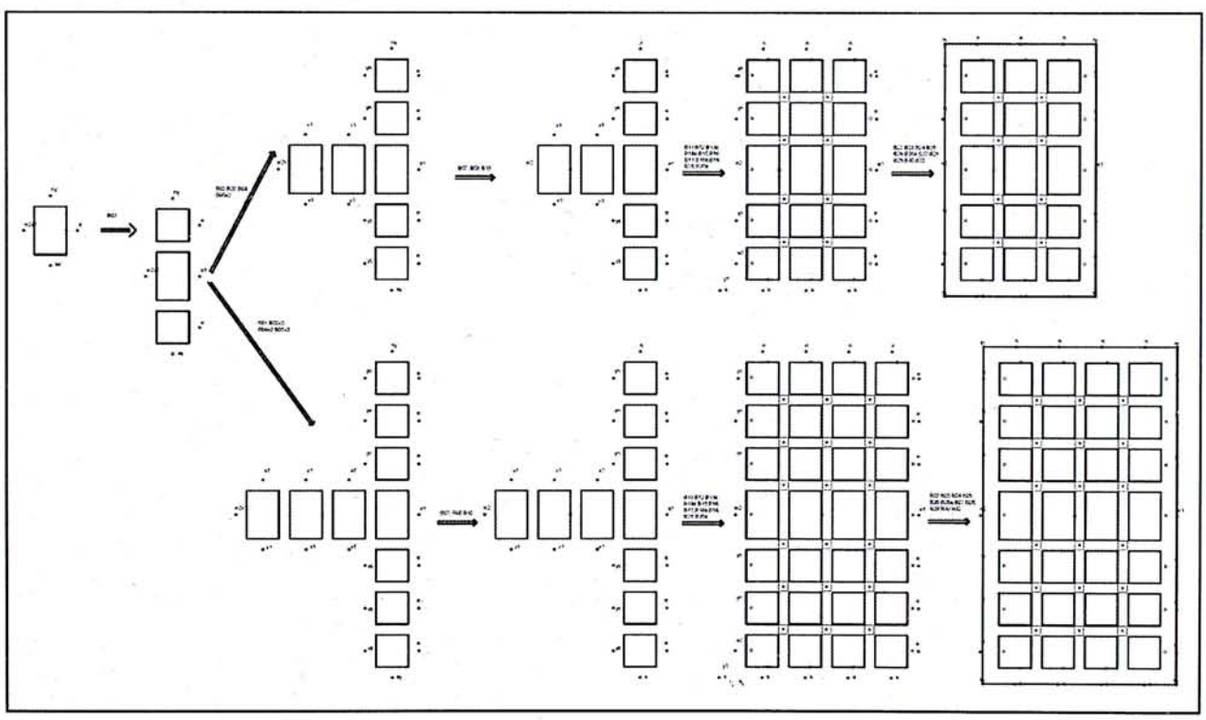


Figure 7.4b- Derivation in Stage 3 by applying the B rule set to the IsB shape.

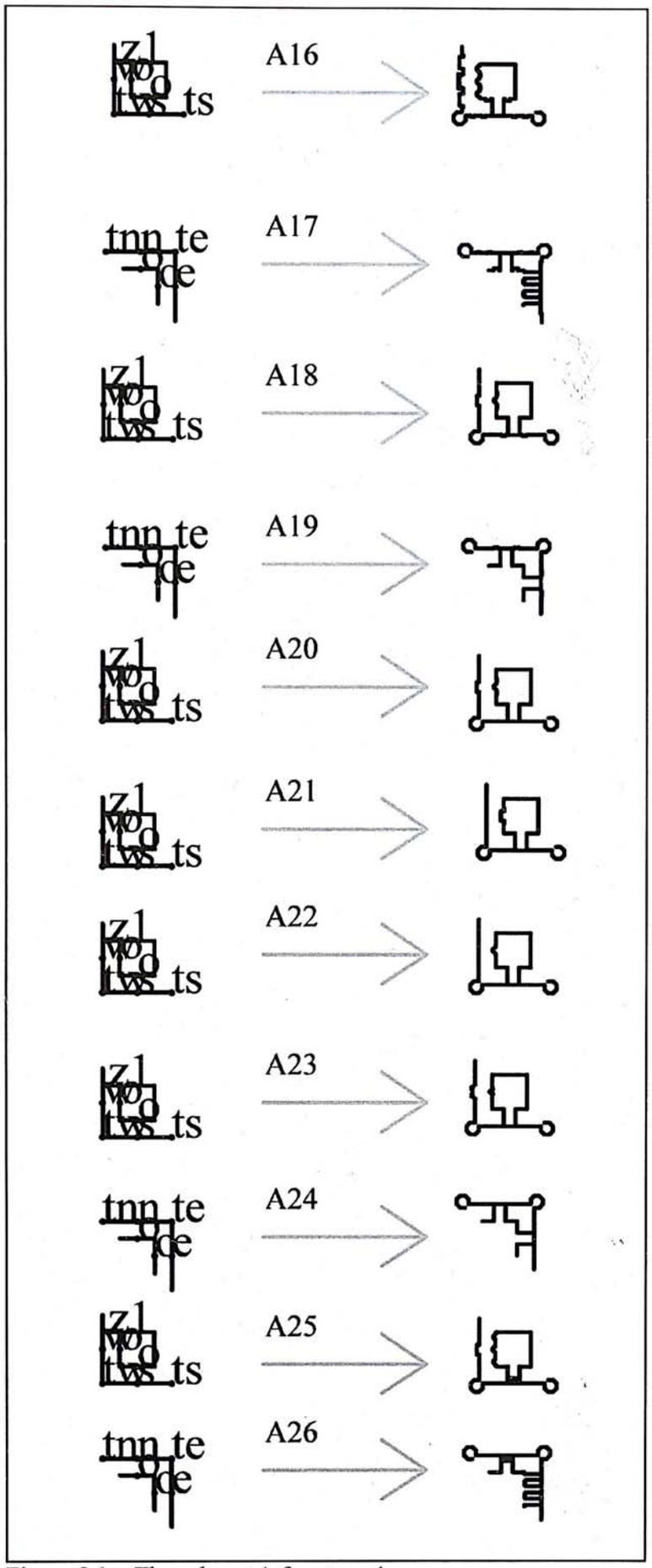


Figure 8.1a- The rule set A for stage 4.

