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A FRAMEWORK FOR CONSIDERING THE USE OF COMPUTATIONAL DESIGN TECHNOLOGIES IN THE BUILT ENVIRONMENT DESIGN PROCESS

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SUMMARY: *This research proposes a Computation in Design (C-in-D) framework for design practices to consider the adoption of computational technologies in their design process. Examples of computational design technologies include but are not limited to computational algorithms, the Internet of Things (IoT), reality capture and digital fabrications. We develop the framework by categorizing design projects based on their physical scales, defining the work stages in a design project, and decomposing the design process into tasks and data flows. The computational design technologies can then be assessed by mapping its usage onto these data flows. The framework provides a basic structure for practices to customize and systematically assess the impacts of using computational design technologies in their design process. We demonstrate the C-in-D framework in three case studies, a sculpture design, an interior retrofit, and a form-based code development. The demonstration shows that web-based interactive parametric modeling and reality capture technologies can improve collaboration between the artist and modeler in the sculpture design project. IoT and optimization algorithms can improve the daylighting performance of the interior retrofit, and the use of Geographic Information System and reality capture technology can improve site analysis and visioning of the form-based code development process. The framework is a valuable tool for facilitating the adoption of new design technologies in practice.*

KEYWORDS: *design computing; digital design technologies, workflows; GIS; BIM*

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1. INTRODUCTION

The potential use case of a computational design technology is not well-defined and highly dependent on its users. For example, a 3D modeling software can be used to produce photo-realistic renderings for presentation or for modeling 3D forms in an early parametric design exploration. The same technology can be used for different purposes depending on the design project and the user. It is not a straightforward task for design practices to fully understand and leverage the potential of computational technologies in their design process. Furthermore, the cost of the technology and the resources required for applying them in projects such as training personnel can be expensive. Without a good understanding, it is difficult for design practices to decide which design technology to invest and adopt.

To address this issue, we introduced a holistic framework, called the Computation in Design (C-in-D) framework that allows design practices to assess the use of different technologies for different type of design projects. The framework classifies design projects according to their physical scale, breaks down a design project into different work stages, and the design process into manageable tasks and define the data flows between the tasks and stages. Practices can then use these data flows to map the usage of computational technologies onto the design process. In this research, the terms design practice, project and process is defined as in (Lawson & Dorst, 2009). A design practice is a company of designers that can include architects, engineers and planners. Clients hire them to work on design projects. Based on the expertise of the practice, the projects can range from building designs to master planning. Design practices usually develop their own design processes, consisting of the methods employed when a practice approaches a design project.

The framework provides a customizable basic structure for design practices to assess potential technologies for usage in their design process. Key questions such as those listed below could be answered and provide a better understanding of adopting an individual or a suite of technologies.

- What design projects and tasks will benefit from using these technologies? Benefits include reducing time and effort for performing the task and improving the quality of the result.
- What are the potential synergies with other computational technologies?

Due to the differences in design process when working on a project, the answers to these questions will differ for each practice even when adopting the same technologies. Therefore, the framework will allow practices to systematically assess technologies of interest in relation to their design process.

The following section describes the development of the C-in-D framework based on a review of existing studies. Then, we illustrate the framework's usage followed by demonstrating its application with three case studies considering multiple computational design technologies. Lastly, we conclude the case study and discuss further investigations.

2. METHOD: PROPOSED COMPUTATION IN DESIGN (C-IN-D) FRAMEWORK

We have reviewed existing studies that have aimed to facilitate the adoption of computational design technologies in the design process and separated them into two categories. Studies in the first category provide an in-depth description of adopting technologies for benefitting only specific tasks. These studies include acquiring high-resolution geometry data of existing site conditions with 3D LiDAR scanning (Shih et al., 2019, 2020), automatic generation and evaluation of a large number of design options using simulations and algorithms (Haymaker J et al., 2018; Lin & Gerber, 2014; Lorenz et al., 2020), improving design constructions with digital fabrication methods (Melenbrink et al., 2020; Wagner et al., 2020) and better understanding of built designs with data analytics (Fan et al., 2021; V E et al., 2021). They do not provide an overview of the benefits to a design project and a design practice.

Studies in the second category takes a broader view by accounting for the different work stages in a project. These studies decompose the design process into tasks according to the different deliverables required for each stage and identify the tasks that can benefit from using computational technologies. They include the use of Geography Information System and Building Information Modeling in building lifecycle management (Bansal V. K., 2021) and building performance simulation in various stages of a building design (Michael Pelken et al., 2013). By putting the technologies in context of the project, it makes clear to a practice when and how to use the technologies in their design process.

Studies in both categories are limited in scope as they do not account for differences in project types and the many available computational design technologies. They focused on guiding practices to structure their design processes when adopting a specific set of computational technologies for application in either specific design tasks or design stages of a particular type of design project.

Improving upon these studies, we developed the C-in-D framework based on a review of existing studies on the design process and plan of works of various professional design institutions. From the review, we structured the framework to classify design projects into physical scales and divided them into work stages. In each stage, the design process was decomposed into tasks. We listed the main data types that are exchanged between these tasks and the work stages. The framework allows practices to map the technology of interest onto a project's design process. We demonstrated the effectiveness of the framework through applying it on three documented case studies of different project type. The details of the review and the case studies are described in the following sections.

