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Towards Safe Cities & Resilient Communities

13 & 14 SEPTEMBER 2018
IMPIANA HOTEL, IPOH, PERAK

ORGANIZED BY :

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THEORY OF COMBINATORIAL DESIGN FOR MODULAR ARCHITECTURE

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***Abstract* -** Combinatorial is another sub-topic and sub ordinate of Golden Mean theory. This natural law of design has been experimented by various scientists and researchers in the past decades such as an architect Christopher Alexander, Nikos A. Salingaros (architectural theorist) and well known computer scientist, Stephen Wolfram. This paper is part of on-going research of modular construction system (MCS) in Malaysia. Objectives of the research were to propose an appropriate scheme and concept for sustainable design for modular home based on research findings (scope of on-going research by the researcher). The researcher conducted questionnaires survey (pilot study) and case study (Structured Expert Interviews) to collect data of MCS in Malaysia. Combinatorial in modular architecture is the theory of conceptual design for future building design process of MCS. The researcher discuss in details and to clarify the proportion combinatorial for MCS in aspect of building forms and arrangements through proposed combinatorial formula. In Malaysia, design technique should relate to local culture, weather, and available materials sources as mentioned by the experts. Combinatorial design of modular architecture is an alternative design for compact affordable home. This combinatorial geometry (shipping container size) repeated, duplicate and can be oriented in a few ways to forming combinatorial models of building design. Proposed concept possibly can improve user decision making (generating digital way of design process) e.g. building players to plan their building lifecycle projects in term of economical design, green shape, reduced construction time and cost. Thus, it may be able to promote user friendly design, fast track construction, and quality based product, less wastage and varied of design selection can be chosen of the user.
***Keywords* -** Combinatorial Geometry, Modular Architecture, Spatial Planning, Sustainability

1 INTRODUCTION

The basic aspects of architectural design were the buildings must conveniently and functional to use, durable and delight (Morgan, 1960). Nikos A. Salingaros criticized architects nowadays were more on popularity rather than to fulfill the main purpose of basic, function and needs of architecture itself. As the function of architecture were to protect the environment and fulfill human need of habitat. The true architecture not just for visual eye and sculpture but it is for functional structure. The structure that built by several series of spaces with considering the needs of people and the relation of structure to the ecology. Sustainable design is essential for the development of architecture that can meet the needs of future. Alexander stated pattern was important part of architectural design. Pattern defined as ordered and logical structure (Salingaros, 2004). Pattern can be found in natural environment, human, art, space, time, and music. The definition of Mathematics itself is a science of patterns. Successful buildings obey the same system law as a complex organism and an efficient computer program. The user used the building to suite their own needs of common and daily life while the contractor tried to minimize cost and to standardize the building parts. This happened because of to make their activities easier and convenient to their own needs (Salingaros, 2004). Naturally, architects and engineers are not exactly expert in construction means and method (Siang, 2006). In Malaysia, the construction industry is highly aware of the need to improve the integration, planning and control of its design and production process (Nawi et al, 2009). Consequently, the reality of construction is that most of the problems encountered in the field such as reworks, delay, low in quality or productivity and even legal entanglement and claims often compounded by inherent design flaws that generated in the design phase (Nawi et al, 2009). As quoted by Horikoshi et al, to realize sustainable building design, improving energy efficiency by architectural passive design is essential at the conceptual design stage. With the raise of complex social structure and culture, humans began to modify their natural environment to better fit their needs (Werner & Long). Architecture is designed to satisfy the different representational, functional, aesthetic, and emotional needs of organisations and people who live or work in structures (Werner & Long). Affordable home price normally in between RM 250, 000 to RM400, 000 (N.R, 2011). The type of affordable home can come in different range of types and sizes such as for singles, couples, families and flat shares as well as for seniors.

2 MODULAR ARCHITECTURE IN MALAYSIA

In Malaysia, MCS or Offsite Manufacturing included in Industrialised Building System (IBS). The definition of offsite is the manufacture and pre-assembly of components, elements or modules, before installation into their final location (Goodier & Gibb). To relate MCS and Malays culture, Traditional Malay Architecture was successful and be at its best of its time for prefab and modular design in the country. With a direct dependence of a nature for its resources and embodying a deep knowledge of ecological balances, the house is efficiently designed to suit the local climatic requirements using various ventilation and solar-control devices and low-thermal-capacity building materials. The house also evolved a prefabricated building system which is flexible and varied to suit the needs of the users (Yuan). It was known for the first prefab in the world. It has also developed a very sophisticated addition system which allow the house to be extended in line with the growing needs of the users. How to gain this kind of achievement still leave question marks to the building players such as architects, building designers and researchers itself. As modern design of building more focus on reduced cost and to gain more profit then to think to give the comfort to the user. The current available and major materials for building construction were steel and concrete. As mentioned by Z, 2015 the problems of modular construction in Malaysia were about limited durable materials and higher cost. The improvement of constructability rarely been mention as the benefit of offsite but in theory offsite can improve constructability by providing designers with the fresh perspective and outlook on the concept of repetition, preassembly and standardization (Nawi et al, 2009). Form and energy efficiency is related between each other. Cities are main leak of the country. Nowdays, people look at the idea to find alternative urban model in the city itself (Chiri et al. 2012). The configuration of urban spatial structure, together with the different land use patterns, is dependents on the availability of renewable and energy resources in the area. Nevertheless the complexity found in the changeover to new sustainable models cannot be attributed only the moment of transition in which we live, rather than the confusion hidden behind the concept of "sustainability".