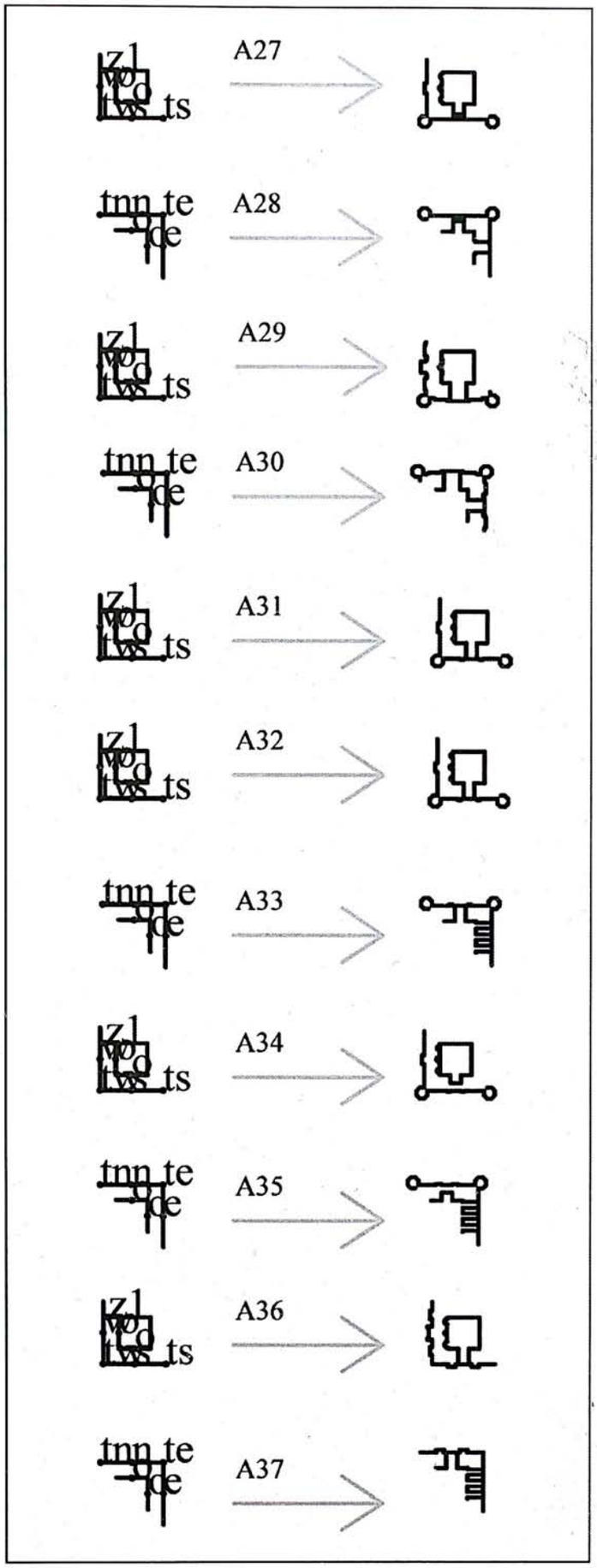


Figure 8.1b- The rule set A for stage 4.

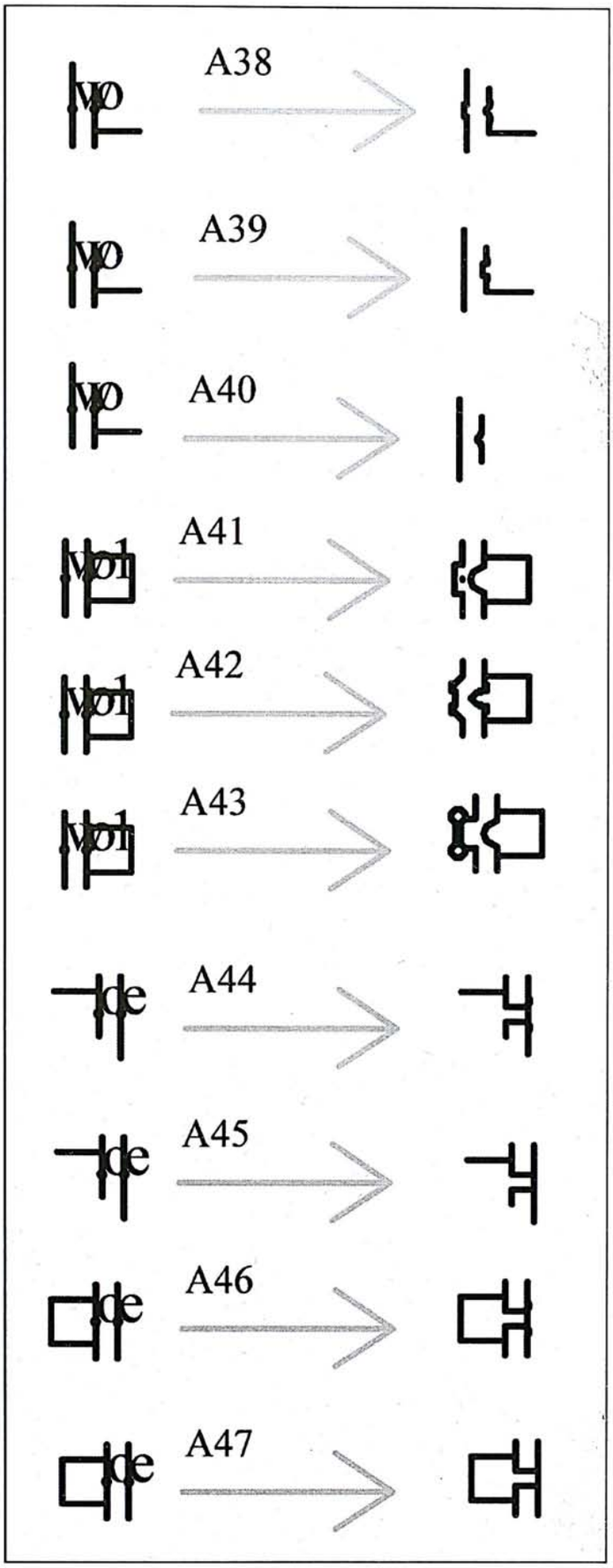


Figure 8.1c- The rule set A for stage 4.