2.1 Type of design projects

We organized the various design projects into seven built environment components as defined in (Mcclure & Bartuska, 2007): Products, Interiors, Structures, Landscapes, Cities, Regions and Earth. Table 1 shows the descriptions and the various design professions associated with each component. The categorization provides a guide for design practices to have a holistic view of their project by situating it within the broader context of the built environment. For example, when a practice is working on a building design project (structure component), they must be aware of the building site (landscape/urban design component) and the interior of the building (interior component). The content of the building is its interior, and the site is its context. There is a content (interior)-component (building)-context (site) relationship (Figure 1). The components and their relationship will help practices define the scope of the design problem. It will also inform them about the specifics of the related design tasks and the content of the data flows.

Table 1: Components of the built environment (Mcclure & Bartuska, 2007)

Component	Description	Professions
Products	Artefacts such as symbols, tools and machines, created to extend human capabilities.	Industrial Designers, Graphics Designers and Artists.
Interior	Interior spaces containing products while enclosed within a structure.	Interior Designers and Architects
Structure	Structures have an external form constructed of products. They usually enclose planned interior spaces.	Architects, Engineers and Construction Managers
Landscapes/ Urban Designs	Exterior areas of planned spaces and structures.	Landscape Architects, Urban Designers and Planners
Cities	Structures and landscapes clustered together to define a community for economic, social, cultural and environmental reasons.	Urban Designers, Planners and Managers
Regions	Cities and landscapes defined by common political, social, economic and environmental characteristics.	Regional Planners, Managers and Environment Scientists
Earth	Includes all of the above components.	Environment Scientists and Global Planners

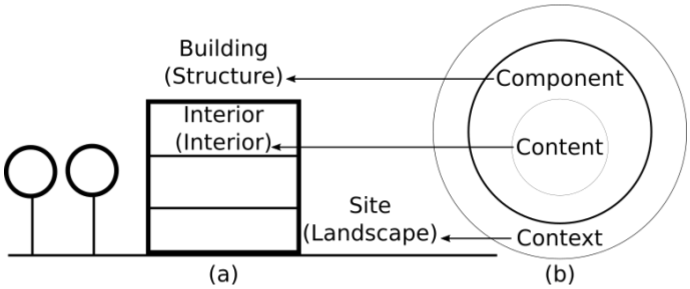


Figure 1: (a) the content-component-context hierarchy for a building design project (b) the content-component-context hierarchy relationship illustrated as a diagram

2.2 Work stages of a design project

We reviewed various existing studies and plan of works to categorize the project lifecycle of a typical built work into four distinct stages: pre-design, design, construction/manufacturing and operation. In the pre-design stage, designers with their client will conceptualize and refine the design brief. The brief describes the scope of work which consists of but not limited to the matters around project specifications, site selections and analysis. If the project proceeds into the design stage, multiple solutions are proposed, refined, and presented by the practice to the clients. A final design is chosen for implementation in the construction/manufacturing stage. The design practice will work with fabricators and builders to construct the design. Once completed, the practice will handover necessary documents to personnel who will manage the built project to ensure smooth operation and adhere to timely maintenance. In Table 2, we fit the various work stages from different studies into these four main stages.

Table 2: Four main design stages for built environment designs according to various research studies and design institutions.

	Pre-Design	Design	Construction/ Manufacturing	Operation
Design for X (DFX) (Becker & Wits, 2013; Chiu & Kremer, 2011)	Problem definition and customer needs analysis	Conceptual Design Preliminary Design/Embodiment Design Detail Design		
Integrated Project Delivery (AIA, 2007)	Conceptualization	Criteria Design Detailed Design Implementation Documents	Agency Coordination Construction	Closeout
RIBA Plan of Work (RIBA, 2020)	Strategic Definition Preparation and Briefing	Concept Design Spatial Coordination Technical Design	Manufacturing and Construction	Handover Use
Integrated Landscape Project Delivery (Andropogon, 2017)	Goal Setting Feasibility Studies	Schematic Design Design Development Construction Documentation	Mobilize Site Preparation Build	Handover Early-Stage Management Long-Term Management
Geodesign (Steinitz, 2012)	Scoping the Geodesign study Designing the study methodology	Carrying out the study		
Master-planning (Simister et al., 2018)	Strategic Framework	Spatial Masterplan Implementation Plan		

In the Design for X methods (Becker & Wits, 2013; Chiu & Kremer, 2011), primarily developed for product designs, stages do not cover the construction/manufacturing and operations stages. Instead, designers consider the mass manufacturing of the product in the detail design stage. In comparison, buildings and smaller-scale landscape design projects include all four main stages (AIA, 2007; Andropogon, 2017; RIBA, 2020). Localizing the designs to the specific site is often necessary for these projects. Construction and operations of the project are less likely to be overseen by designers as the project grows in scale (Simister et al., 2018; Steinitz, 2012). These are projects in the Landscapes, Cities, Regions and Earth components in Table 1. They can take many decades to realize. The design team will usually produce an implementation plan for guiding future developments. Future buildings and smaller landscape designs will then study and factor in the planned guidelines in their pre-design stage.

