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Selecting Design Process Modelling Approaches for Building Design: A Review

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Abstract

Design process modelling is well-founded in fields of mechanical engineering, and product design and development but not in Building Design (BD). This paper looks at the selection process when choosing appropriate models for specific BD processes. The paper adapts process model selection criteria from Trauer's work and combines it with anecdotal evidence from the authors to select these models. The selection criteria were ranked, categorised, and applied to BD processes explained. Process models related to each selection criteria were then selected from backward snowballing of literature.

Keywords: process modelling, design research, criteria, architectural design, building design

1. Introduction

Design process modelling is well-founded in the fields of mechanical engineering and product design and development. The selection of a model to use in a specific context is difficult because there are a plethora of design process models used for various purposes. Choosing an appropriate process model to document and analyse processes in a different field like Building Design (BD) is even more challenging. This is because the multidisciplinary nature of BD processes involves stakeholders (i.e. clients, architects, engineers, contractors/ builders) communicating and making decisions across organisations where the traditional design approaches do not allow for proper integration of such disciplines.

Furthermore, design process methodologies are not widely deployed in the study of design processes (and consequently engineering productivity) in the AEC industry despite being applied to other fields of engineering (Wong et al., 2021). Comparing design process models across disciplines, Gericke and Blessing, (2012) showed the process models used in BD, albeit few, have overlapping and similar design stages to other disciplines. This reflects the possibility of applying process models from other disciplines to BD. Tzortzopoulos et al., (2005) further identified the need and benefits of adopting process models in construction companies, reemphasising the importance of design process model selection for the AEC industry.

As such, this paper looks at the selection process and considerations when choosing a process model to document, analyse, and improve BD processes. We are interested in modelling the BD processes in the Architecture, Engineering and Construction (AEC) industry, in particular the workflows of structural design engineers and the stakeholders involved in obtaining the approved-for-construction design and drawings, as a requirement to start construction.

This is the Descriptive Study I stage of a PhD project exploring engineering design productivity in the AEC industry using the DRM methodology. The PhD research was motivated by the first author's industry experience and observations of the complex BD process and hence the model will be a researcher tool to help visualise iteration, to make suggestions to improve the current processes. For this reason, we are specifically looking at analytical models that can provide situation-specific insight, improvement, and/or support (Wynn and Clarkson, 2018). At the end of the PhD study, the model could potentially be a tool for the industry to self-assess iteration in processes affecting engineering productivity.

This paper discusses the processes in identifying which design process models are most suitable to apply to model the iterative nature of workflow of structural engineers to accommodate design changes requested by the approving bodies at the final stages prior to construction. These iterations are more complex as the approval process involves multiple organisations agreeing to a final, unique, and one-off design. The paper adapts process model selection criteria recommended by Trauer *et al.*, (2021) and combines these with the experience of the first two authors as practising engineers in the AEC industry. The study first ranks the 5 most important criteria chosen to select process models that can be used to effectively document the characteristics of the BD process. These 5 criteria were further categorised into the two characteristics of process models they impact: modelling system and representation system.

In Section 2 we discuss the objectives of modelling the BD process and describe the problem the process model aims to capture. Our methodology is summarised in Section 3. Considerations behind the choosing and ranking selection criteria in the BD context are presented in Section 4. A discussion of preliminary findings can be found in Section 5. The paper concludes with a discussion and future work in Section 6.

2. Objectives and Context

2.1. Objectives

The objective for modelling the BD process is to understand and analyse a phenomenon in Singapore's BD process that creates substantial iteration and rework due to change requests at the critical and final stages of the detailed design process. Due to the nature of the checks (refer to Section 2.3) and the cost of rework under strict time pressure, the final approved designs are, by experience, overdesigned with respect to structural safety. This means that the structural elements require more material than needed, which is not only costly but also results in a large environmental footprint. We assume that a suitable analytical model will provide the insights that are necessary to improve the BD process.

2.2. Authority Approvals in Singapore

In Singapore's construction industry, as in most if not all countries, building plan submissions are mandatory and come with certain unique regulatory requirements and processes. The iterative nature of this approval process impacts the BD process in several different ways. Understanding this approval process is therefore crucial for improving the BD process.

Approvals are granted by the Building and Construction Authority (BCA), the main regulatory body for the construction sector in Singapore. First, the **building plan** has to be submitted. Building plans are architectural plan drawings that show locations and overall dimensions of structural elements (beams, columns, walls, slab etc), overall building layout without the structural details. The building plan is equivalent to the embodiment design drawings used in mechanical engineering (Pahl and Beitz, 1994). Figure 1 summarises this building plan submission and approval process and the stakeholders involved.