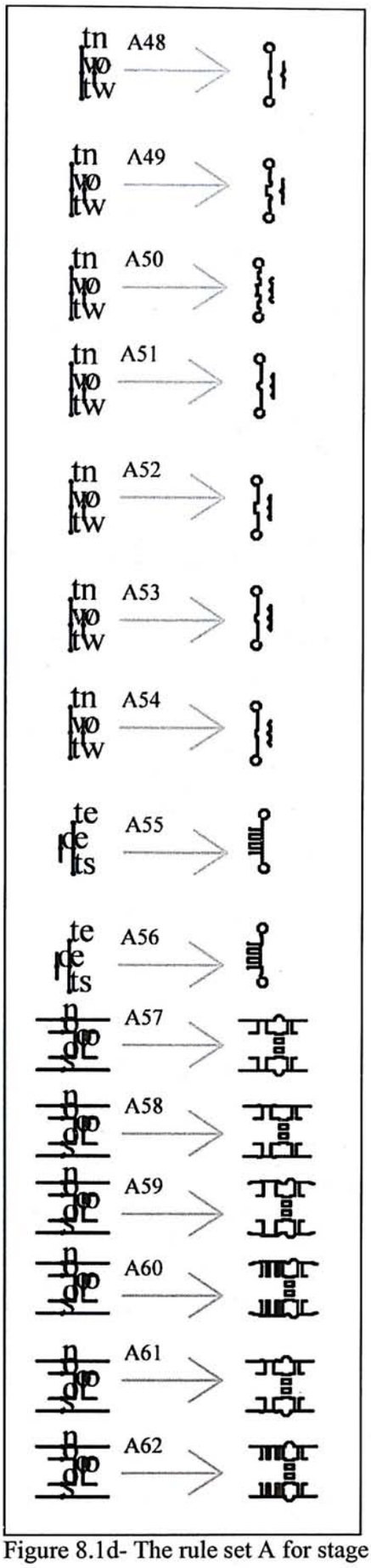


Figure 8.1d- The rule set A for stage 4.

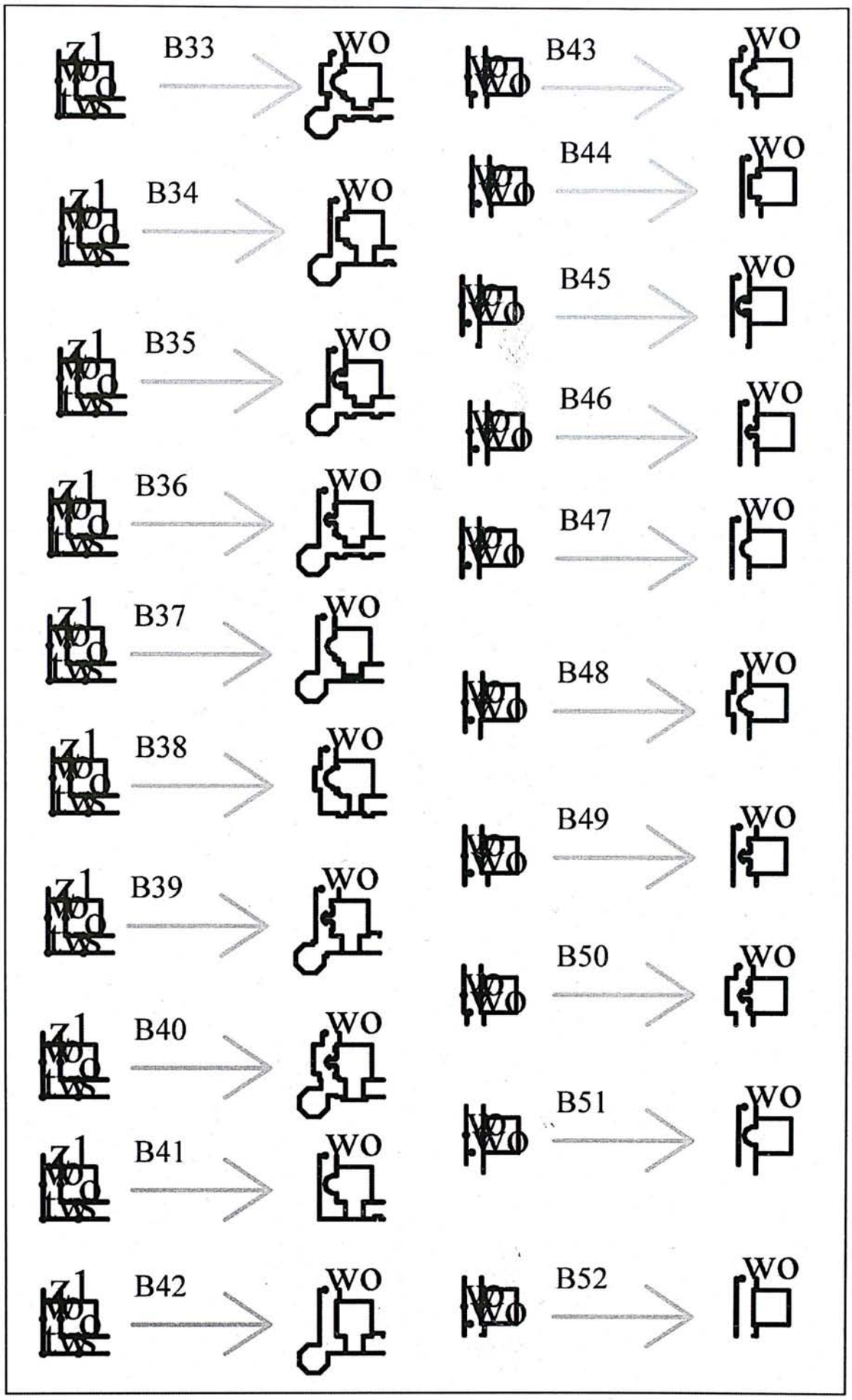


Figure 8.2a- The rule set B for stage 4.