2.3 Design tasks and data flows of the design process

We broke down the design process into tasks. At each work stage, the design tasks executed will vary accordingly to produce the required deliverables. To guide practices in breaking down their design process, we organized design tasks into types based on various models of design. Table 3 illustrates the four models of design that we have reviewed. The Model of Design by (Lawson & Dorst, 2009) and the Design Thinking Model by the Stanford d.school (Lee, 2018) are models that describe the general act of designing, which can be considered for all domains. Next, the Geodesign framework (Steinitz, 2012) focuses on collaboration among several geographically-oriented sciences and design professions to influence large and complex built environment projects. Lastly, the Parametric Engineering Design Process Model (Schotborgh et al., 2012) describes the routine design process of product designs. These four models cover the various project types in our framework. They provide a good overview of the design processes in the built environment sector.

In the Model of Design by (Lawson & Dorst, 2009), design tasks are grouped into five main types: **Formulating, Moving, Representing, Evaluating and Managing**. **Formulating** tasks identify and frame the design problem. **Moving** tasks propose new solutions or modify previous solutions. **Representing** tasks externalize solutions through drawings and modeling. **Evaluating** tasks assess the solutions based on specific criteria. **Managing** tasks reflects on the design process and decide on the next step.

The Design Thinking Model by the Stanford d.school (Lee, 2018) is very similar to the Model of Design. The Design Thinking Model also separates tasks into five different types. The task types, namely **Ideate**, **Prototype** and **Test** correspond directly with **Moving**, **Representing** and **Evaluating** of the Model of Design. The two task types of **Empathize** and **Define** fall within the scope of the **Formulating** task type in the Model of Design. The Design Thinking Model encourages designers to take a people-centric approach to understand the needs of the users before defining the scope of the design project. Despite its similarities, it does not have a task type for reflecting on the design process.

The Geodesign framework (Steinitz, 2012) is developed for large scale landscape and urban planning projects that involve the complex negotiation of domain-specific knowledge. An understanding of the current state of the project site is of priority. It has six design task types. Three of the six types, **Representation**, **Process** and **Evaluation**, are dedicated to tasks that aim to model the existing state, and processes of the site and evaluate the site's current performances. These three task types will fall within the scope of **Formulating** in the Model of Design and the **Define** task type in the Design Thinking Model. Geodesign classifies the tasks of proposing and representing a design solution into a single task type called **Change**. However, there is still an advantage in differentiating the tasks into two types, **Moving** and **Representing** in the Model of Design and, **Ideate** and **Prototype** in the Design Thinking Model, to capture the conversation between the solution visualization and the thinking process of the designers. The task types of **Impact** and **Decision** correspond directly with the **Evaluating** and **Managing** task types in the Model of Design.

The Parametric Engineering Design Model has four design task types: **Synthesis**, **Modification**, **Analysis** and **Evaluation** (Schotborgh et al., 2012). Design tasks that involve proposing new solutions are categorized as **Synthesis** tasks and improvement to previous solutions are categorized as **Modification** tasks. **Analysis** tasks assess the performance of the solutions and **Evaluation** are decision-making tasks to decide if the solutions satisfy the project requirements. Like the Geodesign framework, it does not differentiate tasks that propose, modify and represent solutions. The model was developed to automate routine well-structured design problems. As a result, it does not consider defining and formulating the design problem as part of the design process.

Table 3 maps and illustrates the corresponding task types of each model. The Model of Design by Lawson and Dorst provides a balance and extensive coverage of the design process appropriate for the C-in-D framework. However, the model does not clearly define the data flows between these tasks. The Parametric Engineering Design Process Model has defined the data flows between the tasks. However, the data types in the built environment design process are usually more varied than the data types defined in the model developed for automating routine product design with parametric modeling.

From our review of the various studies in this section and our experience using computational design technologies, we listed the major data types exchanged during the design process. Table 4 shows the eight types of digital data and common formats associated with each data type. The high variability of data types and formats creates an interoperability issue between different design tasks and stages. Research has suggested using standards such as cityGML for city modeling and Industry Foundation Class (IFC) for building modeling to streamline the exchange of information in the design process (Biljecki et al., 2021; Gilbert et al., 2021). Another approach is to develop modular interfaces to facilitate data exchange between different design tasks (Augenbroe et al., 2004). However, interoperability is still an issue that remains to be fully resolved in the design and construction industry.

