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Modular coordination-based generative algorithm to optimize construction waste

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Abstract

In line with the growing global trend toward more sustainable built environment, this research aims at introducing a novel approach in construction waste optimization in light of the integration of parametric design theory with offsite construction. To do this, a generative algorithm was developed in the integrated platform of Rhino and Grasshopper software based on the modular coordination rules and ASTM international standards as the design constraints in modules array. Two sets of horizontal and vertical modules were obtained from a prototype model and the evolutionary solver function was employed for optimizing the waste areas. As a result, different modular design variants which generates minimum amount of waste and are fully compliant with the international standards were developed. This study contributes to the field by presenting one of the first studies in its kind focusing on the integration of parametric design into offsite construction practices with respect to the construction waste optimization.

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Keywords: Offsite construction; parametric design; generative algorithm; modular coordination; waste optimization.

1. Introduction

Offsite construction is an effort initiated to increase the productivity, time efficient delivery and mass production of construction projects via manufactured houses, panelized components and prefabricated structural frames. It can be defined as a construction system in which components are manufactured in a factory, transported and assembled into

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structure with minimal additional site work [1]. Modular Coordination (MC) is a key asset in the employment of this technology. It is a pre-engineered structure involving the creation of discrete-volumetric pre-fabricated components in light of their dimension and space. In essence, MC is a methodology which drives offsite construction towards the adoption of an integrated design according to a basic unit or module and encourages parties in the construction industry to produce and utilize pre-fabricated and mass production of the building in a standardized format [2]. It is widely believed that offsite construction and MC, particularly, provide great benefits such as lower environmental impact, higher productivity and more project handling [3] but its implementation is far below than the current potentials. For instance, its utilization rate is less than 3% of residential buildings industry in US [4]. It is attested to this fact that considering MC imposes some pragmatic constraints on the design scope and exploration options. The challenge here is the transformation of the conventional design and construction to an approach based on MC in which the creative design options to be explored and generated. To tackle with this challenge, parametric design system, as a result of parametric architecture, can be effectively applied to deliver the generative modeling of pre-designed sets of rules and explore various design schemes [5].

Parametric design allows for generating innovative compositions, in a formal and conceptual manner by virtue of implementing a group of criteria that could be in concordance to MC rules and mark a new area of innovative mode of design thinking within offsite construction arena. Nevertheless, a holistic review on the literature shows that there is a salient gap on the coupling of MC with the parametric design theory to enhance the offsite construction process. This gap is especially widened where the sustainability performances and environmental impacts of offsite construction come to the light. Extensive research proves that among the myriad of industries, construction waste constitutes 40% of landfill material [3]; yet, full settlement of this damage seems a long way off in the current situation. The literature is to some extent replete with the studies focusing on the waste minimization aspects of modular construction by either conducting survey [6] or case studies of real offsite construction [7]. Furthermore, the application of innovative design methods in modular construction mostly fall to its integration with BIM process [8] and BIM authoring tools [9] but no research hitherto investigates this topic out of the integrated approach of MC and parametric design perspective. To fill the identified gap, this research aims at developing a novel approach toward the construction waste minimization in which MC principles of offsite construction are simulated through parametric design, different design options are explored using a generative design algorithm and finally, adhering to the minimum amount of produced wastes, schematic deliverables are presented to be as guidelines for architects and practitioners in preventing waste during the design.

1.1. Modular coordination (MC)

MC is a system to standardize the measurement and placement of building components according to the dimensional coordination rules within a referenced system [9]. It facilitates the dimensional compatibility among the size of a building, its associated spans or spaces, the size of components and equipment used. A three dimensional integer lattice provides the reference arrangement and a module identifies the typical unit for the components. These dimensional coordination principles are used in the prefabricated and offsite construction to identify the optimum dimension of components, reduce on-site waste and simplify their interchanges [10]. Five major rules of MC deriving from the literature are as the below [9]:

- Using modules as the basic, multi and/or sub modules
- Defining a reference system to coordinate spaces and zones
- Locating building elements within the reference system
- Measuring building components to specify work sizes
- Identifying building layout and coordinating dimensions for buildings

Basic module forms the fundamental entity of size and dimension in MC. Sizes of building components and building layout should be coordinated in multiples of the basic module. It equals to 100 mm (M) and could be defined in n*M resulted in multi-modules. The basic module is addressed through a reference system which is composed from a system of points, lines and planes to establish a basis of layout for building components [10].