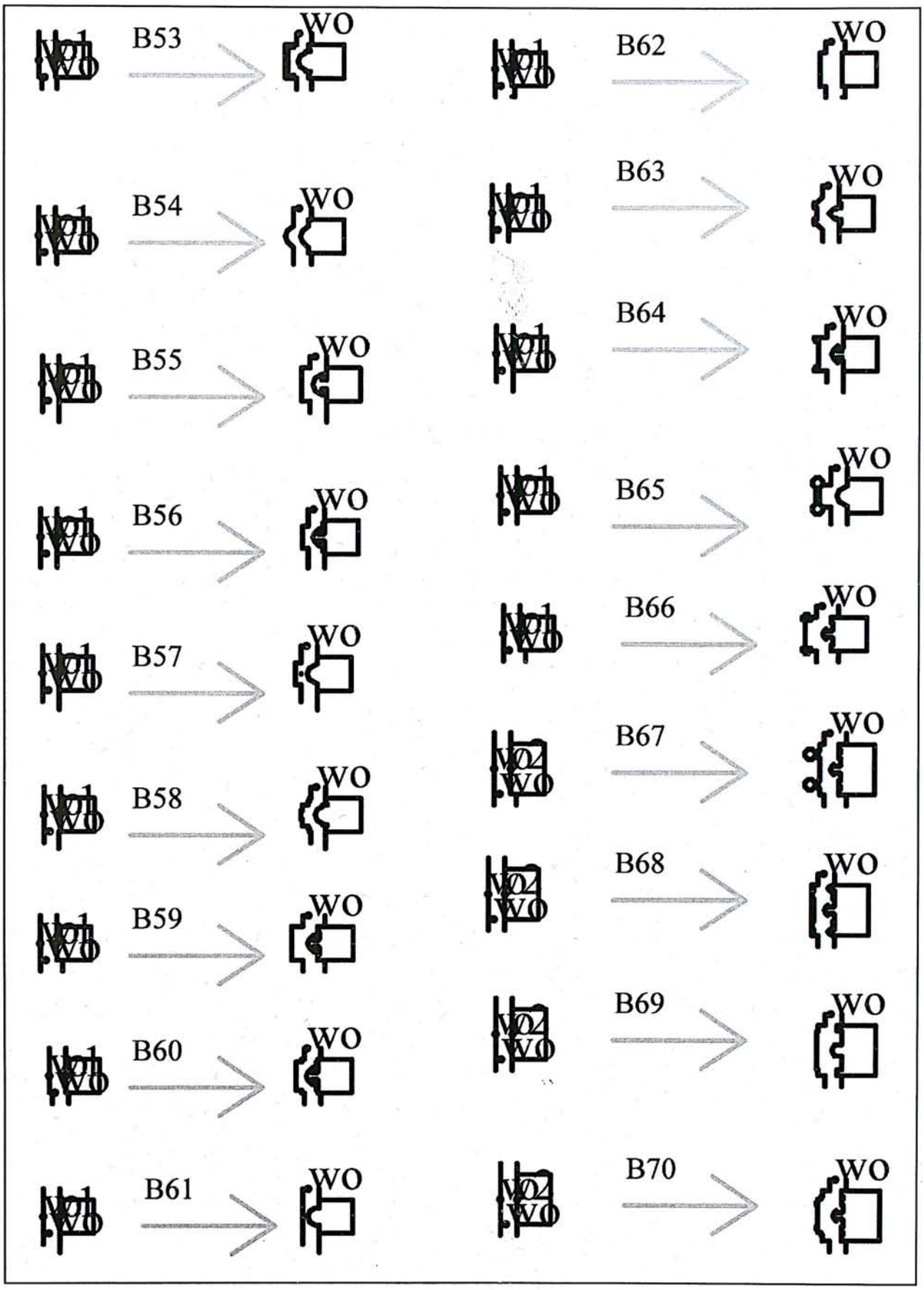


Figure 8.2b- The rule set B for stage 4.

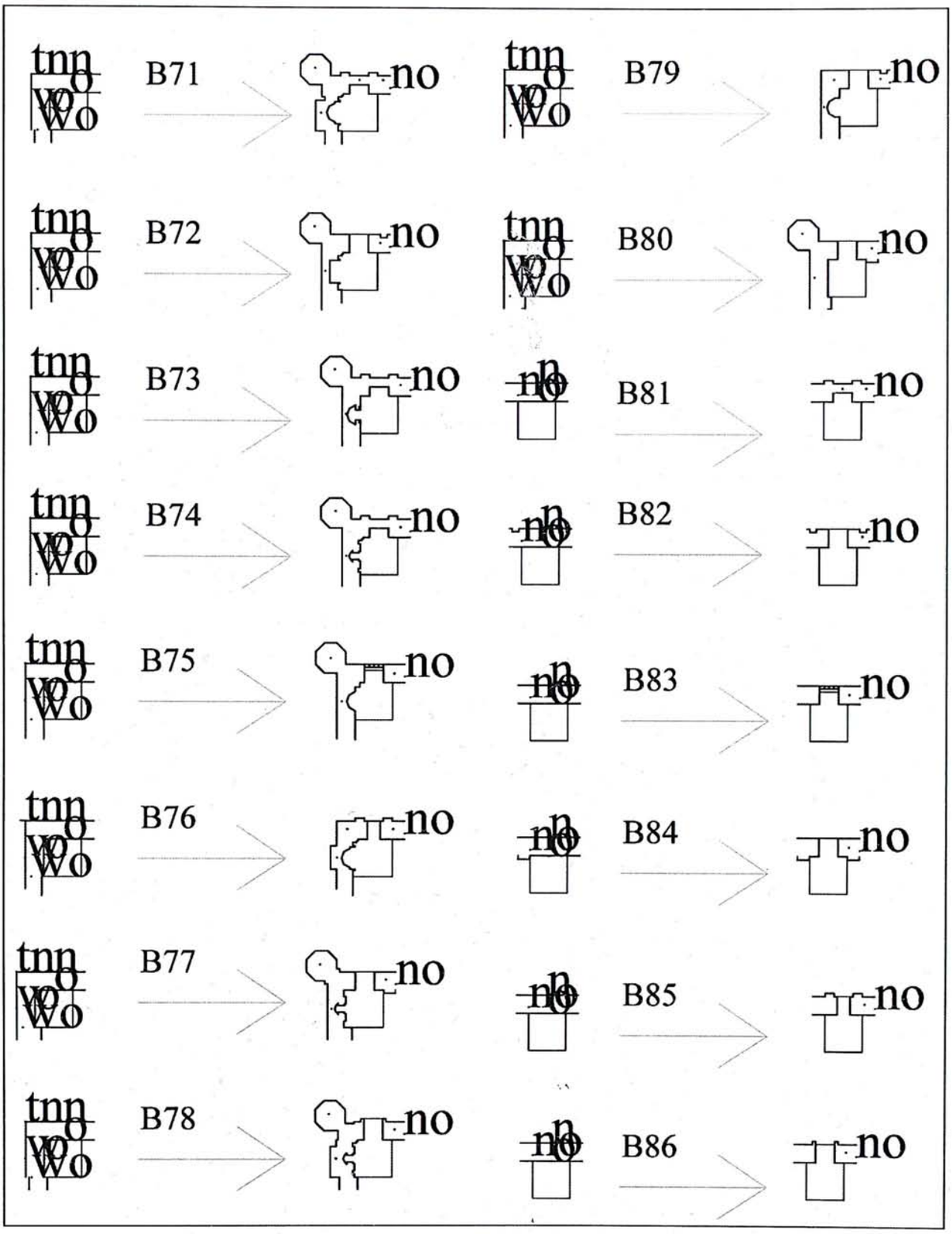


Figure 8.2c- The rule set B for stage 4.