Table 3: Models of design process

Models of Design Process	Design Tasks				
Model of Design (Lawson & Dorst, 2009)	Formulating	Moving	Representing	Evaluating	Managing
Design Thinking (Lee, 2018)	Empathize	Ideate	Prototype	Test	
	Define				
Geodesign Model (Steinitz, 2012)	Representation	Change		Impact	Decision
	Process				
	Evaluation				
Parametric Engineering Design Process Model (Schotborgh et al., 2012)		Synthesis		Analysis	
		Modification		Evaluation	

Table 4: Input and output data of each design task

Tasks	Input-Output Data Type	Data Format
Formulating, Representing, Evaluating, Managing, Moving	Text	odt, docx, pdf …
	Table	csv, xls, database …
	Raster	jpg, png, geotiff …
	Vector	svg, pdf, dxf, shp …
	Point Cloud	e57, xyz, las, pts …
	3D Model	cityGML, ifc, obj, stl …
	Algorithm	py, java, js …
Evaluating, Managing	Simulation Model	idf, rad …

2.4 The basic C-in-D framework for considering computational design technology in built environment design projects

Table 5 shows the C-in-D framework summarizing the built environment design process based on six scales, four design stages, five design task types and eight data types. We dropped the earth component as it is unlikely that a practice gets a project to design on the global scale. The computational technologies considered is specified at the top right corner of the table. This is the basic C-in-D framework that can be readily customized for different practices and their projects. We demonstrate its usage in the next section.

Table 5: Basic C-in-D framework

<table>
<tr><th></th><th>Formulating</th><th>Moving</th><th>Representing</th><th>Evaluating</th><th>Managing</th><th colspan="8">Technologies X</th></tr>
<tr><td>Pre-Design</td><td></td><td></td><td></td><td></td><td></td><td rowspan="4">Text</td><td rowspan="4">Table</td><td rowspan="4">Raster</td><td rowspan="4">Vector</td><td rowspan="4">Point Cloud</td><td rowspan="4">3D Model</td><td rowspan="4">Algorithm</td><td rowspan="4">Simulation</td></tr>
<tr><td>Design</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Construction</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Operation</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="5">Scale: Product, Interior, Structure, Landscape, City, Region</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

2.5 Using the C-in-D framework

The C-in-D framework enables design practitioners to decompose their projects into data flows, which allows them to systematically map the inputs and outputs of design technologies onto the design process. Figure 2 illustrates an example workflow using Geographic Information System (GIS) to prepare vector files to model a site of interest in 3D. The data from the vector files and the 3D model are then used to simulate and analyze the design and site.

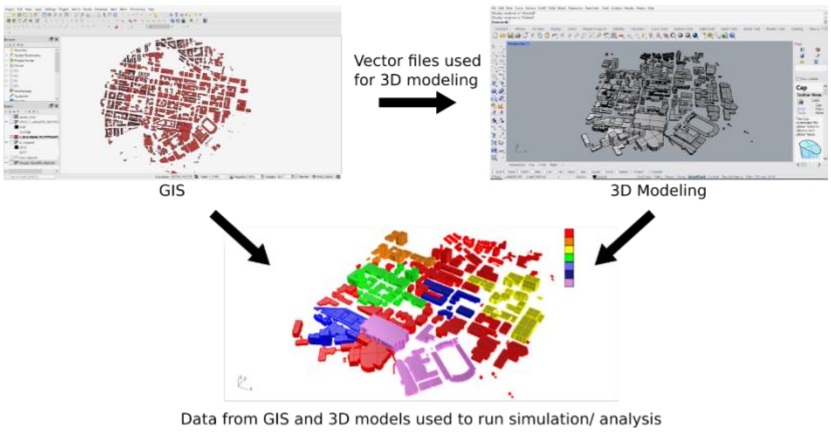


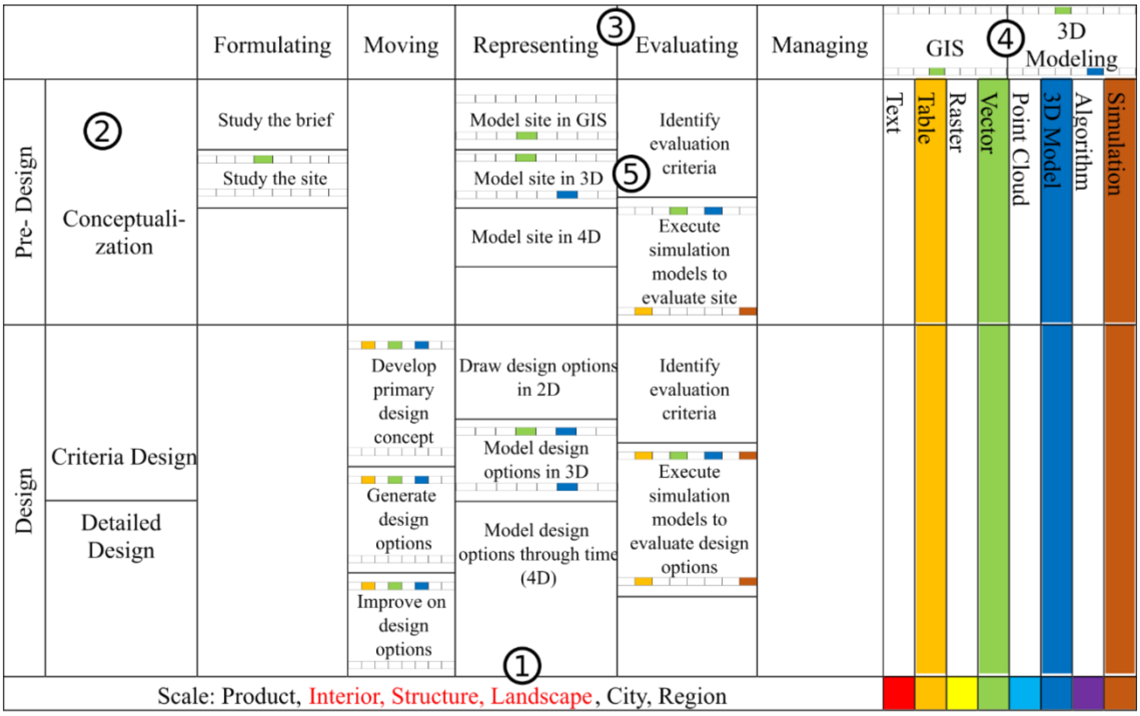
Figure 2: The use of GIS and 3D modeling software for preparing data for analysis

