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Modular coordination-based generative algorithm to optimize construction waste

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Abstract

In response to the growing attention to sustainable built environment, this study aims at introducing an approach in construction waste optimization through integrating parametric design with offsite construction methodology. To this end, a generative algorithm was developed within the integrated platform of Rhino and Grasshopper software based on 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 while an evolutionary solver function was employed for optimizing the generated waste. This resulted in developing different modular design variants which generate the minimum amount of waste while being fully compliant with international standards. 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 methodology through the lenses of construction waste optimization.

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

1. Introduction

Offsite construction is an attempt geared towards increasing productivity, time efficient delivery and mass production on construction projects via using manufactured houses, panelized components and prefabricated

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structural frames. This refers to a construction system in which components are manufactured in a factory, transported and assembled into structures with minimal on-site activities [1]. Modular Coordination (MC) is a key asset in deploying of offsite construction. That is, MC is a pre-engineered structure that entails creation of discrete-volumetric pre-fabricated components in light of coordination of dimension and space. MC is a methodology which drives offsite construction towards adopting an integrated design according to a basic unit or module and encourages parties involved in the construction industry to produce and utilize prefabrication to facilitate mass production of buildings in a standardized format [2]. Delivering projects through implementing MC results in great benefits such as lowering environmental impacts, enhancing productivity and facilitating effective project handling [3]. Despite such advantages, current implementation rates are far from satisfactory. For instance, the utilization rate among residential building projects in the US is below 3% [4]. That is because, use of MC makes project delivery prone to a wide range of complications in terms of the design scope and exploration options. The special challenge is the need for transforming conventional design and construction practices to an approach based on MC in which the creative design options are to be explored and generated. To overcome this challenge, parametric design 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 the virtue of implementing a group of criteria in line with MC rules. Nevertheless, a review of literature shows that there is a lack of research that looks into coupling MC with parametric design to enhance the processes applied in offsite construction. This gap is especially widened where the sustainability performances and environmental impacts of offsite construction come to the light. Construction waste constitutes 40% of landfilled materials [3], yet full settlement of such a damage seems a long way off. There is no shortage of research studies that focus on waste minimization aspects of modular construction by either conducting surveys [6] or case studies of real-life projects [7]. Likewise, application of innovative design methods in modular construction through integration with BIM processes [8] and BIM authoring tools [9] have recently come to the fore as active research areas. However, no research study has hitherto investigated construction waste optimization through the lenses of integrating MC and parametric design. To address the identified gap, this study aims at developing a novel approach geared towards construction waste optimization in which MC principles of offsite construction are simulated through parametric design and different design options are explored using a generative design algorithm. Adhering to the minimum amount of generated waste, the study concludes with presenting a number of schematic deliverables. These could be translated into guidelines for architects and practitioners to facilitate preventing waste during the design.

1.1. Modular coordination (MC)

MC aims at standardizing the measurement and placement of building components according to a number of dimensional coordination rules within a referenced system [9]. MC facilitates dimensional compatibility among the size of a building, its associated spans or spaces, the size of components and any 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 prefabrication and offsite construction to identify the optimum dimensions for components, reduce on-site waste and simplify their interchanges [10]. Five major rules of MC are provided 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 the building layout and coordinating the dimensions for buildings

A basic module forms the fundamental entity of size and dimension in MC while the sizes of building components and the building layout are coordinated in multiples of this basic module. This equals to 100 mm (M) and could be defined in n*M which results in multi-modules. The basic module is addressed through a reference system which is composed of 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 models and streamlines the shift from modelling designed objects to design logics [11]. In parametric design, computational attributes are used in setting design principles to provide a platform for design exploration and variations. Besides, different degrees of artificial intelligence are applied upon computational specifications. These include rules, constraints, parametric dependencies and heuristic and meta-heuristic structures to encode them and act as a generator to yield a parametric-generative model. The procedure of parametric-generative design constitutes the four major elements as presented below [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 inputs to establish the initial parameters which are later transformed through a generative mechanism towards the initial population of design. This mechanism entails a finite set of instructions, rules and/or algorithms to fulfil a specific purpose in certain number of steps. Upon the generation of variants and various design schema, a benchmarking or a selection procedure is determined to identify the best variant and the final output [12]. There is no best 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 as defined.