3 COMBINATORIAL FOR MODULAR ARCHITECTURE

Modularity in general is part or series module of something whether it became appliances, furniture, machinery, automotive, aerospace, or buildings. Constructed a modules or unit packaging schemes. Standard parts of modular approaches offer gains in time, cost and quality (Bertram, 2005). For building design, modular refer to parts of a building define by 3D compartments such as LEGO. As combinatorial is arrangements and combination of geometric objects and with discrete properties of these objects. Mentioned by Christopher Alexander houses were generated by patterns. Spatial configuration is concerned with finding feasible locations and dimensions for a set of interrelated objects that meet all design requirements and maximize design quality in term of design preferences (J.J Michalek et al, 2002). Spatial configuration is relevant to all physical design problems, so it is an important area inquiry (J.J Michalek et at, 2002). Reported attempts to automate the process of layout design started over 35 years ago (Levin, 1964).

Geometry decomposition was one of the ideas on ways to relate modular construction and combinatorial things. Combinatorial geometry is the study of combinations and arrangements of geometric objects and with discrete properties of these objects. Historically, modularity has played an important role in the study of combinatorial geometries (Brylawski, 1975). The questions might concern, for example, the complexity of arrangements of objects of the above type or the occurrence of certain substructures in such arrangements. Besides that, the term combinatorial geometry related to the field of combinatorics. The divaricate of mathematic dealing with combinations of objects belonging to a finite set in following certain limitations, like those graph theory called as combinatoric. Theory development of combinatorial design has brought incredible success; in the application is not expected, in connection with basic math, and the desire to produce order out of chaos, obviously (Colbourn, 2003). Moreover, he questioned about the future of application of combinatorial geometry. He explained that new mathematical truths will be found and that unanticipated application will arise. The challenge is to seek both and to know that each profit from the other (Colbourn, 2003). Christopher Alexander in his book, Pattern Language, defines patterns in a solution of space. In an aspect of design, combinatoric as mathematical approach can be found in the research by Alexander Christopher. The building blocks can be combined in an infinite number of ways (Alexander, 1977). The question is for a given fixed area which shape will create the greatest feeling of spaciousness (Alexander et al, 1977). There is mathematical answer for this question. In this research proposed square as building blocks. The general objective of combinatorial concept for Modular Architecture are; To reduced design and construction cost, To reduced design and construction time, Greater flexibility in term of shape to maximize building function in aspect of space and usability, Shorter and cheaper maintenance periods, To reduced maintenance cost, and To optimize building function and design.

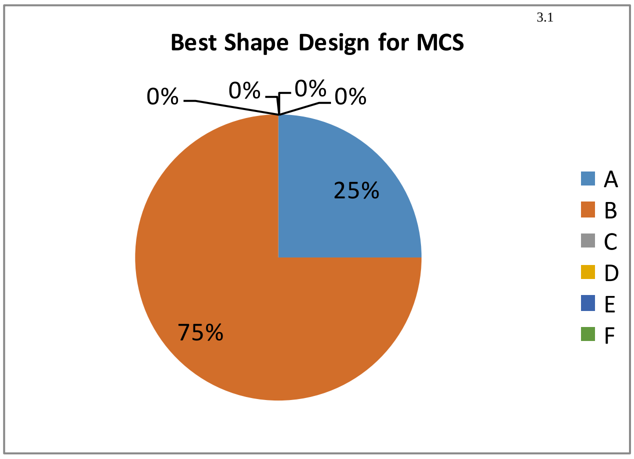
3.1 The Methods of Combinatorial Concept for Modular Architecture such as following diagram:

The objective was to develop of necessary strategies, standards, designs, specifications and procedures for cost reduction through equipment modularization, equipment standardization and process simplification. The products of combinatorial providing a repetition of identical units, both in the dimensioning building spaces as well as in the layout of the building. This theory may give option and maximize option focusing on affordability home project in Malaysia for the users. Its response on the issue of individual housing needs. Neither the demand of affordable home in Malaysia is increasing nor the demand to own the house itself. With this theory, it might provide more idea in producing affordable home in the near future. Figure 3.1 shows best shape for MCS of public housing design has been choosing by the experts through structured interviews questionnaires in Malaysia. The experts chose Pattern B as the most practical shape of affordable home design. It was 75% from the total rating by the experts. Concurrently, 25% chose pattern A as the best shape design for MCS in Malaysia. This is the second best shape for modular design by using combinatorial concept. Pattern A and B were considered to be the best as it was economical and practical. Other patterns were not favorable due to issues such as less economical, used a lot of footprint and poor ventilation in terms of arrangement and orientation.