1.2. Parametric design

Parametric design is a computational method, capable of delivering both generative and analytical model and streamlines a dramatic shift from modelling a designed object to the design's logic [11]. This method utilizes the computational attributes in setting the design principles to provide a platform of design exploration and variations. In fact, different degrees of artificial intelligence are applied upon the computational specifications such as rules, constraints, parametric dependencies and heuristic and meta-heuristic structures to encode them and act as a generator in order to yield a parametric-generative model. The procedure of parametric-generative design constitutes four major elements of [12]:

- Start conditions and parameters (input)
- A generative mechanism (rules, algorithms etc.)
- The act of generation of the variants (output)
- The selection of the best variant.

Each generative process starts with the inputs to establish the initial parameters which are then transformed through a generative mechanism toward the initial population of design. This mechanism is a finite set of instructions, rules and/or algorithms to fulfil a specific purpose in a finite number of steps. Upon the generation of variants; various design schema, a benchmarking or a selection procedure should be determined in the identification of the best variant and final output [12]. It is widely recognised that there is not a single and definite solution; rather an iterative divergence/convergence process is required to deliver the most comprehensive range of possibilities and then, explore, analyse and identify the best design option with regard to the desirable criteria.

2. Algorithm development

Given the above context, in order to identify the way forward, this research focused on two main stages of developing design variants via parameterizing the modular coordination principles and analysing and filtering the variants based on the optimal solutions (minimised waste). Therefore, for the purpose of fully design automation, variants creation and considering parametric modular coordination, Rhino and Grasshopper software package were used as an integrated computer design tool with algorithmic method. Parametric modelling tools can simplify the widest possible range of concepts for design exploration by allowing the automatic generation of a group of alternative design solutions. Rhino is a 3D modelling software where authorizes the designer to link the layout to its underlying parameters by a plugin called Grasshopper. Grasshopper is regarded as the most suitable parametric modelling platform embedded in Rhino for developing the design variant algorithms in light of its powerful parametric programming capabilities [13]. It is a graphical algorithm editor tightly integrated with Rhino 3D modelling tools which features an advanced user interface. The main window consists basically of the component 'palettes' and the 'canvas' or user interface. The major interface of the algorithm development in Grasshopper applies the node-based editor in which Data is processed from a component by connecting wires which always connect an output grip to an input grip where data can either be defined locally as a constant, imported as a variant parameter.

2.1. Prototype development

The developed model is basically a simple rectangular cube with fixed-dimensions that is formed of six surfaces in which each two parallel surfaces were set to the same normal axis for further variations. In the first step, by exploding the cube (Fig. 1a), three different types of surfaces based on their unique normal axis were generated (Fig. 1b):

- Wall_Type_1 (WT1)
- Wall_Type_2 (WT2)
- Floor_Roof (FR)

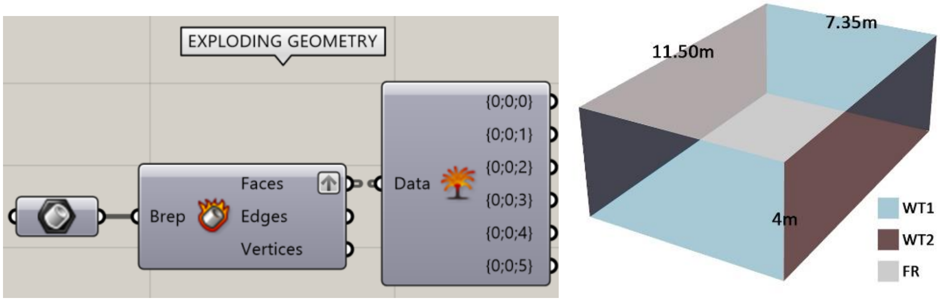

Fig. 1. (a) model explosion; (b) surface development.

2.2. Modules calibration

In the second step, for each component of the cube, the reference system and M were fixed according to ASTM International Standard [14] where preferred horizontal and vertical dimensions for building components of larger than M shall be multiple of the registered multi-modules (Table 1).