2. Algorithm development

This study targeted two main stages of developing design variants via parameterizing the modular coordination principles and analysing and filtering the variants based on optimal solutions (minimised waste). For the purpose of achieving a fully automated design, variants creation and considering parametric modular coordination, Rhino and Grasshopper software packages were used as an integrated computer design tool with an algorithmic method. Parametric modelling tools can simplify a wide range of possible concepts for design exploration by allowing the automatic generation of a group of alternative design solutions. Rhino is a 3D modelling software that 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 due to its powerful parametric programming capabilities [13]. This is a graphical algorithm editor tightly integrated into Rhino 3D modelling tools and features an advanced user interface. The main window consists basically of the component ‘palettes’ and the ‘canvas’ or the user interface. The major interface of the algorithm development in Grasshopper deploys a 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 or imported as a variant parameter.

2.1. Prototype development

The developed model was basically a simple rectangular cube with fixed-dimensions that were formed of six surfaces with two of the parallel surfaces set to the same normal axis for further variations. As 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)

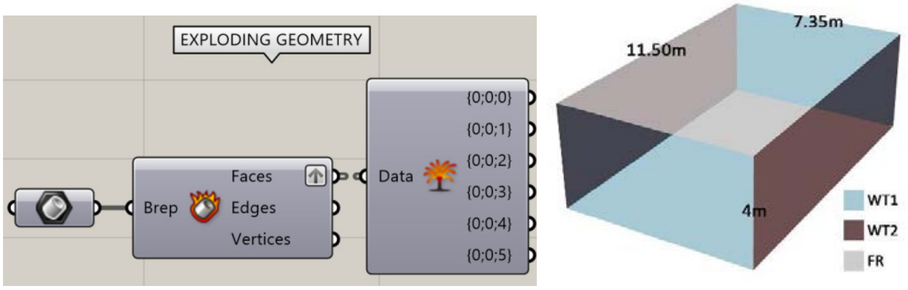

Fig. 1. (a) Model explosion; (b) surface development.

2.2. Modules calibration

In the second step, the reference system and M were fixed according to ASTM International Standards for each component of the cube (hereafter referred to as ASTM) [14] where preferred horizontal and vertical dimensions for building components larger than M were multiples of the registered multi-modules (Table 1). ASTM International is an open platform for the development of high quality and market relevant standards for materials, products, services and systems used in the engineering industries.

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

As for the third step, the algorithm (Fig. 2) was set to allow the user to evaluate the selected surface for modularization by considering the above preferences and choosing one of the surface options in view of the considerations presented below.

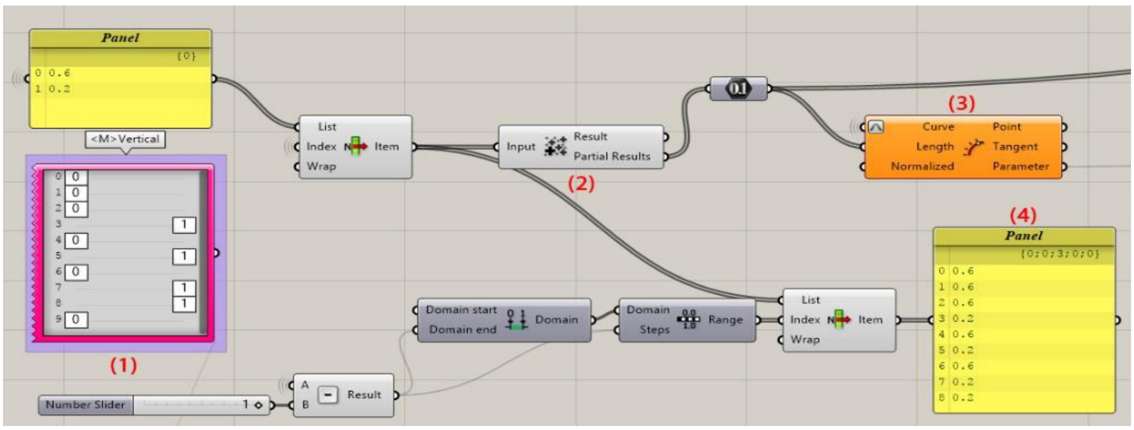

Fig. 2. Surface modularization.