As suggested by experts, Pattern A and B were the best shape for house pattern arrangement. Therefore, the researcher proposed five (5) combinatorial ways of most practical pattern for affordable homes as agreed by architectural and design experts on the most practical pattern arrangement. The pattern proposed is based on a single unit of high-rise home. The method proposed by the researcher entitled as Combinatorial Concept of design. The combinatorial tiling is defined as a process or technique to figure out the floor plan and pattern composition by repeating the modules in the given square area. The figures (3.3, 3.4, 3.5, 3.6, 3.7, 3.8, and 3.9) in the next discussion were house pattern suggested by the researcher for affordable homes (Type A, B, C, D and E) in Malaysia. Methods and calculation of combinatorial design stated and described in next discussion as below:

a) Home Type A (600-800 sqft)

Home Type A (Figure 3.3) consists of approximately 600 to 800 square feet (sqft) of floor plan area. The selection of five (5) methods of combinatorial designs has been carried out from the geometric probability formulation. Proposed methods as logic modules combination and serve only as a guideline where in practice outcome of pattern proposal will depend on land topology. The pattern formulated is simplified in a diagram as shown in Figure 3.4.



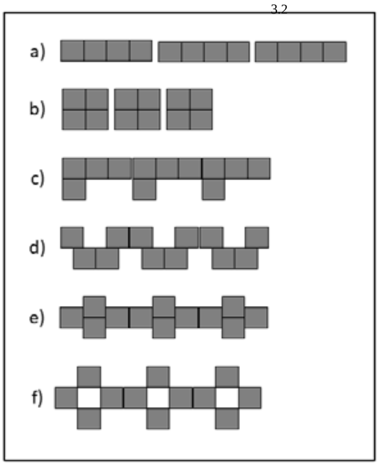


Figure 3.1 Best Shape for MCS of Public Housing Design (Source: Salmiah, 2016)

Figure 3.2 Modular Home Pattern

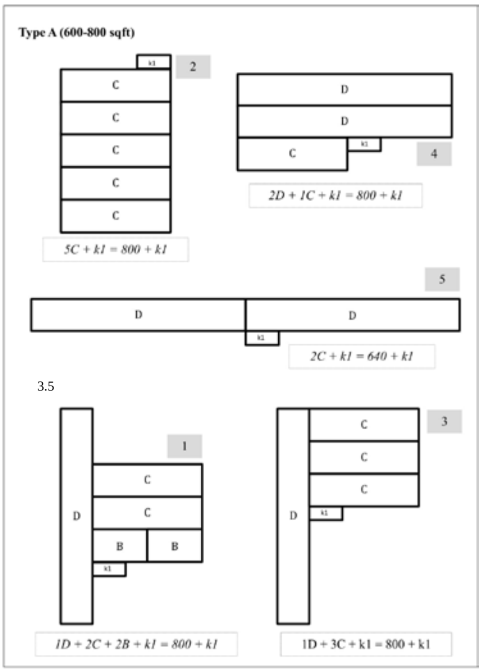


Figure 3.3 Type A Affordable Home Pattern

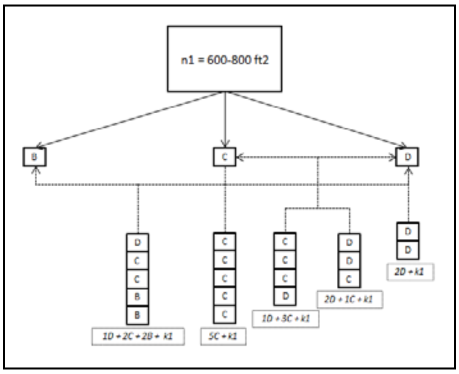


Figure 3.4 Morphology of Home Pattern Type A

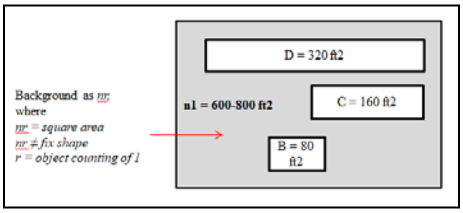


Figure 3.5 Geometrical Probability Approach for Home Pattern Type A

There are five methods of combination using geometric probability idea. In the Method 1 combination, the module combination is the combination of two B modules, two C modules and one D module. Method 2 incorporated the combination of five C modules. The combinatorial pattern of Method 3 consists of one D module and three C modules. Meanwhile, method 4 consists of two D modules ad one C module. The fifth method embraces of two D modules. The pattern was formulated using combinatorial probability and geometrical probability equation as further explained in the points below. Figure 3.5 shows geometrical probability, ***P*** approach of Home Type A. The shaded area indicates the expected total area of Home Type A. Below is formulation example of combinatorial design for Home Type A:

n1=600*ft2* to 800*ft2*
x2=80*ft2*, *x3*=160*ft2*, *x4*=320*ft2*

Given equation for Combinatorial Probability as ***C***,

C=nr=(xr)!

