

Degrees of Parameterization: Rewiring design-to-construction for prefab modular products

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Degrees of Parameterization

1. Introduction

The wood construction industry is going through a pivotal moment. The use of innovative materials and practices are awarding this segment of the construction industry with worldwide recognition, financial interest, and the opportunity to rethink the design-to-construction process. We can now see that utilizing wood as a primary structural element complemented with secondary modular and/or prefabricated components – also made from wood – can make a lot of sense. At the same time, breakthroughs in cloud-based platforms, generative design, VR, AR, robotic fabrication, machine learning, and AI – to name a few – allow us to reimagine the future of construction.

However, for small and medium enterprises (in the following referred to as SME's), investing in these solutions may simply be cost and know-how prohibitive. From an SME's point of view, dissecting the extent of digital solutions with good fit and discerning their overlapping functionalities and compatibilities, is tough enough. More complicated still are the challenges faced in the planning stages of a project. Which are intensified in the wood construction industry by the lack of standards, inconsistent building norms, and a misunderstanding of construction and manufacturing constraints by many customers. This master thesis focused on the sequence of events occurring in the planning stages of a project from the perspective of a small specialty subcontractor. Considering the first interactions in sales to the delivery of fabrication data. The study acknowledges that owners, architects, and general contractors should be able to quickly, and reliably, compare alternatives for cost control and expediting schedules. But it also recognizes the challenges a subcontractor providing design-to-construction products encounters while designing, engineering, coordinating, and fabricating their scope of work. And how these create complicated and sometimes overwhelming conditions that only well-balanced enterprises can handle. The proof of concept was meant to provide aspiring subcontractors in this space with a product development strategy that can easily translate schematic proposals into production-ready BIM models.

2. Integrative Design

«While the information-based world is now moving exponentially, our organizational structures are still very linear (1).»

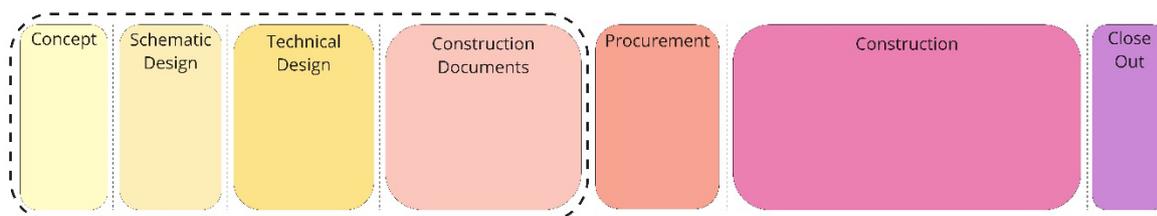


Figure 2.0.1: Universal Construction Stages. (Diagram by Author)

According to the book *Architecture Design Data* by Phillip G. Bernstein, the construction process around the world is fairly universal and has mostly remained intact for decades (2). Figure 2.0.1 is a representation of the seven typical stages of a construction process and highlights those dedicated to planning. Changing scales, specialty subcontractors providing Engineered to Order (in the following referred to as ETO) services also follow a sequential pattern. One that flows from general to specific as information is gathered and integrated into the working model. Figure 2.0.2 shows a generic version of a product creation process (in the following referred to as «PCP») for an ETO architectural product.

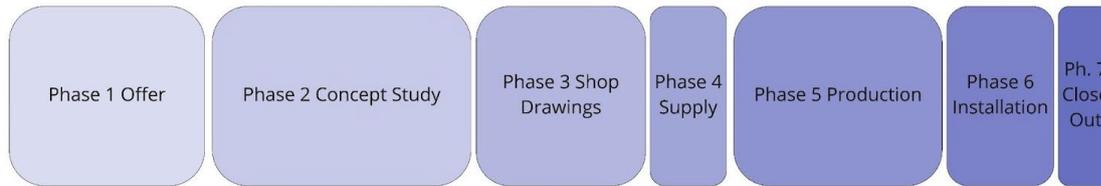


Figure 2.0.2: Product Creation Process. (Diagram by Author)

This thesis recognizes that architectural designs are multi-variant, dependent on an intricate interplay of factors ranging from aesthetic to technical to economic. That a product is selected by balancing questions of appearance, performance, availability, and cost (3). Because most construction projects are unique, adaptations to ETO products are prevalent. In construction, there are different trends and pressures in the market creating an expectation that individualized design and sublime craftsmanship can or should happen faster and cheaper than ever before. (4)

On the other hand, just-in-time (in the following referred to as «JIT») supply chains and manufacturing methods have spread throughout the construction process. These sequential schedules, although effective, also require a high degree of communication and clear transitions among the different stakeholders at every stage. «But construction is a dynamic process that relies heavily on an understanding of sequence, assembly logic as well as complex orchestration of labor, materials, and delivery – not to mention cash flow (5).»