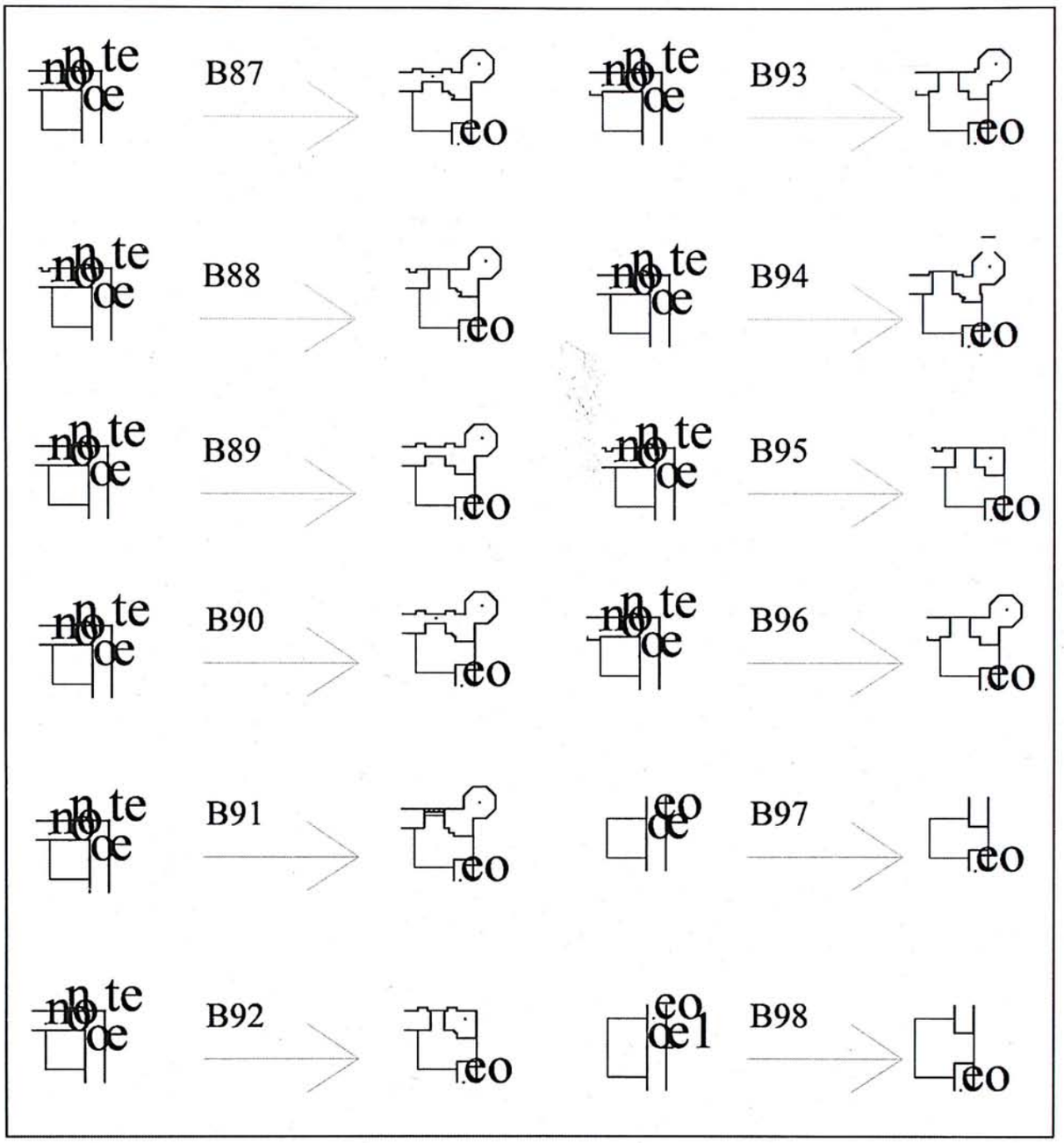


Figure 8.2d- The rule set B for stage 4.

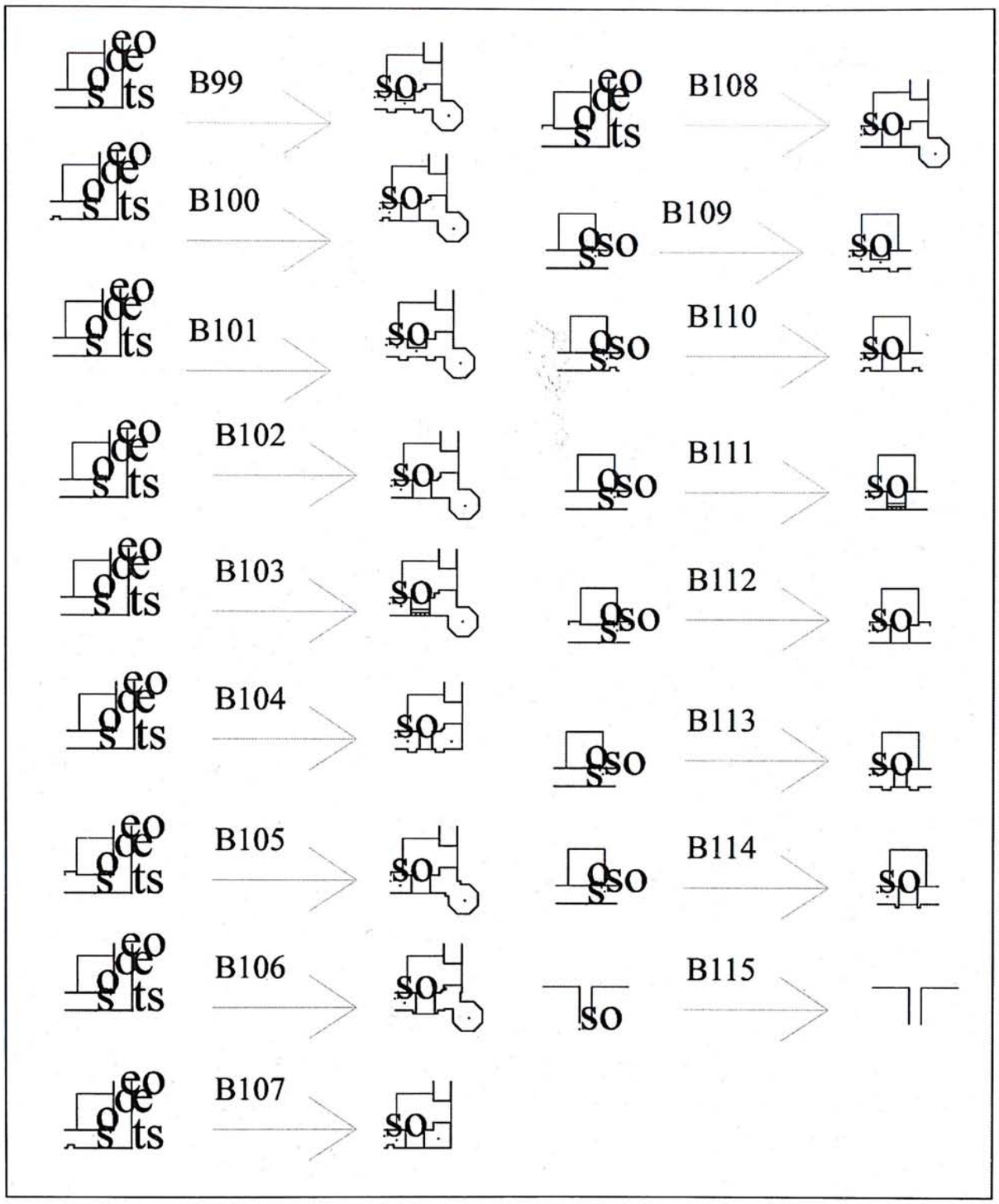


Figure 8.2e- The rule set B for stage 4.