Once the building plan has been approved, **structural plans** have to be submitted and approved before construction can start (see Section 2.3 for details). Structural plans refer to structural plan drawings with details of structural elements like exact dimensions, steel reinforcements and detailing, material properties- steel and concrete grades etc. The structural plans are equivalent to the detailed design drawings used in mechanical engineering as defined for mechanical engineering by Pahl and Beitz, (1994). The documents to be submitted together with the structural plans are the building plans and related planning permission, application forms, design calculation reports, plan fee computation, and buildability score calculation (BCA, 2021).

Singapore regulations BCA, (2021a) stipulate that "before starting on building works, the relevant plans […] need to be submitted to BCA for approval through a **Qualified Person** (QP)". To qualify, the QP has to be "a registered Architect with the Board of Architects (BOA) or a Professional Engineer with the Professional Engineers Board (PEB) and have a valid practising certificate issued by the BOA or PEB". The QP required for the different types of building works is listed in the so-called Third Schedule of the Building Control Regulations. For example, "building plans for a warehouse or factory may be submitted by an Architect or a Professional Engineer but plans for a retaining wall must be submitted by a Professional Engineer." The consequence is that different parts of a design may require different QPs to be involved.

Apart from the building and structural plans, other plans have to be submitted to and approved by a variety of authorities before construction can start, such as plans for greenery surrounding the building, road diversion works, etc.

Our interest is the structural plan preparation, submission, and approval process, as this is where the many iterations take place.

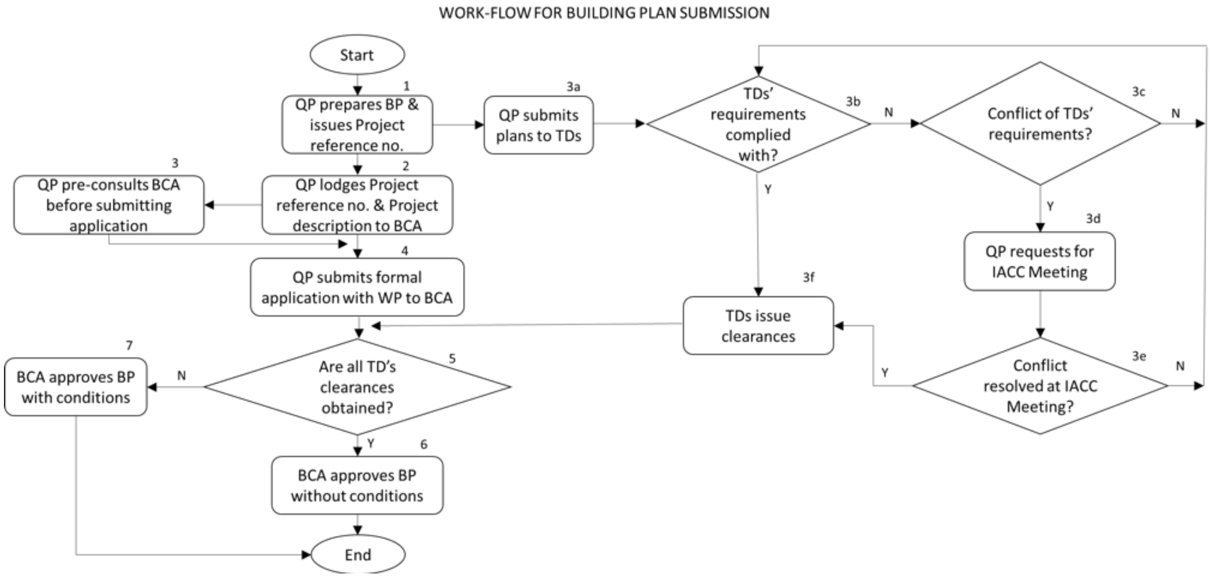

Figure 1. Building Plan Submission Process (BCA, 2021a) (BP = Building Plan, QP = Qualified Person, TD= Technical Department, WP= Written Permission, IACC= Inter- Agency Coordinating Committee)

2.3. The Structural Plans Approval Process

The structural plan submission process, done by the QP, involves two gatekeepers: BCA and the so-called **Accredited Checker (AC)** who is appointed by the client. The unique AC is a third-party independent checker (organisation), who checks and approves the structural plans and calculations performed by the QP, in this case, a certified structural engineer.

The process to obtain approval for the structural plans and related documents are illustrated in Figure 2. The Architect issues the finalised architectural drawings (red arrows in Figure 2) to the Appointed QP and AC to prepare for submission.

