Evolution of Modelling in Architecture

A Framework for the categorisation and evaluation of digital models in Architectural Design

Adonis Haidar
University of Liverpool
Adonis.Haidar@liverpool.ac.uk

Apart from being an integral part of the architectural design process, modelling is becoming central to architecture as well as to neighbouring fields. The technologies and tools applicable for the generation, development and coordination of models are growing rapidly. In one single project, a wide range of models is used which poses challenges in practice in terms of establishing a systematic way to utilise those modelling techniques and access their potential benefits.
Aiming to enhancing the effectiveness and efficiency of the various modelling methods, this paper establishes a framework for the different types of models where the models are categorised and evaluated based on different criteria. To achieve this, a critical review of the literature related to the history of modelling in architecture and the emergence of the different methods of modelling is conducted.
Beyond classical, CAD-based 3D models, the framework identifies four categories of modelling methods: performative modelling, algorithmic modelling, parametric modelling, and BIM. Each category is evaluated based on the generation and modification process, model entity and model function. Subsequently, the paradigm shifts associated with each modelling method are identified and discussed.
Keywords: *3D Modelling History, CAD, BIM, Generative/Algorithmic Modelling, Parametric Modelling, Performative Modelling, Paradigm Shift, Computational Design.*

INTRODUCTION

Alongside the expeditious digital innovation in architecture, the role of models is becoming increasingly pivotal. Historically, models were created as supplementary items to the 2D drawings, providing the client with insights into the form and style of their building. However, a plethora of modelling methods have since evolved, offering architects unprecedented opportunities to view and navigate their future building, walkthrough their virtual spaces, develop algorithms and associate parameters to explore design alternatives, and simulate and analyse building performance within the building's virtual space prior to construction. This is added to the ability to embed different types of information within models to streamline the design and construction processes. These rapid developments have significantly enhanced the centrality of models in project delivery.

Within a single project, multiple models are produced for different purposes. Haidar (2019) attributes the barriers associated with implementing computational design to human mindsets and attitudes rather than to the technology per se. In the context of modelling, there is a rapid proliferation of diverse modelling methods, making it arduous for architects and engineers to comprehend the true potential of each method and how to utilise them effectively to enhance efficiency in project workflows. To address this issue, this paper establishes a framework for the categorisation and evaluation of different types of models. This is accomplished through a critical review of relevant literature focusing on vernacular design, design by drawing, 3D CAD, performative modelling, generative/algorithmic modelling, parametric modelling, and BIM. The paper concludes with a discussion section that evaluates the different modelling method and scrutinises the paradigm shifts associated with each method.

EVOLUTION OF MODELLING IN ARCHITECTURE

The centrality of models in the architectural design process can be traced in Ancher's (1965) definition of design as the "formulation of a prescription or model for a finished work in advance of its embodiment". While Whitehead et al. (2011) define a model as "a representation of an idea that externalises a thought process", Klassen, 2002 in Veliz et al. (2012) offers another perspective, describing a model as "a representation of a conscious simplification of reality filtered and determined by cultural and individual backgrounds which necessarily conceives a systematic understanding of the reality and a set of reductional constraints". A comparison of these two definitions reveals a notable distinction. The first focuses on the function of the model within the design process, viewing it as a medium that communicates the designer's thoughts to other project participants, while the second emphasises the entity of the model representing a simplified version of a real product. This disparity underscores the necessity to evaluate models from different perspectives. Accordingly, this paper categorises and evaluates modelling methods based on various criteria, encompassing model general and modification, model entity (content, components and internal relations), and model function.

From Vernacular Design to 'Design by Drawing'

Historically, objects were designed and crafted simultaneously in a 'vernacular manner' (Lawson, 2006) as part of a craftsman's work (Jones, 1992). In this approach, objects were crafted to the required shape without the need to provide a 'scale drawing' in advance. Any problem was solved directly on the final product. Later, it was possible to evolve the shape of a product through a 'scale drawing' provided by a 'designer' before the making starts. This shift resulted in a separation between thinking and making, which, according to Jones (1992), represents both the strength and weakness of an industrial society.