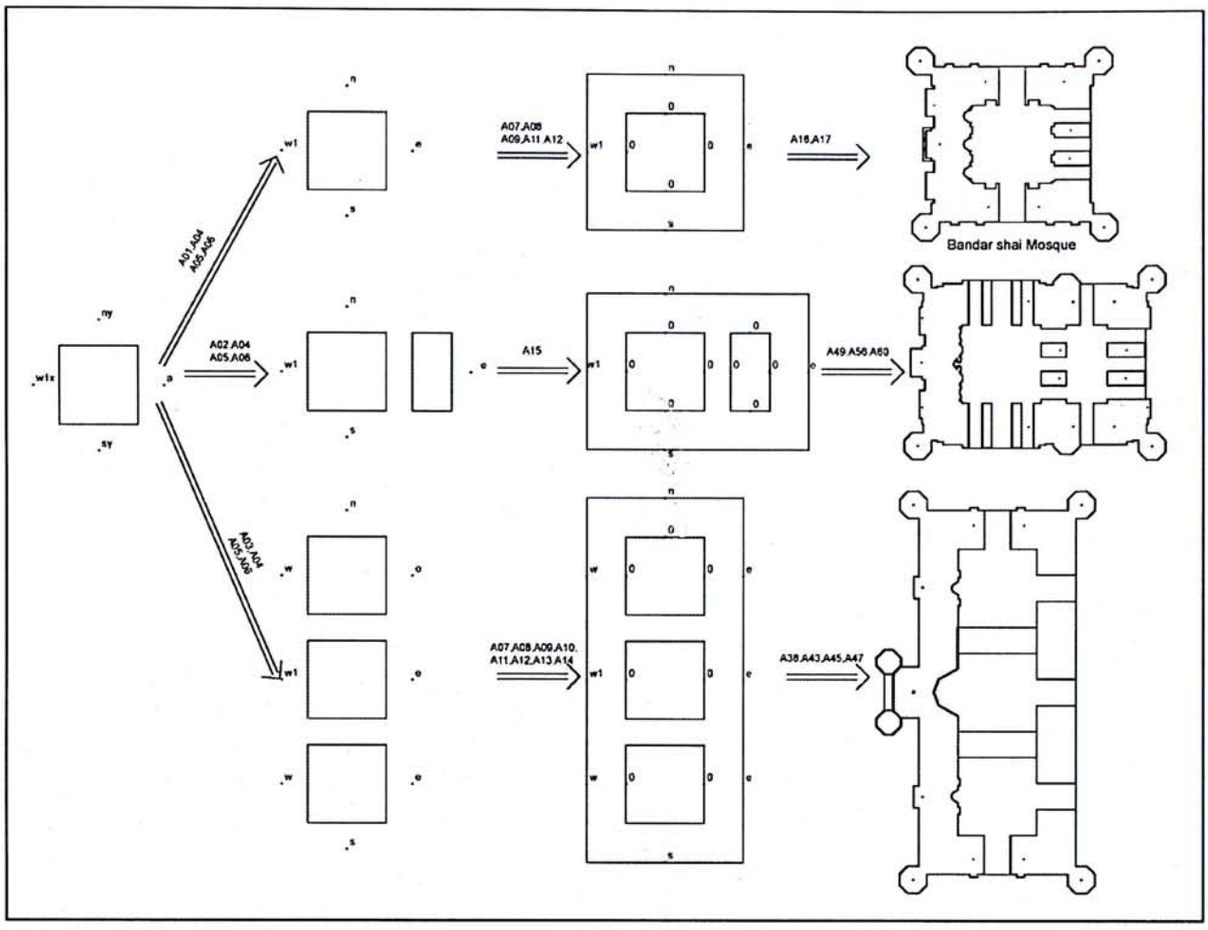


Figure 8.3- Derivation in Stage 4 by applying the rule set A.

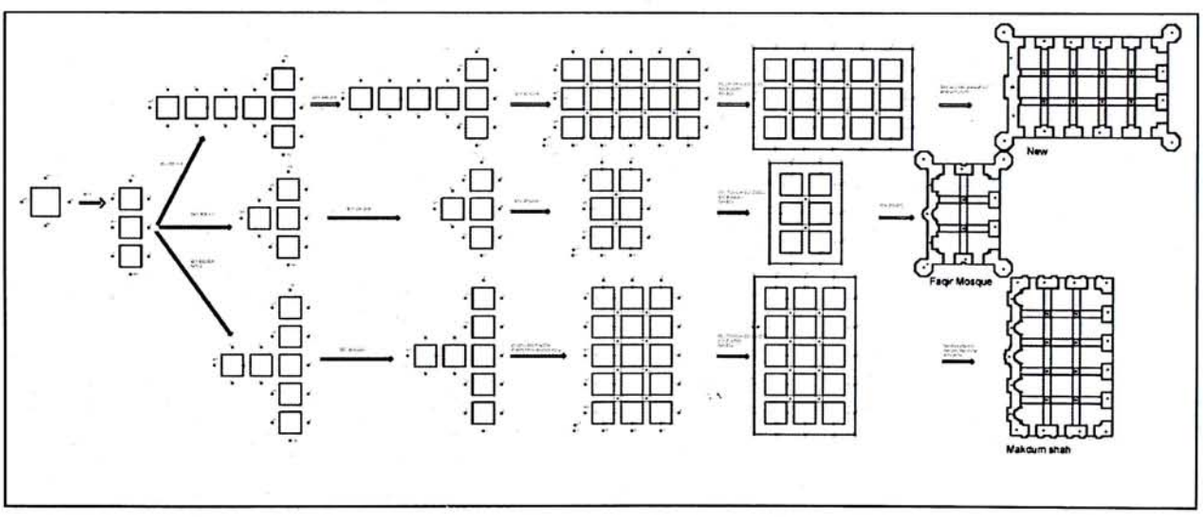


Figure 8.4a- Derivation in Stage 4 by applying the B rule set to the IsA shape.