The QP tends to be on board first. They will create the structural plans and related documents (blue arrows in Figure 2). Once the AC joins, he/she will prepare their own set of structural plans, albeit in lesser detail, to form their own opinion about the structural form and integrity of the architectural drawings. That is, the QP and AC perform structural design using the architectural drawings independently from each other. Only then, does the AC checks the structural plans of the QP.

The designs of QP and AC need to be in agreement. For example, if there is a discrepancy in the amount of steel reinforcement required in a structural element, both the QP and the AC will need to justify their design and agree to the final value. The structural plan has to also be in agreement with the architectural drawings: any deviation of structural element sizing and material from architectural drawings issued by

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the architects requires approval from the architect. Moreover, the structural plan has to be in agreement with the already approved building plan. If this is not possible, the building plan has to be revised and resubmitted following the process outlined in Figure 1.

In this submission preparation process, each stakeholder bases their decisions on their own considerations as they represent different people: the Architect normally represents the Client, the QP the building contractors (depending on the nature of the contract). When all three, the architect, QP and AC (and their clients) agree on a final design, the QP and AC endorse the structural plan drawings and related documents that are then submitted by the QP to BCA through the CORENET e-submission system and vetted by a submission officer.

The submitted documents (orange arrow in Figure 2) undergo various checks and usually result in Written Direction requests to the QP and AC. This leads to extensive correspondence between Architect, QP and AC to answer the request, make the necessary changes to the design and update the drawings, calculations and other documents, before resubmitting. This cycle is repeated for each Written Direction request following a submission, resulting in a very iterative process at the end of the BD process, which is likely to delay the start of construction. Once BCA is satisfied, the structural plan is approved for construction.

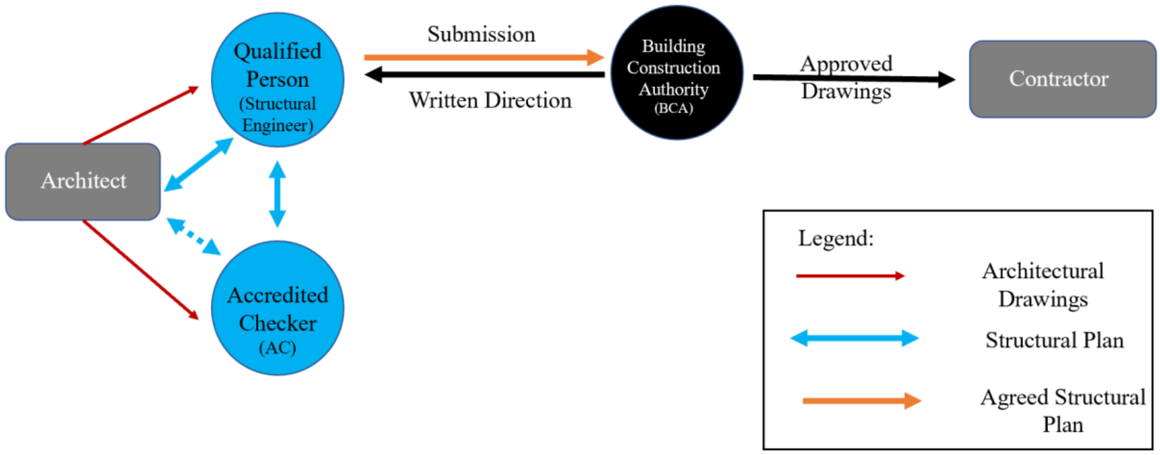

Figure 2. Simplified process of structural design work required for structural plans approval

3. Methodology

The study adapts the criteria for selecting modelling approaches by Trauer *et al.*, (2021) to the specific BD process. Based on the experience and understanding of the entire process of the first author, the knowledge of the process, stakeholders, documents, decisions, and redesigns involved forms the anecdotal evidence and objectives of the process modelling (See Section 2.1). With this anecdotal evidence, the 5 criteria that were considered the most important for our context and objectives were chosen and ranked (Refer to Table 1 for ranking). Section 4 describes how the criteria are relevant to the modelling of the BD process in more detail.

Backward snowballing of literature mentioned in Table 1 of Trauer *et al.*, (2021)work for each of these 5 criteria, led to the articles describing the various design process models fulfilling those criteria. From these articles, a total of 59 unique process models and their corresponding literature were collected. We then selected those design models that seem to meet our process modelling objectives as described in Section 2.1. The final set of 12 models is listed in Table 1. In this table, the models are linked to one criterion each, based on Trauer's work. To find the most appropriate model(s) for our objectives, we analysed which models fulfilled most of the criteria (Table 3) and contributed most to our objectives. The preliminary results can be found in Section 5.