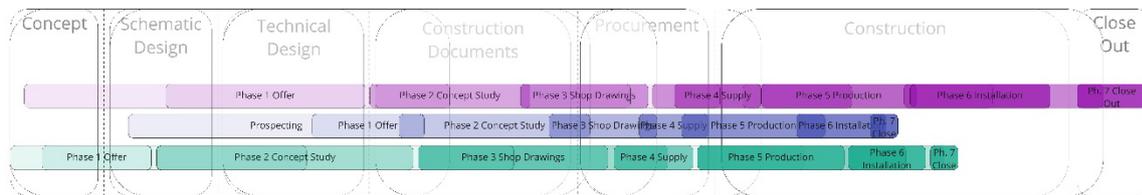


Figure 2.0.3: Different PCP's across the Universal Construction Stages. (Diagram by Author)

Figure 2.0.3 overlays a few Product Creation Processes over the Universal Construction Stages of a construction project. This diagram is meant to help visualize the simultaneous progression of several ETO products (micro) across the different stages of a construction project (macro). This figure also shows the «waterfall effect» occurring within each subcontractor's PCP. The overlapping areas represent setbacks in the product's progression. For example, activities or work packages began in one phase are carried to subsequent phases until completed. These delays can occur for many reasons. Among them is the unreliable precision and timing of the exchanges of information among stakeholders (6). In essence, we don't get what we need when we need it. And when we do, it's wrong, off, or missing key details. But why? An argument made is that modifications are mainly carried out by manually adjusting a model via typing commands, clicking, picking, and dragging in a 2D and 3D environment. Meaning, that they take time and are prone to human-error.

In 2020, a study in Chile analyzed the behavior and performance of a design and engineering team working on a 2-story building. In short, the experiment tracked each participant's log data. And examined the relevance of commands used, and their effect on the progression of the project

Table 2. Total number of commands executed by each designer.

Designer	Total	Contributory Commands			Non-Contributory Commands			Contributory Vs Backwards
		G	NG	C	N	U	B	
Architectural	9430	1770	169	372	3291	3228	657	2150
Structural	6433	1353	203	228	2470	920	1296	1425
Mechanical	5555	1032	121	141	2496	726	1039	1052
Electrical	6523	1296	165	184	2918	994	966	1401
Plumbing	7360	1190	366	165	3101	776	1762	1309

G: Geometrical modeling; NG: Non-geometrical modeling; C: Collaborative; N: Necessary; U: Unnecessary; B: Backwards.

Table 2.0.4: Total number of commands executed by each designer. [Table 2.](#)

(Image courtesy of Forcael & et al., 2020)

Table 2.0.4 is an excerpt from the study and summarizes the findings. The number of times the designers typed in the wrong command, hit back, exit, or undo, makeup about one-third of all commands. (7). This finding aligned with the author's experience perfectly and became the focal point for the proof of concept (in the following referred to as «POC»). In short, it triggered the following question. How can we get to zero non-contributory commands?

The same study in Chile recommended improvements in the precise timing of information delivery to improve activity flows and streamline the work packages. But JIT logistics align material orders from suppliers directly with production schedules (8). Consequently, timing becomes everything. Therefore, being able to update the working model with speed and accuracy is crucial. The team handling the model must ensure that the information passed on between departments and 3rd parties is accurate every step of the way.

According to the Innovation Scouting Report, data-driven technologies and business models can only truly be scaled when the current silo mentality is overcome (9). As the construction industry goes through its digital transformation, attempts towards holistic building systems for wood-based multi-story developments have emerged. In most cases, the aim is to standardize design solutions that work in a multitude of environments and minimize the complexity in managing all the stakeholders along the value chain. One system under development is from Build-in-Wood (in the following referred to as «BiW»), a European Horizon 2020 project focused on offering high-quality, affordable, and environmentally friendly housing with timber construction. Figure 2.0.5 lists a set of criteria for the BiW building system and contains a couple of illustrations exemplifying its sequential characteristics.