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 the 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

In the fourth step, an algorithm was established in order to apply module dimensions and connect them through cross-lines on the six surfaces. This was through using ASTM for both horizontal and vertical components in which the procedural instruction of vertical components was described representatively by the process as illustrated in 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

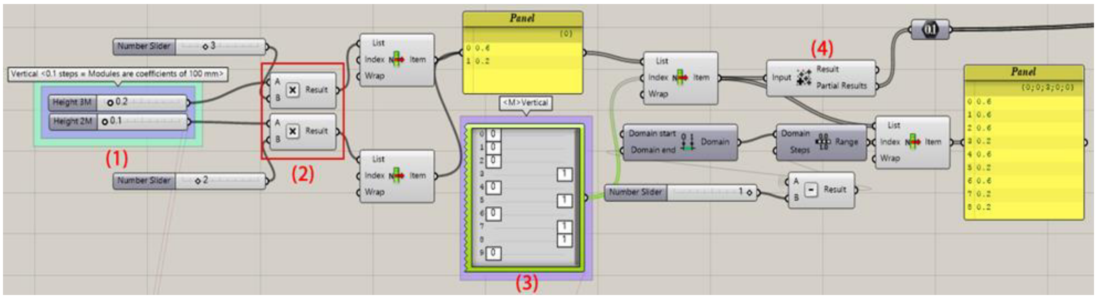

Fig. 3. Modules calibration

The modules calibration was followed by cross referencing of the surfaces and distance measuring of the components. The basic model was updated by using the algorithm in Rhino 3D modelling interface within this procedure. As such, a designer was able to test different cube panelizing without assuming waste coefficient parameters.

2.3. Waste coefficient

Eventually, an especially designated algorithm was linked to the results of the module calibration process to calculate the waste coefficient and waste surface area for each of the components. This algorithm comprised of a flow of simple equations as the outcome of following the approaches as described below (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

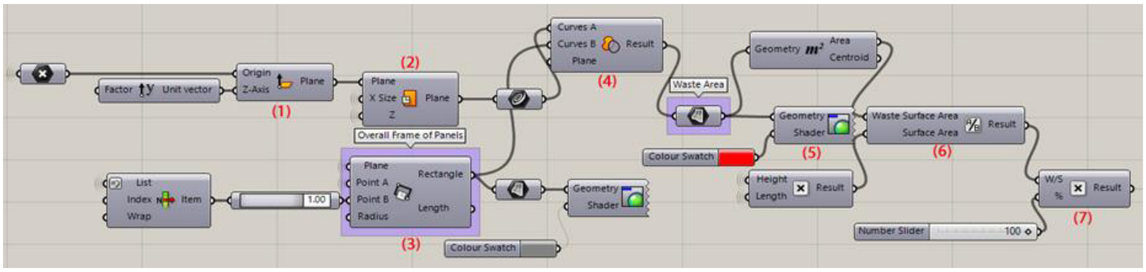

Fig. 4. Modules waste coefficient calculation

The same approach was further applied to the other two surface typologies to develop the prototype and link the modular coordination to waste optimization by taking the ASTM into account. The algorithm provided different measures of modularization. These could 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 developing the algorithms to parameterize 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 alongside total number of panels and horizontal and vertical frequencies were obtained. At this stage, a designer was able to choose the optimum waste coefficient by streaming the available contents, composed of the least acceptable amount of panels and preferred modular dimensions based on the ASTM. Therefore, this framework can be used when waste coefficient values are similar while the other two parameters are different.

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 range of problems by non-programmers and produces convergent outputs from the algorithmic input parameters as ‘Genes’. By applying a genetic algorithm methodology through Galapagos, the user is able to devise an algorithm, thus allowing a 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 typology (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
- Preferred Vertical Dimensions of V3M and V2M with respect to ASTM

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, available design variants in terms of the input parameters and attempts to minimize the waste reduction coefficient were randomly generated via a convergent approach (Fig. 5), in which the outlier and higher values are neglected, thus the optimum coefficient is achieved.