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Table 1. Process models final selection

Criteria (XX) = number of models fulfilling this criterion	Design process model
1. Coverage (23)	DEPNET (Ouertani and Gzara, 2008)
	Design History System (Shah *et al.*, 1996)
	IPPOP (Robin *et al.*, 2007)
2. Verification/ Validation (34)	DSM Work Transformation Matrix (Smith and Eppinger, 1997)
	DSM Monte Carlo Simulation Matrix (Browning and Eppinger, 2002)
	DSM Causal Network Modelling (Browning, 1998)
	Rework Cycle Model (Cooper, 1980)
3. Connectivity (1)	Task and Decision Network Model (Eckert, 2006)
4. Effort (34)	Design Structures Matrix (DSM) (Eppinger *et al.*, 1994)
	Work Transformation Matrix (Smith and Eppinger, 1997)
	Monte Carlo Simulation Matrix (Browning and Eppinger, 2002)
	Causal Network Modelling (Browning, 1998)
5. Viscosity (0)	NIL

A separate literature review of design process models specific to the AEC industry (and construction management) resulted in few such models (see Table 2). These too underwent the same analysis as the above models (see Section 5). For example, Austin *et al.*, (2000) adapted the Design Structures Matrix (DSM) into a design support tool ADepT to apply to the building design process. His paper builds the groundwork for studying design process models for building design. Other process models were also applied in the AEC industry however specifically modelling the construction stages as opposed to design stages. For example, PRECISE modelling language paved the way for automatic support for construction process management (Marengo et al., 2016).

Table 2. Process models in the AEC industry

IDEF0 (Laitinen, 1998)
PRECISE (Marengo et al., 2016)
ADepT (Austin et al., 2000)
Integral Design Model (Quanjel, 2013)
Extended Methodological Design Model (Zeiler, 1993)
Organisation Matrix (Hughes, 2001)

Table 3. Selected building design process model from literature based on criteria, numbers ranked according to importance and criteria from (Trauer *et al.*, 2021)

Process model	Modelling system				Representation system
	Coverage	Connectivity	Effort	Viscosity	Verification/ Validation
DEPNET	X				
Design History System	X				
IPPOP	X				
DSM			X		
DSM-Work Transformation Matrix			X		X
DSM- Causal Network Model			X		X
Rework Cycle Model					X
DSM-Monte Carlo Simulation			X		X
Task and Decision Network Model		X			

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4. Selection Criteria for Process Models for Building Design

Adopting (Kaschek *et al.*, 2006) model classification, we grouped the selection criteria into modelling and representation system. The reasons why the selection criteria were chosen, backed by anecdotal evidence are explained correspondingly.

4.1. Modelling System

The modelling system includes suggested modelling notions, abstraction concepts, patterns, and anti-patterns (Kaschek *et al.*, 2006). As the multidisciplinary nature of the building design process is broadly similar to product development and other engineering design processes, there is great value in applying process modelling to study and analyse it. However, the modelling system for the chosen models should have characteristics that are suited to model such situations and the more significant factors are elaborated in this section.

4.1.1. Coverage

"A measure of which different elements (artefacts, stakeholder, tasks, steps, etc) can be included by the method" (Trauer *et al.*, 2021)
This is the most important selection criteria due to the nature of the building design process that is to be modelled. The building process as described in detail in section 1.1 involved many stakeholders and information exchange. Depending on the size of the construction project, the number of designers involved in a single submission process can range from 5-20 people; construction projects would require 50-1000 submissions typically. Given the scale and size of this design process, coverage is hence the most important selection criteria, a process model should be wide enough to model the stakeholders, processes and tasks involved.

4.1.2. Connectivity

"A measure of how easily additional internal elements can be connected" (Trauer *et al.*, 2021)
The nature of building design processes involves many different teams and stakeholders where information and decision making interconnected. This interconnectivity and information dependencies should be modelled as it has a high potential to be streamlined to minimise redundancies or decoupled.

4.1.3. Effort

"A measure of the money or time a user has to invest to use the tool" (Trauer *et al.*, 2021)
As there are many variations on how the building design process is for different project teams, the tool will be used by different users/ multiple times. The amount and type of data that can be collected to map the design process are also reflected by the effort of the modelling tool. In the case of building design processes, data can be in the form of structural drawings and their versions, time spent by design engineers, number of email correspondences etc. Data collection will form an important consideration for the effort of the user. It should also be considered that the data collected for the model must be coherent and obtainable from all the stakeholders.