Jones (1992) states that scale drawings facilitate advanced planning by providing a medium for experimentation and changes, enabling accurate dimensioning ahead of manufacturing. Additionally, he notes that scale drawings serve as 'a rapidly manipulatable model of the relationship between the product components, especially when the desired object is larger than what a single craftsman can make on their own'. The separation between design and making allows for the involvement of multiple individuals in the production process, dividing the work into tasks that can be executed simultaneously by repetitive hand labour or machines over a shorter period (Jones, 1992).

In summary, drawing permits exploration of a wider scope of design alternatives, accelerating the design and production process and facilitating the representation and production of larger and more complex forms. Drawing enables the fragmentation of the production process, allowing multiple participants to contribute and support collaborative work. This significant impact of design by drawing has resulted in the emergence of drawing as the primary method for design. Thus, ‘the typical design is believed to be an individual’s creative effort, conjuring up images of late nights at the drawing board’ (Cuff, 1992).

2D Drawing with CAD

Paper-based drawing is recognised for its cumbersome nature, especially when it comes to the production of shop drawings with abundant sets of detailed drawings needed by the project construction team. CAD was introduced to architectural practice, offering designers the tool to facilitate and accelerate the production of drawings seamlessly with less effort. CAD soon became a catalyst for architectural practice around the world in the 1980s (Penttilä, 2006).

The management of design changes (Aljabi, et al., 2017) and change propagation (Whitehead et al., 2011) are often cited as key aspects of the architectural design process. Jones (1992) states that the most frustrating aspect of design is the need to go through cycles of modification and re-modification throughout the design process. This frustration highlights the value of using CAD. According to Holzer (2015), CAD proved its efficiency in project delivery by enabling faster replications within the design process. Furthermore, Simon (1975) in Hudson (2010) claims that all design problems can be solved by searching for a large range of possibilities. Threrefore, CAD appears to be facilitating design due to the speed at which a wider range of design alternatives can be explored.

Despite the advantages CAD offers in facilitating drawing production and manipulation, architectural practice's heavy reliance on drawings has faced intense criticism. Lawson (2006) states that drawings are the main mechanism to communicate design ideas despite their deficiency in encapsulating design information. Jones (1992) believes that drawings are ‘too simple for the growing complexity of the man-made world’. He attributes this to the fact that drawings only show the form of a future building, not its performance. This is added to the difficulty to modify drawings by more than one person, which results in isolating the designer from valuable external contributions. Furthermore, Haidar (2019) states that designers using CAD need to continuously investigate the associated parts when a change is made to maintain consistency amongst all elements in their drawings. Those limitations led Lawson (2006) to call for new modelling approaches capable of addressing the aforementioned separation and to mollify the resulting combative relation between stakeholders that is influenced by the full reliance on drawing.

3D CAD Modelling

The interest in electronic 3D modelling co-evolved with CAD drawing albeit constrained by the early limitations of computer hardware. Later, the development of computer capabilities allowed architects to design buildings in 3D using electronic building models called 3D CAD (Sacks, et al., 2018).

The evolution of 3D CAD began in the 1960s and has continued to evolve until the current times. Sacks et al. (2018) provide a comprehensive overview of the key modelling types that have led to the current advancement in BIM tools. This includes the development of the tools needed to represent compositions of polyhedral forms in the 1960s, followed by additional features to enable the creation and editing of arbitrary 3D solid shapes known as solid modelling in the 1970s. Solid modelling as described by Sacks et al. (2018), enables the simulation and manipulation of the various building components, with the ability to combine different shapes through different ‘Boolean’ operations to simulate complex shapes. Later on, other modelling techniques were added to 3D CAD that enabled the simulation of building components through surfaces, such as Bezier and NURBS curves and surfaces. These features provided designers with interactive and precise control over smooth, doubly curved, and intricate spaces and geometries (Bhooshan, 2017). Furthermore, 3D CAD systems offer designers an interface to modify views and walkthrough the model (Oxman, 2017), which enables a profound exploration of the virtual building in 3D for more informed decision-making. Additionally, the ability to assign materials to certain elements within the virtual building enhances realistic visualisation.