The workflow is translated and represented using the framework as shown in (Table 6). The framework allows a practice to assess the two technologies in the context of a design project. The steps to using the framework are described below:

1. Identify which built environment components the project belongs to and establish the content-component-context relationship. In this example interior-structure-landscape are highlighted.
2. Customize the work stages by adding a sub-column under the stage column of the framework. The project can be further broken down into sub-stages.
3. Break down the design process of each stage into tasks. The practice can identify and sort all the design tasks using the five task types as guide.
4. Fill in the technologies of interest on the top right corner. In this case GIS and 3D modeling software. The color bar on the top of the cell indicates the input and the one at the bottom indicates the output. Each color corresponds to a data type as shown on the data columns. It is indicated that the GIS software outputs vector maps, and the 3D modeling software can take vector files as inputs for reference in 3D modeling and output 3D models. The basic framework can be easily customized to account for other data types depending on the project.

5. Use the color bar to indicate the inputs and outputs of the related design tasks. In this example, GIS vector files are inputs for studying the site, as reference for 3D modeling and evaluating the site. The 3D site model, evaluation results and vector files are then used to generate options in the respective design stages. The data columns give a summary of the data exchanged at each sub-stage.

Table 6: Example of using the base framework



3. RESULT: CASE STUDIES APPLYING THE COMPUTATION IN DESIGN (C-IN-D) FRAMEWORK

When using the framework, a practice can do multiple project mappings or concoct a representative project for the assessment. We demonstrate the usage with two actual design projects and a third representative project of form-based code development. The three case studies are of different physical scales. The first case study is a sculpture design, followed by a building interior retrofit project and lastly a master planning project. Details of the application is described as follows.

3.1 Currents and Planes sculptures

Marina One building in Singapore (ArchDaily, 2017) commissioned Grace Tan of kwodrent an artistic practice, to design and fabricate a series of interior sculptures. In response to the building design, Grace Tan explored organic contours and hyperbolic shapes for the sculptures (kwodrent, 2017a, 2017b; Tan & Chen, 2018). The artist first explored the various geometries with paper models. The design is further refined by converting the paper models into parametric 3D models. The conversion was done manually by a parametric modeler. In order to refine the design, the artist and modeler went back and forth many times. The sculptures were then fabricated manually using precise dimensions from the scaled 3D printed models. It has a height and width of about 2 meters. Each sculpture is made of marine grade stainless steel (Figure 3).

Figure 3: (a) paper models (b) translated parametric 3D model (c) 3D printed scaled models (d) fabricated sculptures

We mapped the design process and decided to assess three computational technologies that could have improved the design process. They are web-based interactive parametric modeling using OpenJSCad (OpenJSCAD, 2022), Matter and Form V2 table top 3D Scanner (Matter and Form, 2022) and Leica BLK360 Terrestrial LiDAR Scanner (TLS) (Leica, 2022). Table 7 maps the design process and data flows with the design technologies under assessment.

Table 7: Mapping of the sculptures design process to the computational design technologies.

		Formulating	Moving	Representing	Evaluating	Managing	Table top 3D scanner		TLS		Interactive Parametric Modeling			
							Text	Table	Raster	Vector	Point Cloud	3D Model	Algorithm	Simulation
Pre- Design	Problem Definition	Study the brief * pair of suspended sculpture in a triple volume space * total fluidity * extend the space and greenery * integrated in aesthetics with architecture * sensible material to architecture Study the interiors		On-site TLS scan of interior										
Design	Conceptual Design		Develop primary design concept: * bands, contours * double curvature, *buckling, *hyperbolic geometry Refine design options	Represent design as paper models Scan the paper models with table top 3D scanner Translate paper models to digital parametric 3D model	Subjective evaluation of form based on visualization of parametric model									
	Detailed Design		Adjust design options to fit into interior Cluster multiple sculptures to form visual interest	Represent final design with group composition Draw construction drawings										
Construction	Construction			Print scaled 3D model for use in manual construction of sculpture		Coordinate the placement of sculptures Reflect on the design process for future improvement	Text	Table	Raster	Vector	Point Cloud	3D Model	Algorithm	Simulation
Scale: Product, Interior, Structure, Landscape, City, Region														

Web-based interactive parametric modeling allows the sharing of a parametric model over internet browsers without requiring any installations on the client computer. It allows exposing only the key parameters for non-expert users to control the model while hiding the complexity of the parametric model. In Table 7, we can see that interactive parametric modeling generates algorithms and 3D models. The artist does not have the required modeling skills to run the parametric model. The capability to share the translated parametric models with only key parameters exposed will allow more efficient edits to the design options. In the original design process, baked 3D models were exchanged during the design process. The artist annotated the 3D model, and the parametric modeler adjusted the parameters accordingly. Mapping web-based interactive parametric modeling to the design process was most useful in the conceptual and detail design stage, where the artist could have adjusted the parametric models herself and efficiently generate design variants that better satisfied her artistic intent.