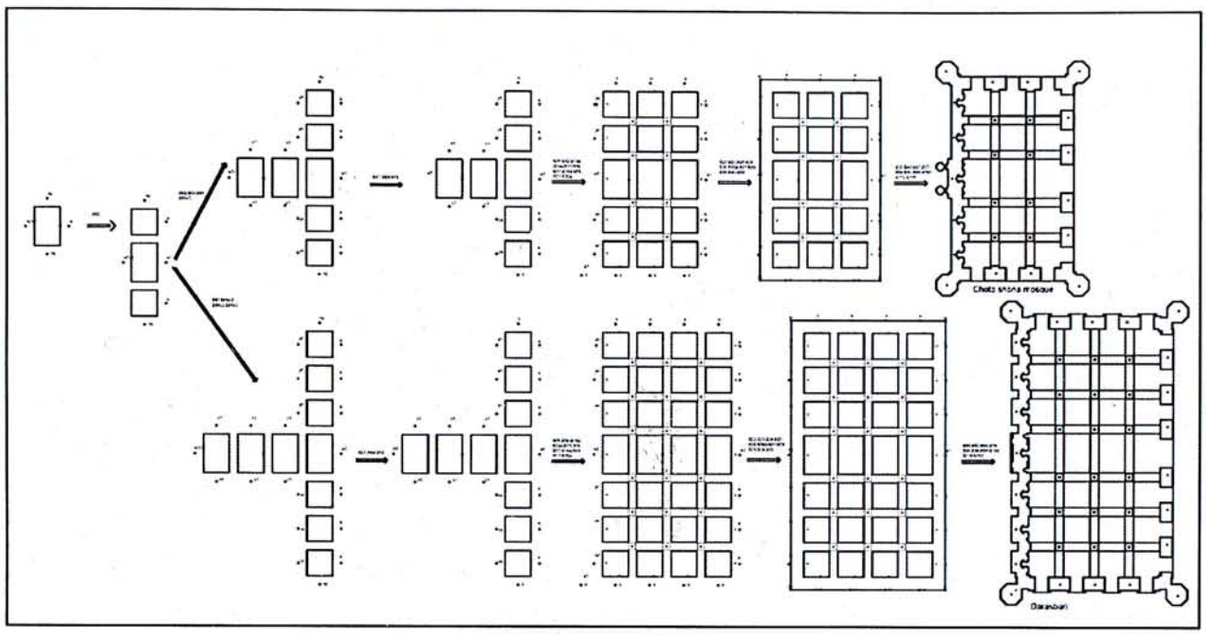


Figure 8.4b- Derivation in Stage 4 by applying the B rule set to the IsB shape.

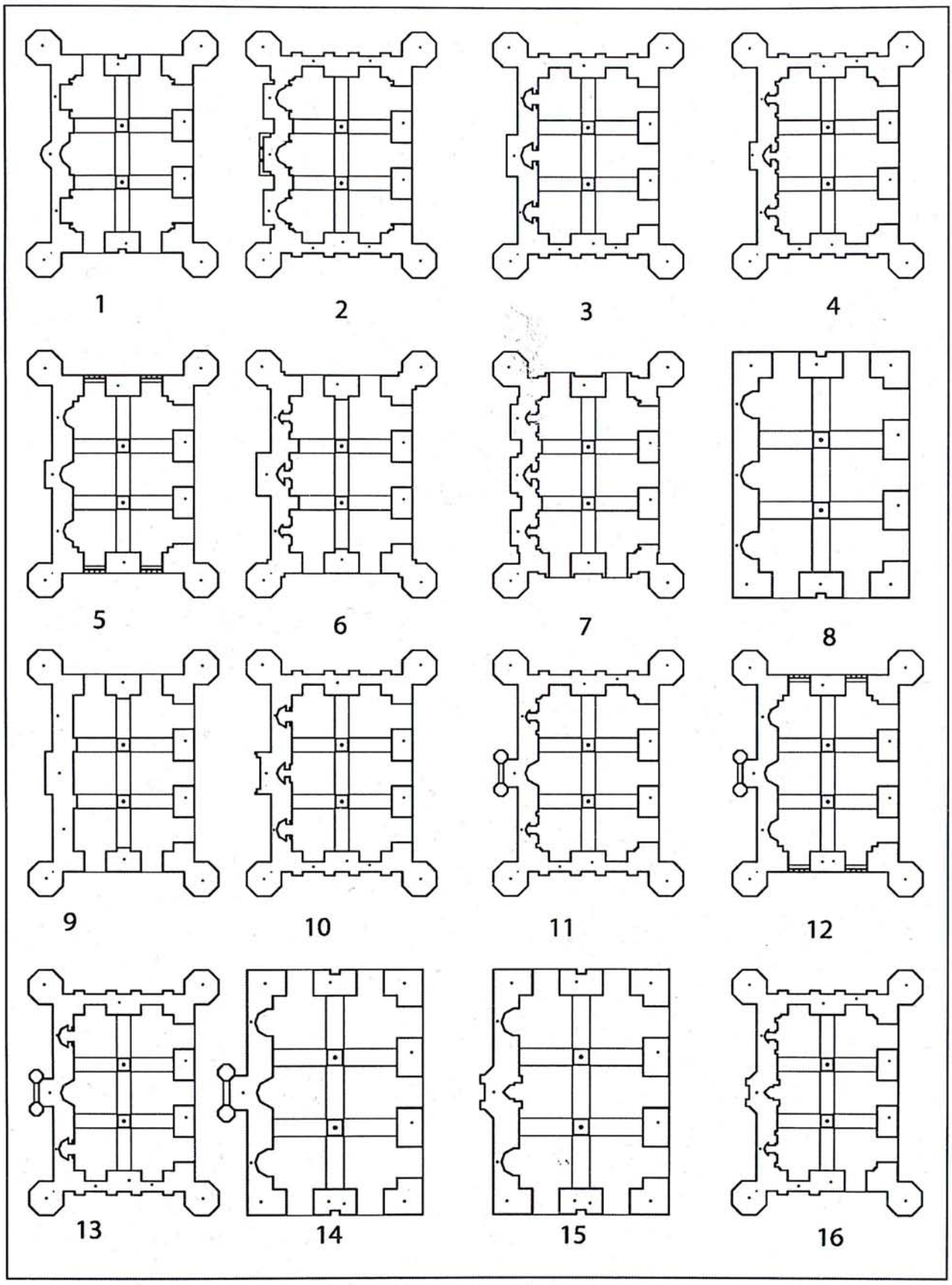


Figure 8.5- Derivation of six domes mosques.