In summary, 3D CAD has revolutionized the simulation of building forms, allowing architects to navigate and profoundly explore a virtual version of future building prior to construction. More importantly, it has granted architects access to a higher level of form complexity that is extremely hard to be achieved through paper-based design. This is added to the advanced visualisation tools that, indeed, resulted in a situation where distinguishing a real image of a building from an image generated from a 3D CAD model becomes increasingly difficult.

Performative Modelling

The previous discussion reveals the effectiveness of CAD systems in simulating and visualising building forms, addressing one aspect of decision-making in the architectural design process. However, architectural design decisions encompass a broader range of criteria that must be considered as early as possible. This sheds light on a significant dilemma in the architectural design process stemming from the sensitivity of the conceptual design stage where the most critical decisions must be made despite the limited information available (Harding and Shepherd, 2017). Traditionally, architects generate and develop designs, which are then communicated to engineers and other consultants to gather feedback on the structural and environmental performance of the building. Unfortunately, this communication often occurs near the completion of the design, making it challenging to make changes without enormous bills (Mueller, 2011). This issue prompts the need to find a modelling technique capable of predicting and simulating building performance, moving beyond mere building form simulation. Indeed, this inclination is commonly known as 'performative design', which is a process of formation that is driven by a desired performance (Oxman, 2006). This tendency in design is supported by a wide range of modelling tools and software applications that facilitate various analyses to simulate building performance. These include estimating energy consumption, analysing building orientations in relation to natural light and ventilation, and conducting structural analysis. These applications serve as powerful tools for performance-based optimisation of building design by accurately predicting how a building will perform under different conditions.

Generative and Algorithmic Modelling

The increasing complexity of the man-made world, coupled with the limitations of CAD systems to cope with this complexity, has instigated the continuous development of modelling tools, including local manipulation of CAD tools. Most existing CAD applications are equipped with an API (Application Programming Interface) to tweak the tool to match the specific needs of the design task in hand. This scripting capability has facilitated the development of algorithms to generate architectural forms. While Aish and Hanna (2017) use the term 'direct manipulation' to refer to the way design forms are modified and manipulated within traditional CAD systems, using algorithms to generate forms can be described as 'indirect manipulation'. This involves designers shift from directly manipulating design forms, to manipulating algorithms to generate and edit forms. In this context, Oxman (2017) defines an 'algorithm' as "a set of rules written by a source code of explicit instructions that initiate computational procedures that generate digital forms".

Furthermore, she states that generative models in digital design involve setting generative rules, relations and principles from which shapes and forms can be derived (Oxman, 2006). These two statements are very similar, and in fact, the algorithm in the first definition is referred to as rules, relations and principles in the second definition. The ability to incorporate rules through algorithms allows for a more comprehensive exploration of the form finding process, shifting the focus from external form to the inner logic of the project (Kolarevic, 2004).

In general, algorithmic design enables the generation of novel design solutions that might be unattainable through traditional methods (Liu, 2010). This capability opens up possibilities for achieving unprecedented levels of form complexity that extend beyond the capabilities of traditional CAD tools.

Parametric Modelling

Parametric modelling is similar to algorithmic modelling, as algorithms are also developed to generate geometry. The added value of parametric modelling lies in the ability to associate parameters, enabling changes in certain parameters to automatically trigger corresponding adjustments in associated parameters within the model (Haidar et al., 2019). More precisely, in parametric modelling, geometric entities are represented alongside their relationships through associated components and attributes within a hierarchical chain of dependencies, wherein each geometric attribute is expressed through a parameter (Turrin et al, 2011). The parametrisation entails determining which parameters are to be fixed, which are independent, and which are dependent (Haidar et al., 2019). The independent parameters can then be changed manually to feed data to the dependent parameters, which dynamically update in response (Barrios, 2005). This a approach allows for the establishment of various types of relationships between parameters, including geometric relations, descriptive relations, equational relations and "if-then" conditions (Sacks et al., 2018).