The table-top 3D scanner can capture scaled physical models and digitally represent it as point clouds. This will be the most useful when translating the paper models into parametric 3D models. In the original process, the translation was very time consuming as the modeler had to estimate the curvature of each model manually (Figure 3a & b). The modeler will be able to use the point clouds as a reference in the 3D modeling software to construct the parametric model, ensuring higher fidelity to the paper model and eliminating potential error.

Similarly with the TLS technology, the interior of the building can be captured in point clouds with high fidelity. In the original process, construction plans, sections and elevations were used as references for the sculpture context. The interior point clouds are very useful throughout the design process. It can be used for studying the context, design development, parametric modeling and construction as shown in Table 7.

3.2 Autodesk AEC headquarters

Autodesk decided to retrofit an existing building's interior into their new headquarter in Waltham, Massachusetts, USA with the Integrated Project Delivery (IPD) process (AIA, 2010; Bendewald et al., 2010). IPD supports collaborative and coordinated project delivery. The main aspects of IPD as defined by the American Institute of Architects (AIA) are early involvement of key project stakeholders, shared risk and financial rewards for achieving jointly developed goals, collaborative decision making, liability waivers among consultants and multi-party contracts (AIA, 2007). Throughout the project, the design team consisting of the architects, constructors and clients have embraced the use of computational design technologies such as Building Information Modeling (BIM), daylighting simulation, digital fabrication and Terrestrial Lidar Scanner (TLS) to improve the design process. For this project, we will use the framework to assess two potential technologies, the optimization process in the Revit Dynamo plugin Optimo (Rahmani Asl et al., 2015) and Internet of Things (IoT) lighting sensors (Particle, 2022) to further improve the design process.

Optimo allows designers to use Non-dominated Sorting Genetic Algorithm II (NSGAII) to optimize their design in the Revit Dynamo environment. The Dynamo environment enables designers to readily parameterize a BIM model and evaluate it with connected simulations. In Optimo, the optimization algorithm uses a parametric model to generate an initial population of design variants randomly and evaluates them according to the performance objectives. In this case, they were maximizing both view and daylighting (Table 8). Based on the performances of the evaluated population, the algorithm varies the parameters of the model to find better performing design variants. A better performing population replaces the previous population in each generation. At the end of the process, the generated design variants can then be Pareto ranked and analyzed to support design decisions. This is the most useful in the criteria and detailed design stages as shown in Table 8. The original design process manually exported the Revit BIM model for evaluation in the view and daylighting simulations. By automating the generation and evaluation of design variants using Optimo in the Revit Dynamo environment, the design team will be able to explore thousands more design variants and potentially find a better performing design.

IoT describes a network of things that are embedded with sensors and software that communicate and exchange data with each other through the internet. The cost and technical barriers to deploying IoT networks have been significantly lowered with the availability of internet access, low-cost sensors, low-cost electronics and open-source software. In this case, the design team can readily deploy a network of low-cost lighting lux sensors to evaluate the daylighting condition of the existing interior. The data can be used in the criteria design stage to calibrate the daylighting simulation model to obtain better modeling results that can be used in the optimization process. Finally, at the closeout stage, the sensors can be deployed to obtain post-occupancy daylighting performance. This will allow the design team to understand the performance impacts of their daylighting design strategies and reflect on potential improvement for their next project.

Table 8: Mapping of the Autodesk AEC headquarters design process to the computational design technologies.

		Formulating	Moving	Representing	Evaluating	Managing	IoT	Dynamo Optimo
Pre- Design	Conceptuali-zation	Aim for LEED platinum for commercial interiors Develop spatial programming Shared risk and rewards in contract 8.5 months construction schedule Collaborative decision making Liability waived among key participants BIM execution plan		Contract and agreements	Evaluate existing daylighting condition with IoT sensors		Text Table Raster	Vector Point Cloud 3D Model Algorithm Simulation
Design	Criteria Design		Layout of design interior to maximize daylight and outside views	Draw design options in 2D Model design options as BIM model Parameterize BIM model to generate design variants	Execute daylight and view analysis from exported mode from BIM Execute optimization process	Finalize scope, form and spatial relationships Preliminary selection of major building systems Preliminary cost estimate and schedule		
	Detailed Design	Additional 500 sqf of office space Additional cooling for 'regression farm' Addition of 3-storey atrium	Integration of new requirement into the design Development of complex ceiling panels with integrated approach	Draw design options in 2D Model and communicate complex design options in 3D BIM to client Parameterize BIM model to generate design variants	Execute daylight and view analysis from exported mode from BIM Execute optimization process	Finalize all building systems designs Finalize specification of buildings Define cost and construction schedule to a high precision		