Where,
C = Combinatorial probability
n = total area/object
r = Object counting of 1
x = Object counting of 1 x square area
0! = 1, Factorial

Combinatorial Design

Method 1

Modules (*x2*, *x3*, *x4*)
To Simplify *n1*=[1(*x2*), 1(*x3*), 1(*x4*)]

n1 =800*ft2*
=(*x2*+*x3*+*x4*)!
=[2(80ft2)+2(160ft2)+1(320ft2)]!
=(160+320ft2+320ft2)!
xr =800*ft2*

xr =800*ft2*
=[2(x2)+2(x3)+1(x4)]!
=(2+2+1)!=
=5!
=5(1)
=5#
C *=5*

There are five possible methods of 3 different (B=x2, C=x3, and D=x4) modules combination of Home Type A. The combinatorial probability, ***C*** for Home Type A modules define by five (5) methods of combination of modules B, C and D. In short, outcome for Method 1 consists of two (2) modules of B, two (2) modules of C, and one (1) module of D. To specify geometric probability, ***P*** of Method 1 as:

Geometric probability, ***P***
P (X) = ***<u>area of desired outcomes</u>***
area of total outcomes
P (X) = ***<u>xr</u>***
(nr)

Where,
P = geometric probability
X = % of geometric probability
n = total area/object
r = Object counting of 1
x = Object counting of 1 x square area

Note:
To consider ***C=nr*** as earlier formulation for combinatorial probability
P(%) =[2(x2+2(x3)+1(x4)]/*n1*
C =800ft2/800ft2
=1
=[1(100)]/1
P =100%

Ratio of the geometrical probability, ***P*** for Method 1 is 100% successful formulated if the given two (2) modules B, three (3) modules C and one (1) module D to make a home with 800 sqft floor area. The stated combinatorial design of Method 2 can be simplified in equation such as shown below:

2*B* + 3*C* + 1*D* + *k1* = 800ft2 + *k1*

Where,
B = Module with 80 *sqft* floor area
C = Module with 160 *sqft* floor area
D = Module with 320 *sqft* floor area
k1 = Balcony with 30 *sqft* floor area
k2 = Balcony with 60 *sqft* floor area

b) Home Type B (801-1000 sqft)

Home Type B (Figure 3.6) covers approximately 801 to 1000 square feet (sqft) of floor plan area. The selection of five (5) methods of combinatorial designs has been derived from the geometric probability formulation. The proposed method as rational modules combination and it is for recommendation only whereby in practice the proposed pattern will be determined by land topology. The pattern formulated is streamlined in diagram as shown in Figure 3.7. Figure 3.8 shows the geometrical probability approach of Home Type B and it shows the expected total area of Home Type B.

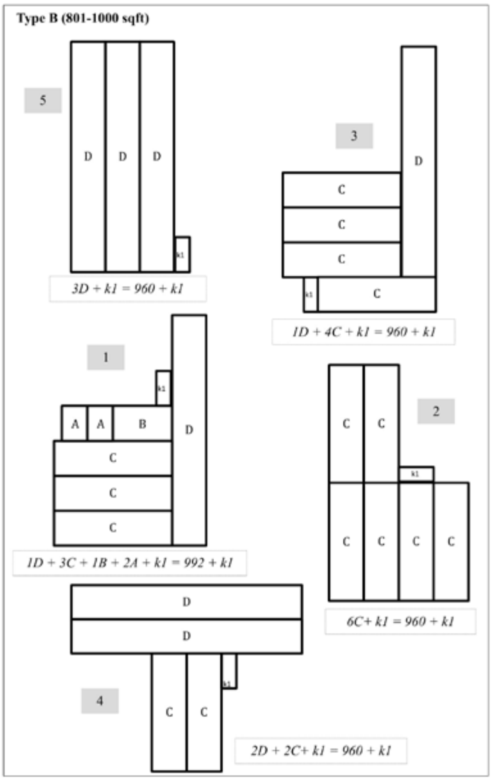


Figure 3.6 Type B Affordable Home Pattern

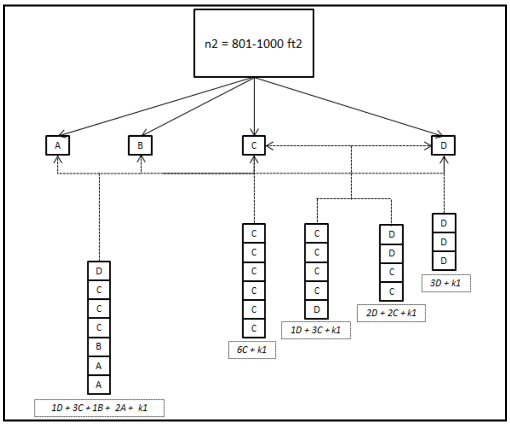


Figure 3.7 Morphology of Home Pattern Type B

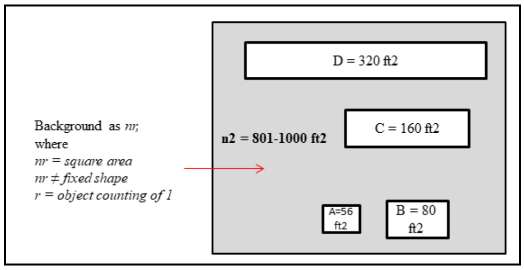


Figure 3.8 Geometrical Probability Approach for Home Pattern Type B

c) Home Type C (1001-1200 sqft)

Home Type C (Figure 3.9) comprises of around 1001 to 1200 square feet (sqft) of floor plan area. The selection of five (5) methods of combinatorial design has been carried out from the geometric probability formula. Suggested methods as practicality modules combination and only for parameter where in practice the proposed pattern will be subject to land topology. The pattern formulated in simplify home morphology diagram as Figure 3.10.