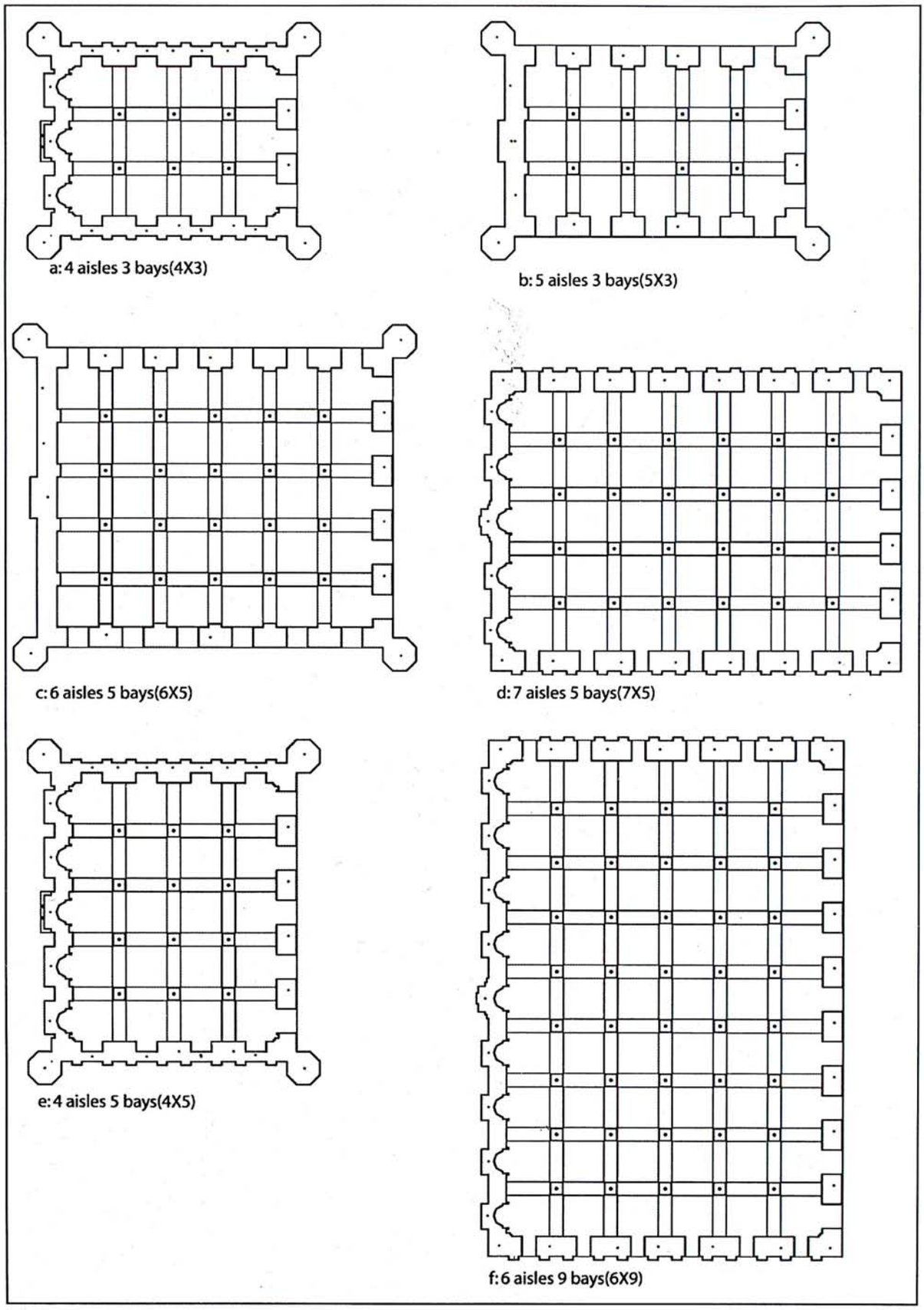
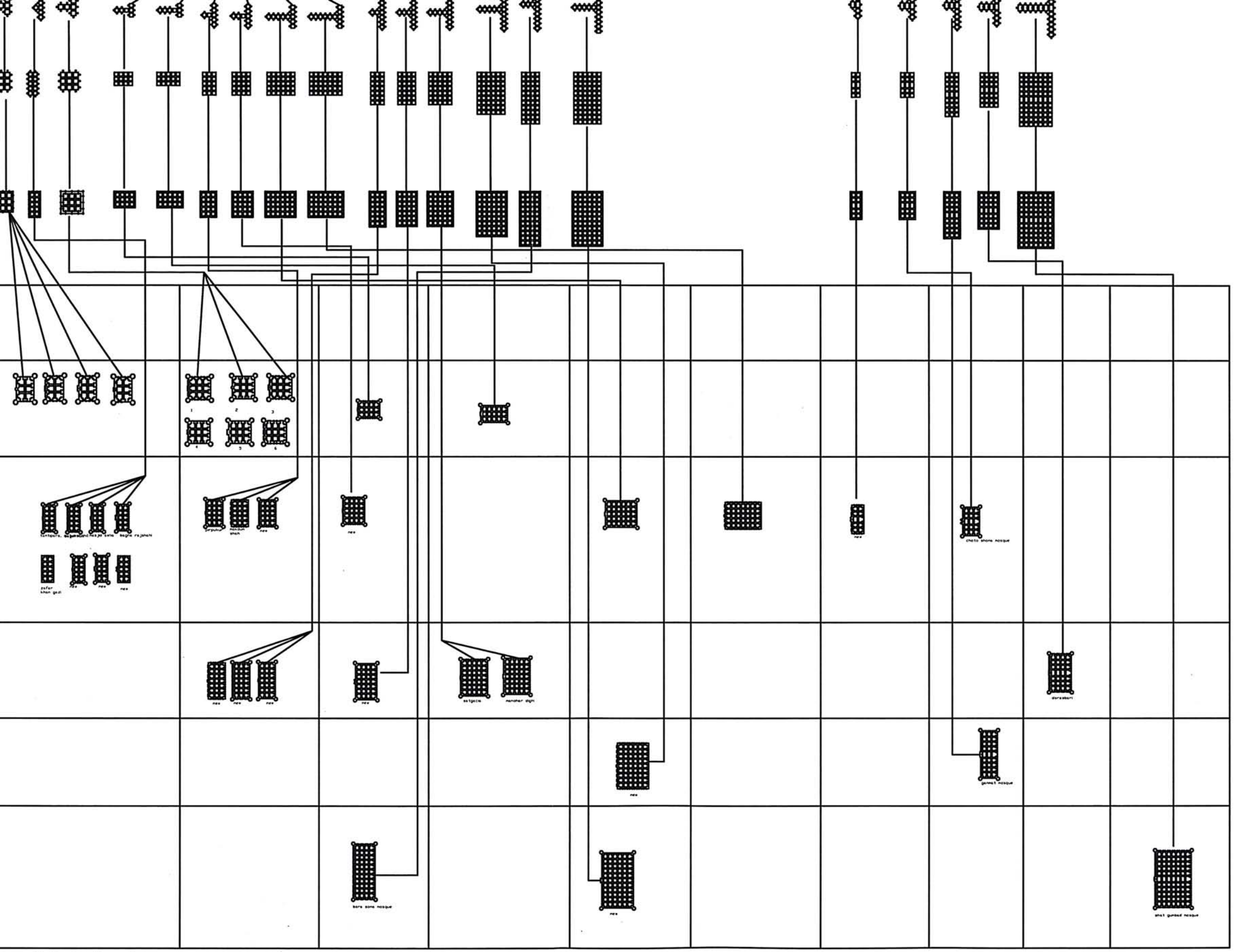


Figure 9.1- New designs in the style.



partial derivation