Table1. Preferred horizontal/vertical dimensions for modules calibration (adapted from ASTM Standard [14])

ASTM Standard	Preferences	Modules	Module identity in the algorithm
Preferred horizontal dimension up to 60M	First preference	n×3M	H3M
	Second preference	n×4M	H4M
	Third preference	n×10M	H10M
Preferred vertical dimension between 30M-48M	First preference	n×3M	V3M
	Second preference	n×2M	V2M

In the third step, by considering the above preferences and choosing one of the surface options, the algorithm (Fig. 2) was set to allow the user to evaluate selected surface for modularization by:

1) Random selection of the coefficient of 'M' from maximum number of 10 panels via a gene pool pattern where the user is able to organize panels dimensions and their order,
2) Assembling panels side by side without any inconsistency,
3) Evaluating curves and module dimensions,
4) Extracting the module dimensions of each surface.

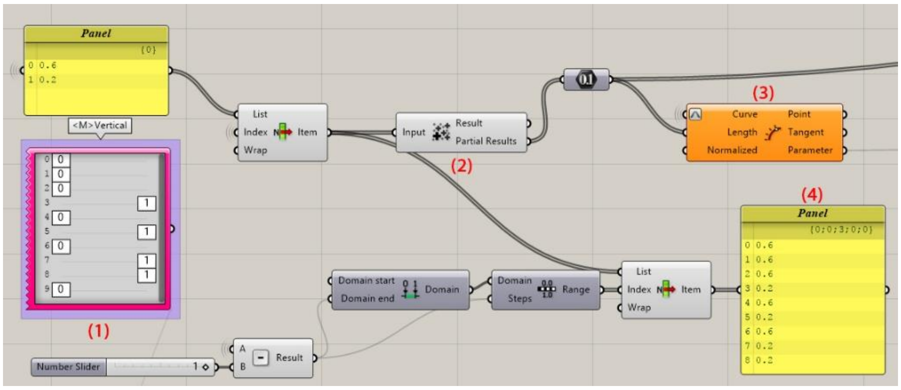

Fig. 2. Surface modularization

In the fourth step, in order to apply module dimensions and connect them through cross-lines on six surfaces, an algorithm was established using ASTM International Standard [14] for both horizontal and vertical components in which the procedural instruction of vertical components are described representatively by the following process (Fig. 3):

1) Implementing V3M and V2M reference preferences in vertical modularization through number sliders to extract variety of module coefficients
2) Applying simple multiplication equations where, A is the modular basic dimension and B denotes M
3) Random selection of M via a gene pool pattern
4) Importing modular dimensions and exporting assembled modules based on pool pattern arrays

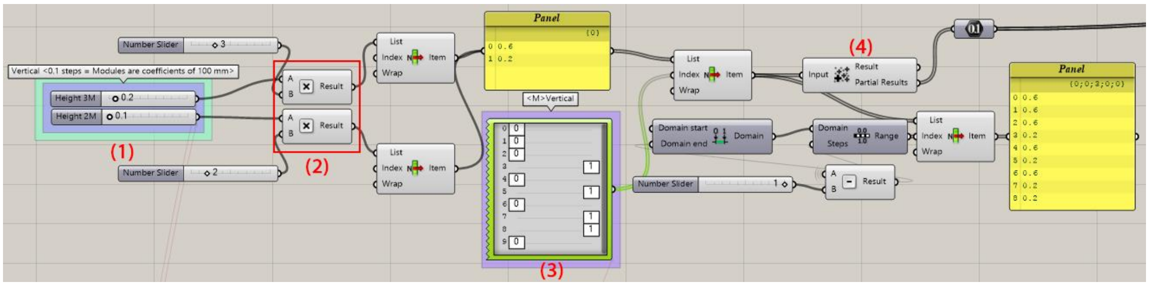

Fig. 3. Modules calibration

The modules calibration was followed by cross referencing of the surfaces and distance measuring of the components. It is worth mentioning that in the meanwhile of this process, the basic model is updated by the algorithm in Rhino 3D modelling interface in which the designer can test different cube panelizing without assuming waste coefficient parameters.