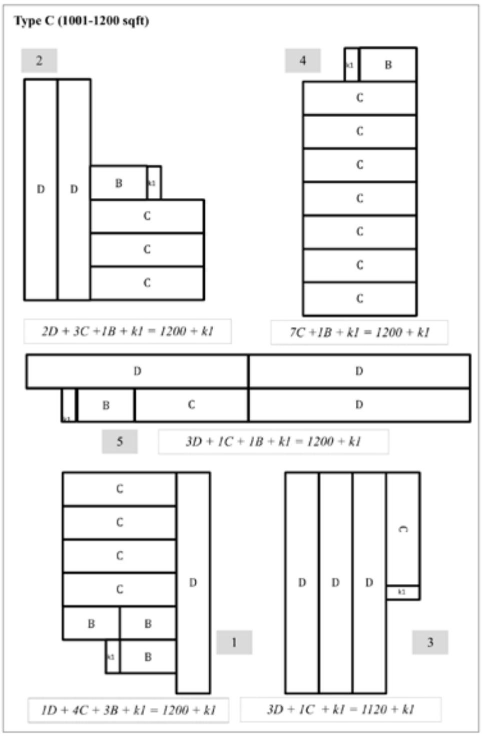


Figure 3.9 Type C Affordable Home Pattern

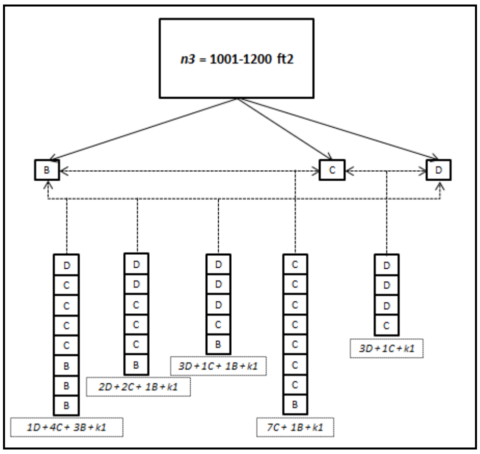


Figure 3.10 Morphology of Home Pattern Type C

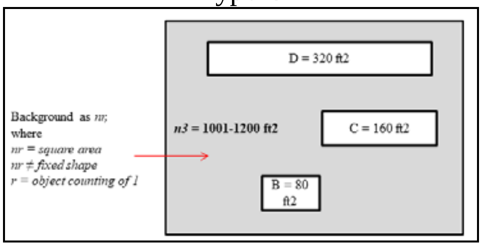


Figure 3.11 Geometrical Probability Approcah for Home Pattern Type C

Figure 3.11 shows geometrical probability approach of Home Type C. The shaded area indicated expected total area of Home Type B.

d) Home Type D (1201-1400 sqft)