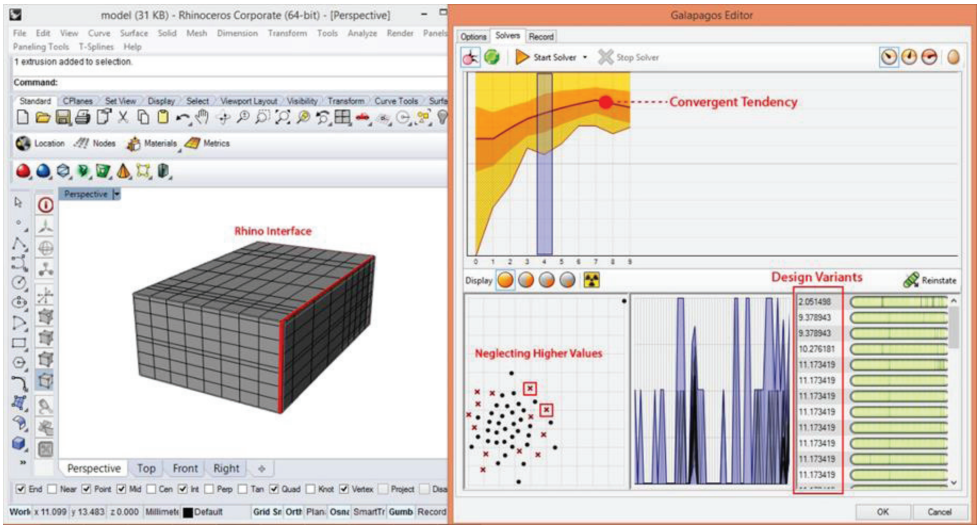

Fig. 5. Waste optimization procedure

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 the surface panels. As illustrated in Fig. 6, the algorithm performed well to converge the genomes and reach a minimum coefficient of waste. That is because, the data were diminishingly scattered toward the minimum value.

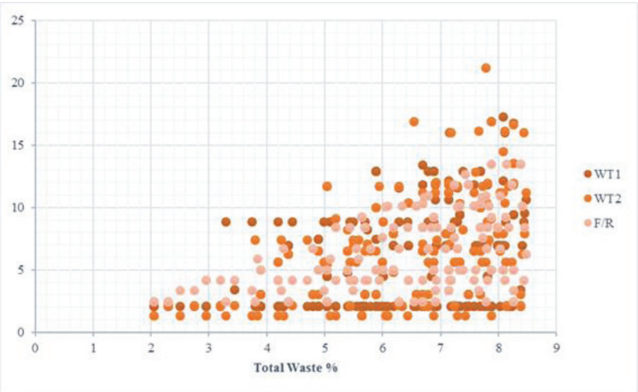

Fig. 6. Waste optimization performance.

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 consisted of extracting the required number of panels of modularization for each generated solution, their multiplication and summing up the total panels for the surface typologies (WT1, WT2 and F/R). As a result of this process, the total number of panels were illustrated vis-à-vis the total waste percentage in the specified threshold. Fig. 7 indicates that as the waste increased, the total number of panels scattered widely and decreased 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 associated with the existing overlaps among different number of panels with the same amount of generated waste. For example, 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 ample opportunity for a flexible design.

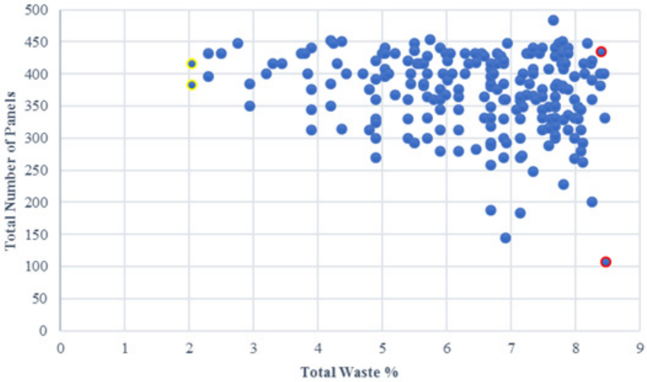

Fig. 7. Total number of panels vis-à-vis total waste.