2.3. Waste coefficient

As the last step, an especially designated algorithm was linked to the results of the module calibration process to calculate the waste coefficient and waste surface area of each component. This algorithm comprises of a flow of simple equations as the outcome of following approach (Fig. 4):

1) Exploring the origin of each surface plane: Y axis as perpendicular vector for vertical surface typologies (WT1 and WT2) and Z axis as perpendicular vector for horizontal surface typology (F/R)
2) Creating the related plane coordinates
3) Extracting the total frame of assembled modules
4) Trimming the frame surface area from the plane area which results in waste area
5) Marking the waste area in colour to highlight the deducted proportion
6) Using a division equation between waste surface area and the plane or face surface area to achieve the coefficient of waste to surface (W/S) area
7) Applying a multiplication factor by 100 to obtain the waste surface area percentage on each generation

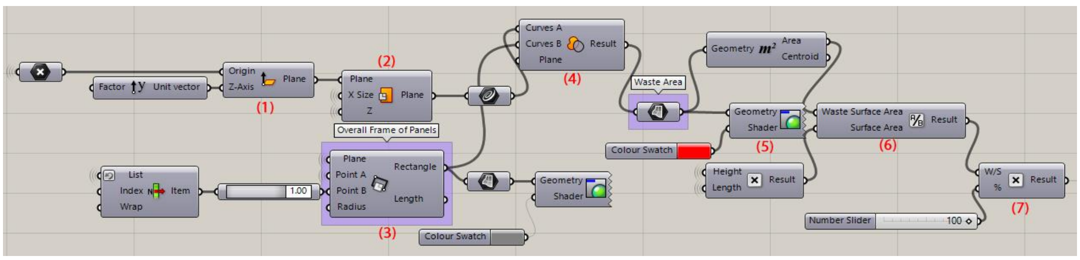

Fig. 4. Modules waste coefficient calculation

Progressively, this approach was further applied on the other two surface typologies to develop the prototype and link the modular coordination to waste optimization by taking the ASTM International Standard [14] into account. This algorithm provides the different measures of modularization that can be selected either by the user manually or with an optimizer element to generate different design variants automatically.

3. Algorithm deliverables

As a result of the developed algorithms to parametrise the modules and compute the generated waste, three significant deliverables of waste optimization, panelling sets and standard preference frequencies along with three datasets of waste percentage, total number of panels and horizontal and vertical frequencies were obtained. At this stage, the designer, by streaming the available contents, is able to choose the optimum waste coefficient where it is composed of the least amount of panels and preferred modular dimensions based on ASTM standard [14]. Therefore, this framework can be used when there are several same waste coefficient values while the other two parameters are different from each other.

3.1. Waste optimization

A parametric optimization algorithm, called Galapagos, was utilized to generate various modular possibilities and minimize the waste coefficient in each generation. This optimizer provides a generic platform for the application of evolutionary algorithms to be used on a wide variety of problems by non-programmers and produces convergent outputs from the algorithmic input parameters as 'Genes'. By applying a genetic algorithm through Galapagos, the user is able to devise an algorithm, allowing wide range of variations in a geometry that searches for the optimum configuration of an objective function with several performance criteria. Therefore, in this study, the below items were considered as the Genomes; waste optimization inputs:

- M of each surface typologies (WT1, WT2 and F/R) via gene pool patterns for evaluating all possible design variants on the cube volume; horizontally and vertically
- Preferred Horizontal Dimensions of H3M, H4M and H10M with respect to ASTM Standard [14]
- Preferred Vertical Dimensions of V3M and V2M with respect to ASTM Standard [14]

Consequently, the evolutionary solver was assigned to minimize the waste coefficient as the Fitness function to optimize the input parameters as the Genomes in Galapagos. By running the solver, it randomly generates available design variants in terms of the input parameters and attempts to minimize the waste reduction coefficient via a convergent approach (Fig. 5), in which outlier and higher values are neglected and the optimum coefficient is achieved.