	Implementation Documents			Draw construction drawings Model design options in BIM for design to fabrication process with CNC tools		Finalize cost and construction schedule Finalize specification and supplemented with necessary documents Interference analysis with BIM to avoid clashes between building systems Use of BIM model to effectively convey design intent to fabricators Coordinate construction and fabrication of ceiling panels, HVAC, plumbing, fire protection and millwork
Construction	Agency Coordination					Obtained all permits and approvals
Construction	Construction			3D laser scanning of existing interior to obtained existing condition Model construction scheduling in BIM		Use of BIM model to effectively convey design intent and coordinate constructions
Operation	Closeout			Model as-built design in BIM	Evaluate daylighting condition with IoT sensors	Reflect on the operations of the design Improve design to facilitate operations

Text, Table, Raster, Vector, Point Cloud, 3D Model, Algorithm, Simulation

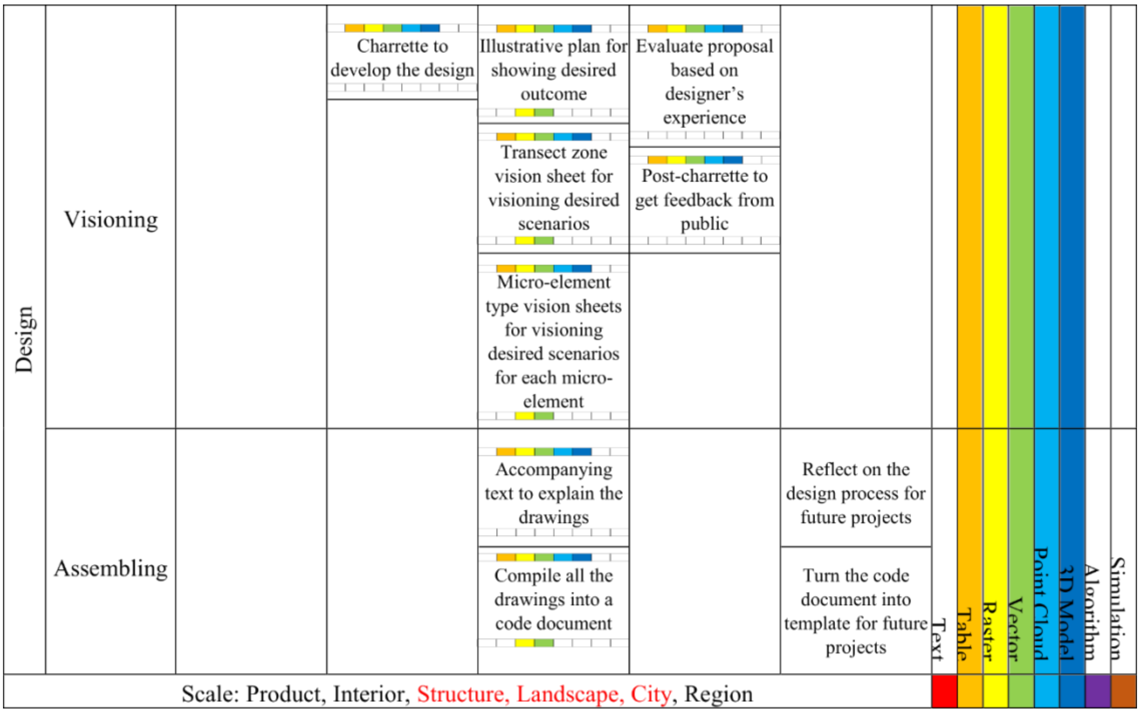
Scale: Product, Interior, Structure, Landscape, City, Region

3.3 Form-based code

Form-based code is a method of regulating development to achieve a specific urban form. Form-based code is a land development regulation that fosters predictable built results and high-quality public realm by using physical form as the primary and land uses as the secondary organizing principle. It is a regulation, not a guideline, adopted into city, town or county law (FBCI, 2022). This case study is a representative project for practices that develop form-based codes. Based on the process documented in (Parolek et al., 2008), we applied the framework and assess potential design technologies that will benefit the development of form-based codes. We assess the benefit of using two technologies, Geographic Information System (GIS) software QGIS and Leica BLK360 TLS for the design process.

Table 9: Mapping of the form-based codes design process to the computational design technologies.

		Formulating	Moving	Representing	Evaluating	Managing	QGIS	TLS
Pre- Design	Scoping	Determine application area and degrees of change					Text, Table, Raster, Vector	Point Cloud, 3D Model, Algorithm, Simulation
		Determine implementation method * replace existing codes, pilot projects etc.						
		Select approach to coding * determine organizing principle * use of existing template						
	Documenting	Planning for macro-scale visit		Gather existing condition maps and existing planning documents to create base drawings				
		Select sampling area for micro-scale site visit		Analyze the materials and create NotatedMaps, Draft Transect Levels and list of places for site visit				
				Micro ad macro site visit, photographs and 3D scan of site				
				Organize and analyze the data from macro and micro site visit to produce maps for presentation				
				Document existing block types, thoroughfares, building types and frontages in each neighborhood				



QGIS is an open-source cross platform GIS desktop software that allows users to manage, edit and analyze geospatial data. With the software, a practice can have access to open geospatial data globally by importing the data into the software. Data sources include open data portal of many cities, vector maps from OpenStreetMap, raster maps from GoogleMaps and remote sensing data such as airborne LiDAR scans from the United States Geological Survey (USGS) portal. These data can significantly influence the tasks carried out in the documenting and visioning stages as shown in Table 9. The practice may significantly reduce the time and effort in producing and editing base maps and annotated maps using QGIS to edit existing map databases.