Benefits of Parametric Modelling.

The benefits of utilising parametric modelling are vast. Using associative parameters offers designers seamlessness and flexibility in the modification of the model, thereby providing an exceptional ability to expand the design space simply by manipulating parameters to generate a much wider range of design alternatives within the form-finding process (Haidar, 2019). In response to the syndrome of repetition (Oxman, 2006) that characterises traditional architecture, parametric modelling allows differentiation in building geometry, empowering the generation, manipulation and rationalisation of highly complex shapes that are beyond the reach of any CAD tool (Wortmann & Tunçer, 2017). Furthermore, Hudson (2010) states that parametric modelling can be used to create alternative models to solve design problems in relation to performance, ease construction, budget, user needs, aesthetics or a combination of these factors. This indicates that parametric modelling extends beyond the form-finding in the early design stage and can be integrated with other design considerations in later stages. By automating variations, iterations, and feedback loops from the initial design stages (Bernal et al., 2015), parametric design allows analysis and performance simulations to be integrated into the parametric modelling environment, positioning it as a form of performative modelling.

Parametric Modelling Tools.

Parametric modelling can be approached through scripting and programming. However, scripting presents cognitive barriers (Oxman, 2017) caused by the inherent contradiction between text-based coding and the visual nature of design representations (Lawson, 2006). Nonetheless, these barriers can be eliminated by using visual programming applications dedicated to parametric modelling such as McNeel's

Grasshopper™, and Autodesk Dynamo™ (Anton & Tănase, 2016), that can be hosted by CAD or BIM applications such as Rhino and Revit. Known as 'graph-based parametric modelling applications', they rely on a simultaneous and interactive display of the model in the host application and a visual graph in the parametric modelling application (Oxman, 2017) (Figure 1). The graph contains nodes representing blocks of scripting that receive data from other nodes through input parameters and send data to other nodes through output parameters (Haidar et al., 2019). Different parameters or objects in the host application can be represented in the graph, allowing designers to develop algorithms by associating parameters, establishing relations, incorporating rules and manipulating those relations, rules and parameters while observing the results in the host applications in real-time.

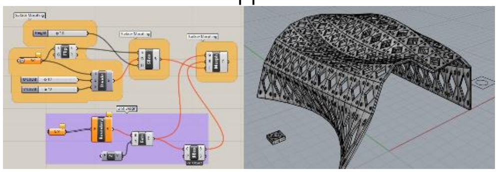

Figure 1: simultaneous and interactive display of the model in the host application (right) and a visual graph in the parametric modelling application (Left)

The main feature of this modelling approach is the parametric graph which acts as a cognitive artefact explicitly documenting the history of the design development (Harding and Shepherd, 2017). In other words, the graph represents a record of the internal logic of the design development process (Bernal et al., 2015), allowing designers to revisit previous stages, change a parameter and immediately get the final model updates without the need to re-run the process or re-create the model as in CAD.

BIM (Building Information Modelling)

Historically, the interest in 3D modelling was primarily driven by architects predating the involvement of other project stakeholders who subsequently started to get involved in modelling by adding their information to building models. Consequently, the term 'information' was inserted into 'Building Model' giving rise to the term 'Building Information Model' (BIM) (Sacks et al., 2018).

About BIM.

When CAD is utilised in the design process, designers create drawings and models separately, resulting in difficulties when managing design changes. Each change made to any drawing requires manual updates to the related model and other associated drawings to maintain consistency throughout the design process. This highlights one aspect of the potential of BIM, wherein an accurate model is created and all the other drawings are represented as views within the model and can be automatically extracted from the model at any time. Eventually, any change in any view will be reflected in other views without the need for manual update to the related parts when a part is modified. Additionally, BIM allows various types of information to be embedded into the model, such as object attributes, quantities and costs, time schedules, and structural and environmental performance-related information. This information can be extracted from the model as needed (Haidar, 2019). In short, Hozler (2015, p.67) defines BIM as "the concept of relating data to geometrical objects that form a digital representation of building component assemblies".

BIM and Parametric Objects.