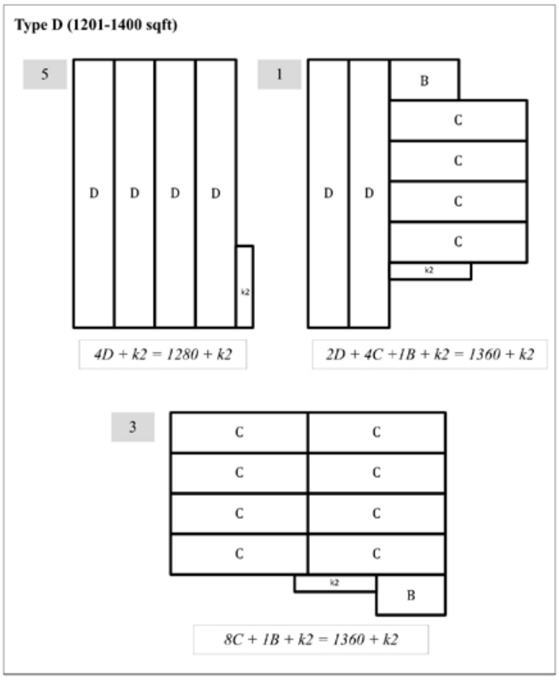


Figure 3.12 Type D Affordable Home Pattern

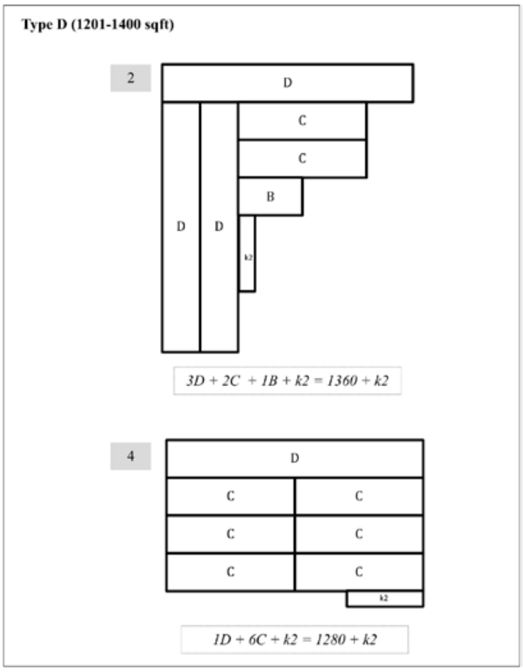


Figure 3.12 Type D Affordable Home Pattern

Home Type D (Figure 3.12 and 3.13) covers of approximately 1201 to 1400 square feet (sqft) of floor plan area. Range five (5) methods of combinatorial designs have been carried out from the geometric probability formulation. Anticipated methods as logic modules combination and only for guideline where in practice the outcome proposal pattern will depend of land topology. The pattern formulated in simplify diagram as Figure 3.14. Figure 3.15 shows geometrical probability approach of Home Type D. The shaded area indicated expected total area of Home Type D

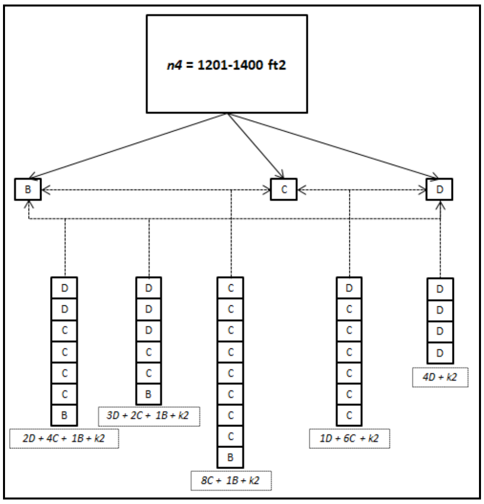


Figure 3.13 Morphology Home Pattern Type D

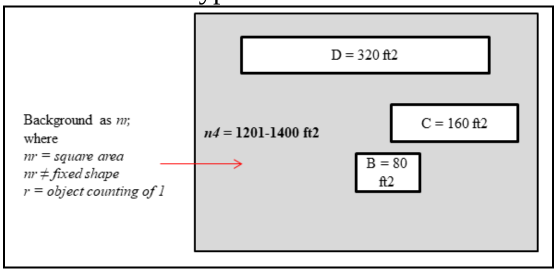


Figure 3.14 Geometrical Probability Approachfor Home Pattern Type D

e) Home Type E (1401-1600 sqft)

Home Type E (Figure 3.16 and 3.17) covers of approximately 1401 to 1600 square feet (sqft) of floor plan area. Selection five (5) methods of combinatorial designs have been carried out from the geometric probability formulation. Proposed methods as logic modules combination and only for guideline where in practice the outcome proposal pattern will depend of land topology. The pattern formulated in simplify diagram as Figure 3.18.

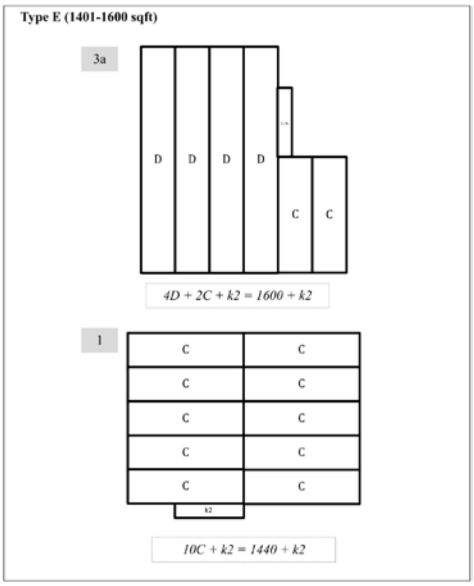


Figure 3.15 Type E Affordable Home Pattern

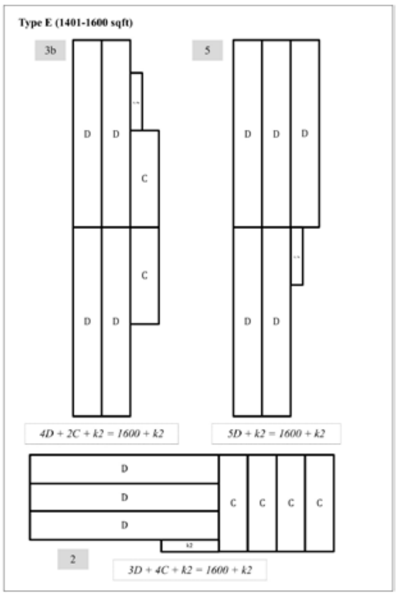


Figure 3.16: Type E Affordable Home Pattern

Figure 3.19 shows geometrical probability approach of Home Type E. Shaded area indicated expected total area of Home Type E.