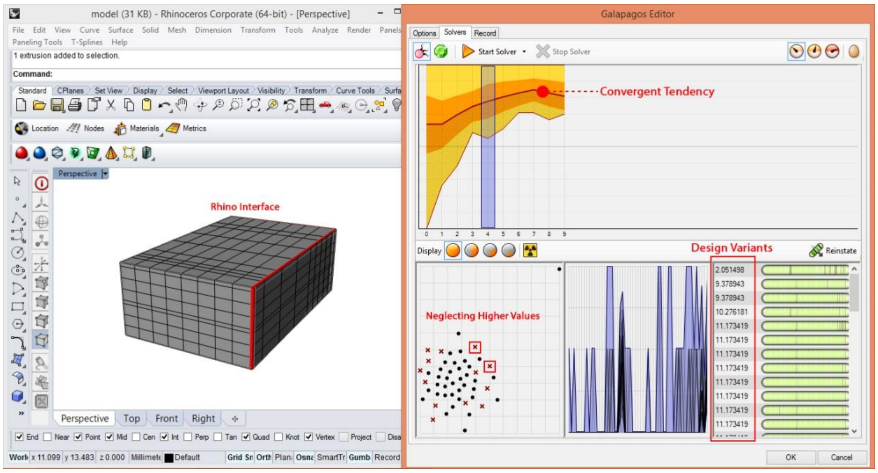

Fig. 5. Waste optimization procedure

Accordingly, the optimization solver was launched and the data logger was set to record the results lower than 10% threshold of waste. Within this range, the minimum and maximum of total waste were recorded at around 2 and 8.5 percent for all surface panels as depicted in Fig. 6. It can be also inferred that the algorithm has performed well to converge the genomes and reach the minimum coefficient of waste because the data have been diminishingly scattered toward the minimum value.

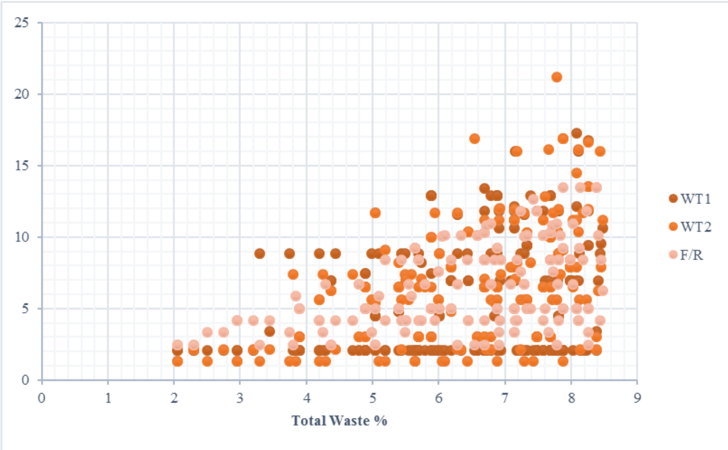

Fig. 6. Waste optimization performance

3.2. Panelling sets

In view of the previously shown waste reduction capability in modular construction, the building components quantity is the next priority that looks for the minimum amount of required panels to draw on the optimum value. Paneling calculation process consists of extracting the required number of panels of modularization for each generated solution, their multiplication and summing up the total panels of surface typologies (WT1, WT2 and F/R). As a result of this process, total number of panels were illustrated vis-à-vis the total waste percentage in the specified threshold. Fig. 7 indicates that as the waste increases, total number of panels scatter widely and decrease gradually. This observation implies that the higher number of panels are employed during the modular construction, the more waste-wise design can be achieved. Another interesting result is the existing overlaps among different number of panels with the same amount of the waste. For instance, at 2% of waste, there are two quantities of panels including 380 and 420, respectively. Such difference is further detected at the maximized waste where 106 and 440 number of panels generate 8.5 percent of waste. These overlaps are the outcome of considering different combinations of panels which provide architects with an opportunity in more flexible design.