The main feature of BIM is the way the different elements are represented. In CAD, the building form is simulated through generic geometrical elements, while in BIM, the elements are represented as objects that emulate the shape and behaviour of real objects, such as, walls, doors and windows, columns, and slabs. These objects are parametrically associated with information that defines the attributes and properties of each object (structural material, acoustic data, energy, etc.) and the way the different objects are interrelated. Therefore, they are referred to as parametric objects. According to Sacks et al., (2018), BIM parametric objects consist of geometric definitions, associated data and parametric rules, which automatically modify associated objects when a new object is added, or an existing object is modified.

Benefits of BIM.

Apart from the design-related benefits of BIM that arise from the ensured consistency provided by parametric objects, BIM allows automated and real-time flow of information across different disciplines and stages throughout the project's lifecyle (Haidar, 2019). This demonstrates the potential of BIM in enhancing efficiency and effectiveness in project management, which relies on collaboration, communication and information exchange across the different project stages. Rather than sharing information as documents and drawings, the models themselves can be shared and exchanged among project participants. BIM offers well-structured, organised and easily accessible information that can be obtained directly from models at any time. This contributes to well-informed and mature decision-making throughout the project lifecycle.

EVALUATION AND PARADIGM SHIFTS

Having reviewed the evolution of different modelling methods, this section evaluates those methods in terms of model generation and modification, model entity and function. In addition, the paradigm shifts associated with each modelling method are explained (Figure 2).

Model Generation and Modification

In CAD, the model is developed in an 'additive manner' by manually adding each element individually with the ability to copy identical parts. Limited modifiability exists in CAD to respond to design changes. Such changes are typically addressed by modifying existing elements or by removing and subsequently re-modeling the parts that require alteration.

When using algorithmic modelling, an algorithm is developed to generate the building form or part of it. The algorithm normally contains rules that constitute how the form will be generated and how the model elements will behave. Modifying the model involves amending and re-running the algorithm, where simple changes to the algorithm might result in a significant change in the building form. The same principle applies to parametric modelling, however, the ability to associate and interrelate parameters gives greater modifiability, where radical changes to the model can be accomplished simply by manipulating the value of certain parameters in the graph. Therefore, modelling algorithmically or parametrically represents a paradigm shift in the model generation process from additive (CAD) to algorithmic, rule-based and associative.

Similarly, there is a paradigm shift in the way models are modified, shifting from direct modifications to indirect modifications mediated by algorithms. This means that elements within the model can be modified and controlled by amending the algorithm. In the case of parametric design, this paradigm shift is even more significant. In addition to the ability to modify the algorithm itself, an additional layer of automation is achieved through the automatic adjustment of dependent parameters when independent parameters are changed.

The generation process of a BIM is similar to CAD in the sense that each object is manually created. However, using objects instead of generic geometries comes with a different mindset while creating a model. The difference mainly stems from the interconnectivity of the different views, and the ability to control a model from any of those views.

In terms of modifiability, the aforementioned paradigm shift in parametric modelling applies to a certain degree in BIM where objects are also associated parametrically and can update itself based on modifications to other objects. The focus on BIM is more about associating geometric to non-geometric parameters where object attributes such as quantity of material or cost can change automatically when the related object form or size changes.

Model Entity and Content

A 3D CAD model consists of homogeneous geometrical elements, such as solids and surfaces, which are used to simulate the building form, with the ability to use a combination of different elements to give shape to complex forms. The content of CAD models is limited to those geometries with minimal ability to store non-geometric information.

Performative models, similar to CAD models, include building geometries, albeit with less detail, along with additional information required for simulations. For instance, when energy simulation is needed to estimate the annual amount of energy consumption, information such as the location of the building and the local climate can be embedded into the model.