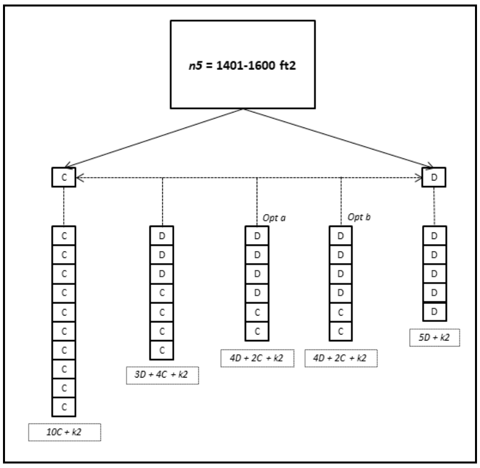


Figure 3.17 Morphology of Home Pattern Type E

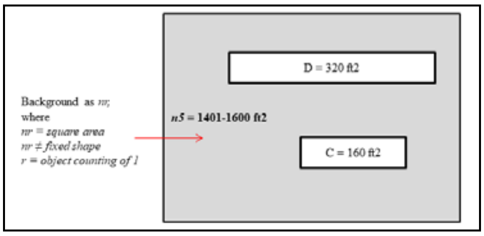


Figure 3.18 Geometrical Probability Approach for Home Pattern Type E

Table 3.1 shows formulated floor area with combinatorial design proposal for affordable home scheme.

Table 3.1 Formulated Floor Area using Combinatorial Probability Approach; Types of Floor Pattern of Affordable Home and Conceptual Formula

Methods	**Types/Floor Area (sq ft.)**				
	A = 600-800	**B**=801-1000	**C**=1001-1200	**D**=1201-1400	**E**=1401-1600
1/ft2	*2B + 3C + 1D = 800 + k1*	*2A + 1B + 3C + 1D + k1 = 992 + k1*	*3B + 4C + 1D + k1 = 1200 + k1*	*1B + 4C + k2 = 1360 + k2*	*10C + k2 = 1600 + k2*
2/ft2	*5C + k1 = 800 + k1*	*6C + k1 = 960 + k1*	*1B + 3C + 2D + k1 = 1200 + k1*	*1B + 2C + 3D + k2 = 1360 + k2*	*4C + 3D + k2 = 1600 + k2*
3/ft2	*3C + 1D + k1 = 800 + k1*	*3C + 1D + k1 = 800 + k1*	*1B + 1C + 4D + k1 = 1200 + k1*	*1B + 8C + k2 = 1360 + k2*	*2C + 4D + k2 = 1600 + k2*
4/ft2	*1C + 2D + k1 = 800 + k1*	*2C + 2D + k1 = 960 + k1*	*1B + 7C + k1 = 1200 + k1*	*6C + 1D + k2 = 1280 + k2*	*2C + 4D + k2 = 1600 + k2*
5/ft2	*2D + k1 = 640 + k1*	*3D + k1 = 960 + k1*	*1C + 3D + 1k = 1120 + k1*	*4D + k2 = 1280 + k2*	*5D + k2 = 1600 + k2*
6/ft3 (Volumetric)	*(5C)8 + k1 = 6400 + k1*	*(3D)8 + k1 = 7680 + k1*	*(1C + 3D)8 + k1 = 8960 + k1*	*(4D)8 + k2 = 10240 + k2*	*(5D)8 + k2 = 12800 + k2*

(Source: Salmiah, 2018)

3.2 Findings: Probability in Modular Architecture

Combinatorial concept proposed by researcher for MCS is correlation with data science process. In combinatorics, probability of things leads to data science. The researcher simplifies the data collected and presented as a scope of data science in term of architectural design especially. In brief, the formulated solution of raw data collected simplified in Combinatorial concept of Modular Architecture Framework as shown as Figure 3.20 below.

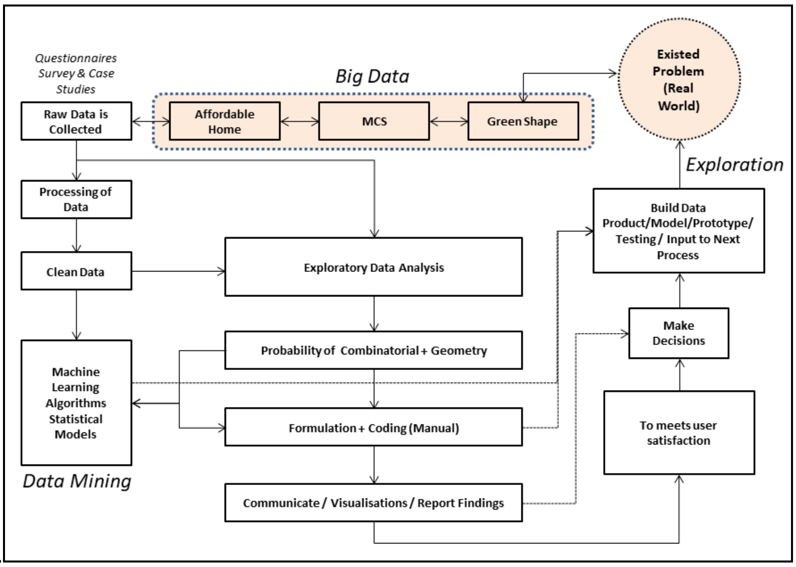


Figure 3.19 Combinatorial Concept of Modular Architecture Framework

Therefore, from the findings the researcher suggested combinatorial concept is design alternative technique to improved current MCS issues in Malaysia. To give an example of combinatory aspect; the formulation of Affordable Home Type A consist of 600 to 800 sqft floor area introduced as equation *2D + k1 = 640 + k1* meaning that the combinatory code for Home Type A is *A(2D).* To explain: *2D + k1 = 640 + k1*
Where,
D = Module with 32*0 sqft* floor area
k1 = Balcony with 30 *sqft* floor area (giving 0 finite of home square area)
Combinatory code produced for Home Typ A is *A(2D, k1).*
To summarise the home combinatory code for example:

a) Home Type A
A(2B, 3C, 1D, k1), A(5C, k1), A(3C, 1D, k1), A(1C, 2D, k1), A(2D, k1), A{[(5C)]8, k1}

b) Home Type B
B(2A, 1B, 3C, 1D, k1), B(6C, k1), B(3C, 1D, k1), B(2C, 2D, k1), B(3D, k1), B{[(3D)]8, k1}

c) Home Type C
C(3D,4C, 2D, 1D, k1), C(1B, 1C, 4D, k1), C(1B, 7C, k1), C(1C, 3D, k1), C{[(1C, 3D)]8, k1}

d) Home Type D
D(1B, 4C, k2), D(1B, 2C, 3D, k2), D(1B, 8C, k2), D(6C, 1D, k2), D(4D, k2), D{[(4D)]8, k2}

e) Home Type E
E(10C, k2), E(4C, 3D, k2), E(2C, 4D, k2), E(2C, 4D, k2), E(5D, k2), E{[(5D)]8, k2}

This code may be presented for user satisfaction assessment e.g. building player or home buyers to give selection of products before proceed for prototype (testing) or construction of the product (home unit). This might be able to reduce product waste with using this statistical satisfactory from user. To clarify, there are needs further exploration of the concept proposed in order to understand and realized what combinatorial concept may help and improve building life cycle. Computer software or apps is linked with code is suitable to develop the concept further.

4 RESEARCH METHODOLOGY

A collection of data analyzed in this paper is obtained through literature review from other authors in the aspect of IBS and MCS development towards meeting green construction and innovation in Malaysia and combinatorial geometry topic. The data has been collected through questionnaires survey (pilot study) and case studies (structure interviews with the experts) in Malaysia. Feedback for the questionnaires was very slow by using online questionnaires survey with total 500 online respondents and 20 questionnaires by postal. 6% of respondents were given feedbacks for the questioners of the total respondents. Based on the feedback of this pilot study, the researcher decided not to continue using this method as a major research method due to the inaccuracy of data. The result of the questionnaires survey might be bias and differs due to the high percentage of non-response. In addition, case studies method were conducted to get reliable data. The researcher contacted Mr. Nazrol from CIDB centre to obtain information on MCS companies which are registered under CIDB in Malaysia. Only four MCS companies were registered in 2015. The researcher also collected relevant documents of MCS from personnel experts throughout the case studies. Besides that, the researcher also collected data relevant to the study such as photos, size and dimensions, specifications, cost, materials using of the construction, location and any other relevant information. The analysis attempts to review the definitions, characteristics, issues, trends and sustainable design of modular construction and scientific way of architectural design (in aspect modular architecture).

5 RECOMMENDATIONS AND CONCLUSIONS

Suggested of the combinatorial concept for MCS might be able to cover issue product modularity in sustainable shape design especially. This concept will improve user decision making e.g. building players in order to look for appropriate methods before to proceed with any decision of prototype, testing and hands-on construction at site. Thus, with the concept proposed by the researcher it may be able to promote user friendly design, fast track construction, and quality based product, less wastage and varied of design selection can be chosen of the user. The combinatorial concept was developed based of economization of product and risk management approach (based on Literature Review) with direct engagement from practitioner in construction industry to choose best shape of design to look for in MCS. Despite this combinatorial concept not been testing yet unto real world consideration, should future research to look into account this method for further research and assessment. Area to be considered in order to sustain of the concept development in future such as computational software based. Due to the formulation of affordable home based on combinatorial probability and combinatory code. As combinatory code has been used in field of Artificial Intelligence (AI) and Internet of Things (IOT) The objective was to develop to necessary strategies, standards, designs, specifications, and procedures for cost reduction through equipment modularization, equipment standardization and process simplification. The products of combinatorial providing a repetition of identical units, both in the dimensioning building spaces, as well as in the layout of the building. With this theory, it might be provided more idea in producing affordable home in the near future. Through the reuse of formwork, sustainable and inexpensive designs can be attained. The system allows for the customization of designs, while maintaining the benefits of a regular prefabrication product, so their cost and performance can be improved over time (Jonas et al. 2014). Challenge of MCS in Malaysia is vastly complex but to apply this alternative construction system in near future is inevitable action. So, the right track and steps of conceptual and construction technique certainly can help narrow down suitable solution of current problem faced by building players to apply MCS in construction industry. In short, the combinatorial design was an experimental design to find out the sustainable shape and economic way of design.

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