TLS can be used in this case study for capturing high resolution 3D point clouds of the urban area of interest. In comparison to photographs, 3D point clouds provide an unrivalled level of details in three dimensional models made up of 3D points. This will allow design teams to perform three-dimensional analysis that is impossible with photographs. It is especially useful in the micro site analysis, where the 3D point clouds will allow the design team to zoom down to details of millimeters resolution. They can extract highly accurate dimensions of urban features to produce existing transect level matrices of building types, frontages and thoroughfares. Design teams will also be able to recreate the urban area based on the 3D point clouds, which will allow for the rendering of realistic illustrative plan in the visioning stage for accurately communicating the design intent to the public.

3.4 Discussion

As shown in our case studies, the C-in-D framework provides a systematic method for analyzing the potential impact of computational technologies on efficient project delivery and quality of the project outcomes. The framework reveals the utility of the technologies in the context of the projects. It will aid the practice in deciding on technology to invest with limited resources.

In the first sculpture case study, although the data provided from the TLS machine is helpful throughout the work stages, it costs about USD 20,000. The tabletop 3D scanner only costs about USD 1000 and the interactive parametric modeler OpenJSCAD is an open-source software. The initial step would be to first invest in the tabletop 3D scanner and learn OpenJSCAD for future projects. Further assessment will be required before investing in a TLS machine. In the second case study, investing in the IoT device is more beneficial as it has more utility throughout the project considering the cost of the two technologies are similar. Lastly, in the third case study, it is apparent that the practice should invest in learning QGIS as it is useful throughout the project stages. The cost of adopting QGIS will only be on personnel training as it is an open-source software. If all three case studies are from the portfolio of a single practice, it will then be worth investing in a TLS machine, as the point cloud data is useful for all the three cases. Its high investment cost can be justified by its usefulness across multiple projects.

The design tasks and data flow depicted in our case studies are not definitive. Another design practice working on similar projects and investigating the same technologies might agree with our depiction or customize the framework (Table 5) differently. The precise specification of the work stages, design tasks and data flows will vary according to different projects and work cultures of the design practice. The framework can be further customized to accommodate for the human resource capability and man-hour accounting of a design practice by specifying the personnel and hours executing each design tasks when considering the technology adoption. This will allow the practice to understand the parties involved in the technology adoption and assess accordingly.

A practice can better assess the computational technologies of interest and integrate them into the design process by using our framework and other existing studies. For breaking down the design process, it is difficult for a practice to capture the design process in retrospect fully. The Design Process Communication Methodology (DPCM) supports documentation of the design process on the fly when the project is still running (Senescu & Haymaker, 2013; Senescu Reid R. et al., 2014). By coupling DPCM with our framework, the design practice can translate the captured design process into our framework. It will allow design practice to understand their design process better and assess potential computational design technologies to improve their process.

Although the C-in-D framework enables practices to assess potential computational technologies to improve their design process, it does not offer support for the next step of integrating the technologies into the design process. The research framework developed by (Purup & Petersen, 2020) integrates building performance simulations into the design process. It is also suitable for integrating computational technologies in general. Their research framework suggests first framing the scope of the integration, followed by a series of iterative activities; planning, acting, observing, and reflecting, to integrate the technologies of interest into the design process. Complementing Purup & Peterson research framework, a practice can use the result from the C-in-D framework for framing and planning the integration. They can again use the C-in-D framework to map out the actual usage of the technology to reflect and improve on the integration attempt. When used together with these studies, our framework can provide a suite of tools to support practices in improving their design process using computational design technologies.

4. CONCLUSION

In conclusion, our proposed C-in-D framework provides a customizable basic structure for practices to assess potential technologies for usage in their design process. The framework has been customized for use in three case studies of different physical scales: product, interior and urban design scales. The demonstrations have shown that by applying the C-in-D framework, practices could discover which tasks and projects can benefit from adopting computational design technologies. They can also see the synergies when multiple design technologies are being considered by examining the data flows between the technologies and design tasks from different stages.

The C-in-D framework can be further investigated and refined by introducing it in design education. The framework is a valuable tool for students to understand the potential impact of computational design technologies on the design process. The framework can be made more accessible to students as a web or mobile application. The shortcomings can be refined and improved as feedback are collected from students participating in design projects. It can also be used to document case studies collected by students and distributed to design practices to inform them of the usefulness of computational design technologies. We hope to facilitate the digitization of our built environment industry by equipping the students who are future practitioners with the tools to consider computational technologies in design.

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