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 preferences. Hence, the third priority; the preference frequencies for each design variant was calculated via the below steps:

1) ASTM 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

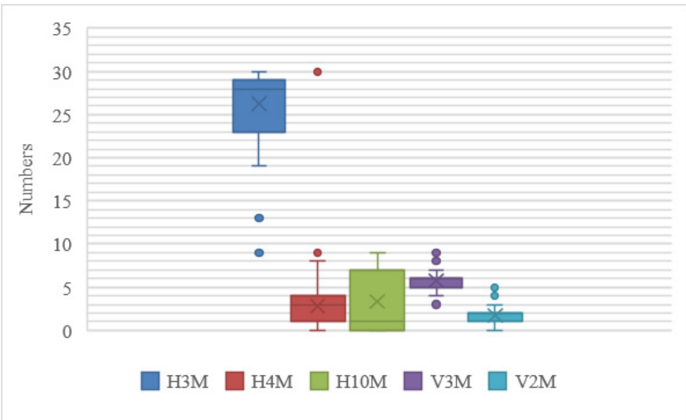

Fig. 8. Boxplot distribution of the panels.

This procedure resulted in creation of a boxplot reflecting the distribution of 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. H4M, however thanks to its skewer, is distributed similar to H3M. For vertical panels, V3M and V2M are the first and the second order of panelling sets, as expected. In essence, these facts provide proof that the algorithm has truly implemented the ASTM with regard to the assumptions of preference frequencies. Therefore, the algorithm is deemed valid and reliable enough to be used by industry practitioners.

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 several ways. As the first study of its kind, it presents a novel approach towards waste optimization of modular construction through 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 offsite construction principles through its generative algorithms to assist architects in designing flexible and aesthetic yet 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 actual buildings as the data were fictitious and collected through generating a hypothetical case study. Moreover, the performance of the developed algorithm is open to enhancement to reach the minimum waste in the interim of minimizing the total number of panelling. These call for further investigation for validating the algorithm by using larger samples that cover various parameters and design constraints.

Acknowledgements

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References

[1] M.D. Taylor, A definition and valuation of the UK offsite construction sector, *Const. Mgmt & Econ*. 28 (2010) 885-896.
[2] M. Anderson, P. Anderson, Prefab Prototypes: Site-specific Design for Offsite Construction, Architectural Press, Princeton, 2007.
[3] I. Nahmens, L.H. Ikuma, Effects of lean construction on sustainability of modular homebuilding, *J. Arch. Eng*. 18 (2011) 155-163.
[4] J. Quale, K.W. Eckelman, G. Williams, G. Sloditskie, J.B. Zimmerman, Construction matters: comparing environmental impacts of building modular and conventional homes in the united states, *J. Indstrl. Eco*. 16 (2012) 243-253.
[5] P. Schumacher, Parametricism: A new global style for architecture and urban design, *Arch. Design*. 79 (2009) 14-23.
[6] M. Osmani, J. Glass, A.D. Price, Architects' perspectives on construction waste reduction by design, *Waste Mgmt*. 28 (2008) 1147-1158.
[7] M. Shakouri, S. Banihashemi, Industrialized wall components impacts on cooling load reduction and carbon production, *Int. J Soc. Sci & Hum*. 2 (2012) 30-37.
[8] S. Banihashemi, The Integration of Industrialized Building System (IBS) with BIM: A Concept and Theory to Improve Construction Industry Productivity, Saarbrucken, Germany: LAP Lambert Academic Publishing, 2012.
[9] M. Singh, A. Sawhney, A. Borrmann, Modular coordination and BIM: development of rule based smart building components, *Procedia Eng*. 123 (2015) 519-527.
[10] R.E. Smith, Prefab Architecture: A Guide to Modular Design and Construction, John Wiley & Sons, 2011.
[11] N. Leach, Digital morphogenesis, *Arch. Design*. 79 (2009) 32-37.
[12] I. Dino, Creative design exploration by parametric generative systems in architecture, *METU J. Fac. Arch*. 29 (2012) 207-224.
[13] I. Abotaleb, K. Nassar, O. Hosny, Layout optimization of construction site facilities with dynamic freeform geometric representations, *Aut. in Const*. 66 (2016) 15-28.
[14] ASTME577-85, Standard Guide for Dimensional Coordination of Rectilinear Building Parts and Systems, ASTM International: West Conshohocken, PA, 2002.