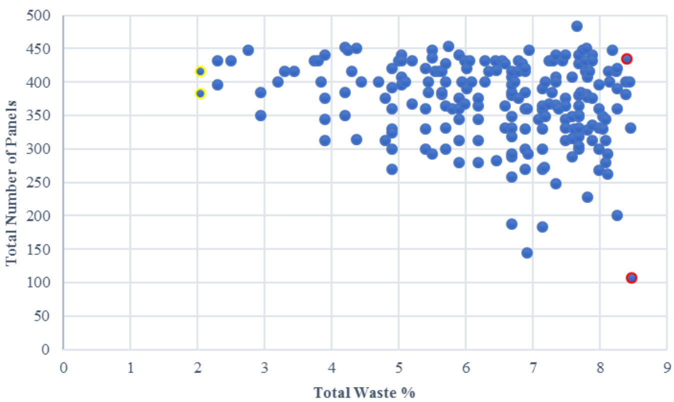

Fig. 7. Total number of panels vis-à-vis total waste

3.3. Standard preference frequencies

Since Galapagos randomly generates the design solutions and constantly changes them, designers require to assort all the generated dataset into specific classifications. For this reason, another algorithm was developed and connected to the chain to categorize the resultant module types according to the ASTM standard [14] preferences. Hence, the third priority; the preference frequencies for each design variant was calculated via the below steps:

1) ASTM Standard [14] preferences consideration in horizontal and vertical modularization
2) M multiplied by horizontal and vertical standard preferences
3) Similarity components application in aligning each module preferences

This procedure was ended up with a boxplot indicating the distribution for the preferences. As illustrated in Fig. 8, H3M is the set of modules having the highest frequency among the horizontal panels. H4M and H10M are the second and third frequent groups of the modules, respectively, but H4M, thanks to its skewer, is distributed as much as H3M. For vertical panels, V3M and V2M are the first and second order of panelling sets, as expected. As a whole, these facts provide proof that the algorithm has truly implemented the ASTM standard [14] on its assumptions of preference frequencies and therefore, can be deemed valid and reliable for industry practitioners.

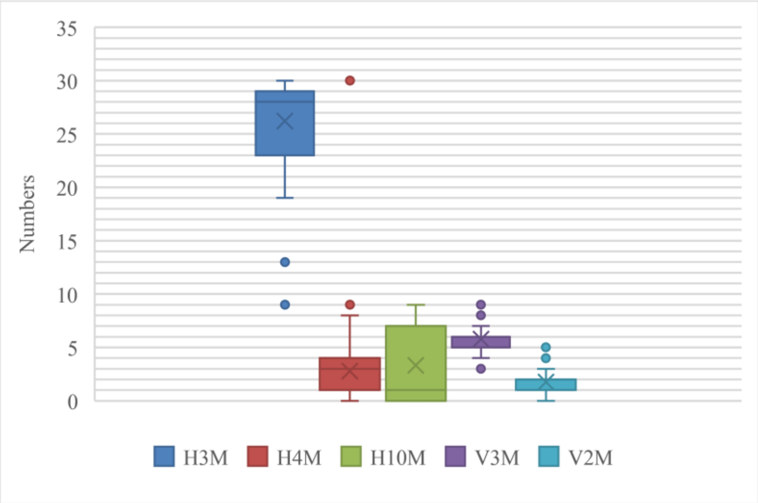

Fig. 8. Boxplot distribution of the panels

4. Conclusion

Driven by the gap in the body of knowledge with regard to the dearth of innovative methods in addressing waste considerations of offsite construction, this research contributes to the field in different ways. As the first study of its kind, it presents a novel approach toward the waste minimization of modular construction from the lenses of parametric design theory and grounded on the modular construction principles. The outcome is an integrated platform which relies on the practical superiority of the algorithmic modelling with logical preferences and applies the recognized international standard of modular coordination as its mastermind to minimize the waste coefficient of panelling sets. The study also goes beyond the existing literature by revealing how parametric design theory could be integrated with the offsite construction principles through its generative algorithms to assist the architects in designing flexible and aesthetic but rule-based and waste-wise buildings. This achievement provides more opportunities with the application of parametric design theory in the built environment issues and alleviates its environmental impacts. However, the study findings should be considered with caution due to a number of limitations in conducting the present research. That is, the findings may not be directly applicable to the actual buildings as the data was collected by the hypothetical case study. Moreover, the performance of the developed algorithm can be more enhanced to reach the minimum waste in the meanwhile of minimizing total number of panelling. These call for further investigation by validating the algorithm in other contexts and using larger samples covering various parameters and design constraints.

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