When algorithmic or parametric modelling is utilised, geometrical elements can be generated and then presented in the host CAD or BIM application. Typically, this geometry is more complex than that created in traditional CAD applications. This is due to the ability of algorithmic and parametric modelling to create and manipulate differentiated components. When graph-based parametric modelling is used, a parametric graph is developed alongside the model in the host CAD application. The graph represents a record of the history of the model that allows changing any step and getting the final result updated in the host application. In other words, using the graph in parametric modelling allows designer to visualize/illustrate the modelling process which represents a paradigm shift in the model entity when compared to CAD, where only the final result of the modelling is shown and the steps cannot be retrieved.

Using parametric modelling also results in a paradigm shift in the relationship between elements within the model from independent to associative. In CAD, each element exists separately without any connection to others, whereas parametric modelling allows for associations between different elements, enabling automated changes throughout the entire model when a part is modified.

In BIM, the model consists of heterogenous parametric objects. Each object is characterised by a distinct behaviour corresponding to its type. These objects represent the virtual versions of the real objects in terms of form, material and behaviour. Therefore, using transitioning from CAD to BIM represents a paradigm shift in model entity from generic geometry-based models to object-based models.

Using BIM can also result in a paradigm shift in the content of the model from a geometric to an information and data-rich model. CAD models host the building geometry with a very limited amount of information, while in BIM, the objects are associated with different types of information that describe each object, its attributes, properties and its relation to other objects. In such a situation, BIMs can act as information containers that host highly structured and easily accessible information that is necessary to streamline the design and construction processes.

Model Function

While the function of CAD models is to represent the building form and show the aesthetic value of the building in advance of construction, performative models simulate the building performance. i.e., designers can conduct analyses to predict the building's environmental and structural performance and behaviour. This process gives significant value as it enables designers to take mature decisions early in the design process. Therefore, using performative modelling signifies a paradigm shift in the model function from simulating the building form to simulating the building performance.

Algorithmic modelling is usually used to tackle buildings with complex or irregular shapes that are challenging to achieve through traditional CAD modelling. Additionally, algorithmic modelling enables the rationalization of forms by manipulating the underlying algorithm. Similarly, parametric modelling is used to generate, manipulate and rationalise complex forms by developing algorithms that contain associated parameters. This approach enables the automated generation and evaluation of a wide range of design alternatives towards the optimisation of the design solutions. Notably, parametric modelling can also act as performative modelling, as performative criteria can also be represented as parameters within the parametric modelling environment.

A BIM is developed to help architects and other project participants to share and exchange data, information and knowledge within collaborative working environments. BIM offers the ability to keep consistency among the different parts of the model and to embed information into the model that can be shared and obtained seamlessly at any time throughout the project lifecycle. This represents a paradigm shift in model function from form representation to a solid project information management tool that is used to facilitate collaboration, integration and design coordination among different project stakeholders.

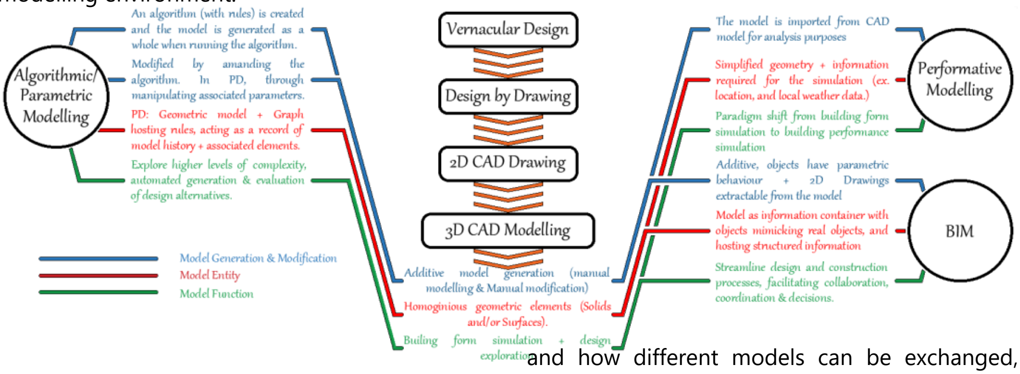

Figure 2: Categorisation and evaluation of digital models + paradigm shifts

CONCLUSION

In this paper, the evolution of modelling was reviewed, starting from vernacular design to paper-based and CAD drawing and 3D CAD modelling. The emergence of digital models was discussed and the different modelling methods were evaluated based on different criteria, while identifying the paradigm shifts associated with each modelling method. A critical understanding of those modelling methods and the paradigm shift that each method entails would be the first step towards unlocking the potential of this diversity of modelling methods towards more effective and efficient project workflows.