4.1.4. Viscosity

"A measure of how much effort is required to perform a single change" (Trauer *et al.*, 2021)
As the building design process varies between different stakeholders and project teams (ie project team structure, technologies used), process models would undergo many tweaks to capture these differences/ changes. Furthermore, the disruption and checks by the authorities at different stages of the building design process would require a viscous process model. The industry is undergoing digital transformation, and different degrees and level of digitalisation occurs at different stages of the design process and different between companies (Ernstsen, 2020). It is important to be able to capture these differences for future analysis.

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4.2. Representation System

The representation system considers the suggested notation for representing process models (Kaschek *et al.*, 2006). In the case of BD process modelling, we refer to the output/ outcome of the design process model.

Verification/ Validation

"A measure of how transparent and ambiguous a method/ tool in representing a certain process" (Trauer *et al.*, 2021)

As the objective of the process model is to reflect the rework and iteration cycle building designers undergo, this has to be verified and validated. A chosen design model and its output should be in a format where it can reflect/do not hide the given trait whilst with a good modelling system. It should be noted that many process models reflect iteration in diagrams with arrows back and forth, but that is not the purpose of our modelling. It has to be coupled with a robust modelling system for further analysis.

5. Preliminary Findings

Initial assessment of the shortlisted process models in Table 1 suggested that Design Structures Matrix (DSM) and its variations would be a very appropriate tool (See Table 3). However, applying some preliminary data RIBA (Royal Institute of British Architects) Plan of Work (Architects, 2013) detailed design stages plus two additional submission stages into DSM, it does not reflect the iteration/ rework cycle effectively (Figure 3). The representation system could potentially be easy to understand by stakeholders, but the modelling system does not have the ample coverage to reflect the modelling objective. ADePT is a design support tool for DSM applications in construction management, but involves very high modelling effort, requires a detailed DSM as input, as well as an information dependency table with programming for analysis. For these reasons, it was not considered appropriate for our objectives.

Detailed Design	1. Organize design team	2. Complete user studies	3. Review cost plan	4. Submit planning application	5. Detail design from architect	6. Engineering detail design	7. Services detail design	8. Cost studies and cost checks	9. Review and confirm completed design	10. Design check by AC	11. Submission to BCA
1. Organize design team											
2. Complete user studies	X										
3. Review cost plan		X									
4. Submit planning application					X						
5. Detail design from architect											
6. Engineering detail design					X						
7. Services detail design					X	X					
8. Cost studies and cost checks					X	X	X				
9. Review and confirm completed design					X	X	X			X	
10. Design check by AC									X		
11. Submission to BCA									X	X	

Figure 3. DSM modelled with adapted riba plan of work

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Other variations of DSM, such as the Work transformation matrix, Monte Carlo Simulation Matrix and Causal Network Modelling, however, do provide more analysis options, while effectively achieving the modelling aim. These were therefore chosen as the most suitable process models for our objectives.
The Rework cycle model by (Cooper, 1980) was also chosen. Although its representation system and application require further work, it is a very useful conceptual model and has a strong modelling system to achieve our objectives.
As to the process models developed for the AEC industry, they are very useful contributions for this industry, but did not fulfil most of our criteria or met our objectives. The IDEF0 is applied in construction phase and not in design, it focuses on information exchange and require high effort. Although it shows iterations, the representation system has low resolution, i.e. processes have to be analysed at the individual designer level to be able to reflect the repetition. Similarly, poor resolution also means representation in maps and flow charts is not ideal. PRECISE is a high effort modelling language which requires specific inputs. for each individual activity/task, such as location, duration, number of workers, sector, unit, section. Every activity and task will also require precedence input. The output is in the form of a Gannt chart form that does not represent clearly represent our modelling objectives. The Organisational Matrix has good coverage and low effort but does not achieve our modelling objective. The models of Savanovic, Quanjel and Zeiler are based on design research and applied to construction. They fulfil the selection criteria but seem to contribute less to our objectives than the chosen models.
The design process model which we intend to test will be an integration of the DSM variations Work transformation matrix, Monte Carlo Simulation Matrix and Causal Network Modelling, and the Organisational Matrix.

6. Conclusion

The selection criteria given in (Trauer *et al.*, 2021) is a useful starting point to select process models not only in product development but also in building design. The selection criteria and their corresponding literature was helpful to shortlist process models and to analyse the process models available building design. However, it was observed that there is a trade-off between the criteria of coverage, effort, and validation of the rework/ iteration cycle (See Table 3) and the reasons can be further explored.
Further work to investigate the feasibility and suitability to integrate the selected DSM models and the Organisational Matrix will not only contribute to the effective study of building design processes but also form the intersection between the fields of design research and construction management. A detailed study of the characteristics of design iteration in different fields and the corresponding design process models used could also further this work.

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