Further research might focus on how those different modelling methods can be interrelated, and how different models can be exchanged, combined and federated while exploring and evaluating other types of modelling such as VR-based modelling and digital twins.

REFERENCES

Aish, R., & Hanna, S. (2017). Comparative evaluation of parametric design systems for teaching design computation. Design Studies, 52, 144-172.

Anton, I., & Tănase, D. (2016). Informed geometries. Parametric modelling and energy analysis in early stages of design. Energy Procedia, 85, 9-16.

Barrios, C. (2005). Transformations on parametric design models. In Computer Aided

Architectural Design Futures 2005 (pp. 393-400): Springer.
Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. Design Studies, 52, 115-143.
Cuff, D. (1992). Architecture: The story of practice: Mit Press.
Haidar, A. (2019). Rethinking Innovation in Computational Design: A Theoretical Framework for Innovative Strategies to Enhance the Efficiency of the 'Digital' in Architectural Design. University of Salford.
Haidar, A., Underwood, J., & Coates, P. (2019). Smart processes for smart buildings: 'sustainable processes', 'recyclable processes' and 'building seeds' in parametric design. Architectural Engineering and Design Management, 1-28.
Harding, J. E., & Shepherd, P. (2017). Meta-parametric design. Design Studies, 52, 73-95.
Holzer, D. (2015). BIM and Parametric Design in Academia and Practice: The Changing Context of Knowledge Acquisition and Application in the Digital Age. International Journal of Architectural Computing, 13(1), 65-82.
Hudson, R. (2010). Strategies for Parametric Design in Architecture: An application of practice led research. (PhD). University of Bath, Retrieved from http://opus.bath.ac.uk/20947/
Jabi, W., Soe, S., Theobald, P., Aish, R., & Lannon, S. (2017). Enhancing parametric design through non-manifold topology. Design Studies, 52, 96-114.
Jones, J. C. (1992). Design methods: John Wiley & Sons.
Kolarevic, B. (2004). Architecture in the digital age: design and manufacturing: Taylor & Francis.
Lawson. (2006). How designers think: the design process demystified: Routledge.
Liu, H. (2010). Generative 3d images in a visual evolutionary computing system. Computer Science and Information Systems, 7(1), 111-126.
Mueller, V. (2011). Distributed Perspectives for Intelligent Conceptual Design. In T. Kocaturk & B. Medjdoub (Eds.), Distributed Intelligence in Design (pp. 16-26). Chichester, West Sussex: Wiley-Blackwell.
Oxman, R. (2006). Theory and design in the first digital age. Design Studies, 27(3), 229-265.
Oxman, R. (2017). Thinking difference: Theories and models of parametric design thinking. Design Studies, 52, 4-39.
Penttilä, H. (2006). Describing the changes in architectural information technology to understand design complexity and free-form architectural expression. In: ITcon.
Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). BIM handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers: John Wiley & Sons.
Turrin, M., von Buelow, P., & Stouffs, R. (2011). Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. Advanced Engineering Informatics, 25(4), 656-675.
Veliz, A., Kocaturk, T., Medjdoub, B., & Balbo, R. (2012). Dialogs between Physical and Digital Modelling Methods on Architectural Design.
Whitehead, H., de Kestelier, X., Gallou, I., & Kocatürk, T. (2011). Interview with the Specialist Modelling Group (SMG)-The Dynamic Coordination of Distributed Intelligence at Foster and Partners. In T. Kocaturk & B. Medjdoub (Eds.), Distributed Intelligence In Design. Chichester, West Sussex: Wiley-Blackwell.
Wortmann, T., & Tunçer, B. (2017). Differentiating parametric design: Digital workflows in contemporary architecture and construction. Design Studies, 52, 173-197.