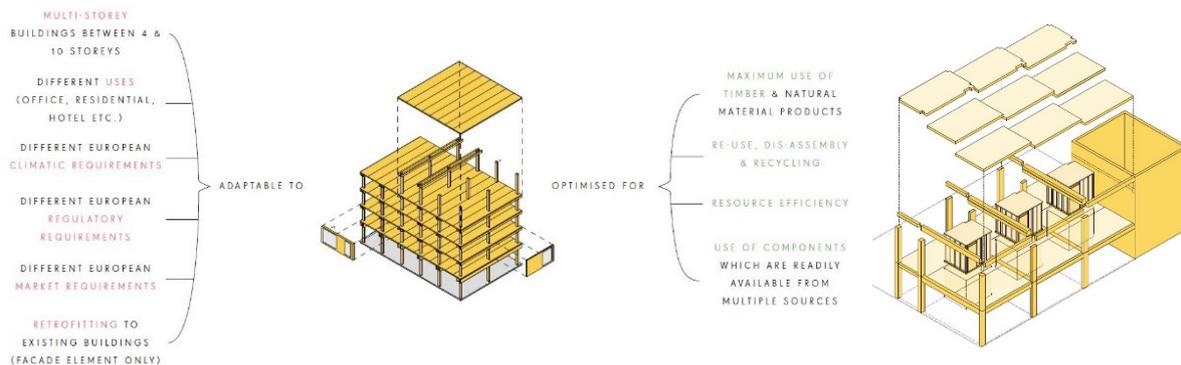


Figure 2.0.5: Left Image: Build in Wood Building System Criteria. Right Image: Installation sequencing.

(Images courtesy of Build in Wood and Waugh Thistleton Architects)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 862820.

One area of investigation for BiW is the integration of third-party modular components. Among the benefits identified by BiW for using non-structural pods in their system is to shorten the on-site construction program and standardize components and installation processes. During the development of this thesis, the researcher represented Tjiko GmbH as a consultant for wet areas with BiW. This collaboration serves as a good example for the cross-integration of knowledge among trades. On one end, subcontractors providing ETO products can be much wiser when developing their designs and fabrication processes. On the other end, BiW builds consensus on how to best integrate modules and their technical arrangements with the other systems in the puzzle.

3. Research Partner: Tjiko GmbH



Figure 3.0.1: Tjiko Products. (Pictures courtesy of Tjiko)

Tjiko GmbH is a start-up from Rosenheim offering design-to-construction solutions for prefabricated modular bathrooms. Figure 3.0.1 gives a glimpse of finished products at different phases. The firm emerged from the Technische Hochschule Rosenheim in 2017 with a clear vision to pioneer in the efforts to reduce building costs for construction by 50%. The author joined Tjiko as Product Developer in early 2019.

In a multi-story prefab building, the bathroom pod is just a piece in the puzzle. But an important one. Their placements can have a substantial impact on the larger MEP strategy. And from a design perspective, their position and functional features influence the shape and activities of the adjacent spaces. When Tjiko collaborates on the MEP strategy early on and the batch size is a good fit, integrating tangential functional elements into their modules can be advantageous. It reduces the management of different trades and combines steps during the installation stage. Figure 3.0.2 shows a consolidated module of a fully functional bathroom pod with a floor-to-ceiling fenestration, including a built-in kitchen, and a built-in closet unit.

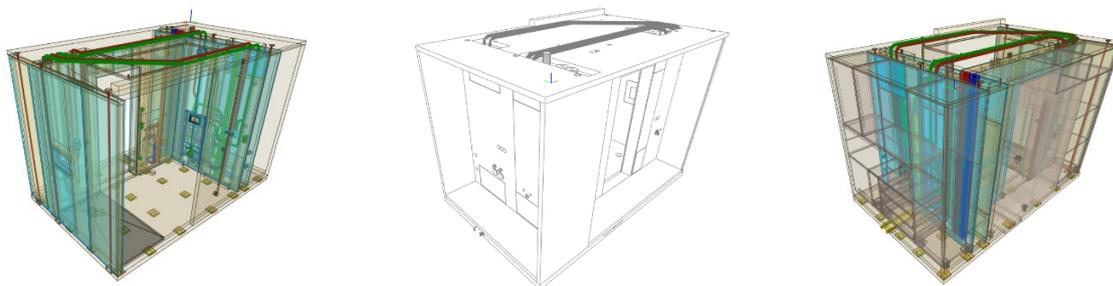


Figure 3.0.2: Multi-functional Module. (Screenshots courtesy of Tjiko)

Tjiko also responds to the fact that bathrooms within the same building may come in a range of sizes, may be standard, accessible, or barrier-free, and come with a variety of washroom assets, accessories, and finishes. Figure 3.0.3 shows a bathroom-pod floor plan with three different options concerning the placement of the vertical service shaft. In a best-case scenario for the production, all modules would be stacked vertically. However, depending on the requirements and orientation of the units within each level, the modules can have multiple door placements, rotated, mirrored, and/or staggered vertically. Therefore, the number of product variations force Tjiko to maintain a highly organized operation to produce small batches efficiently.

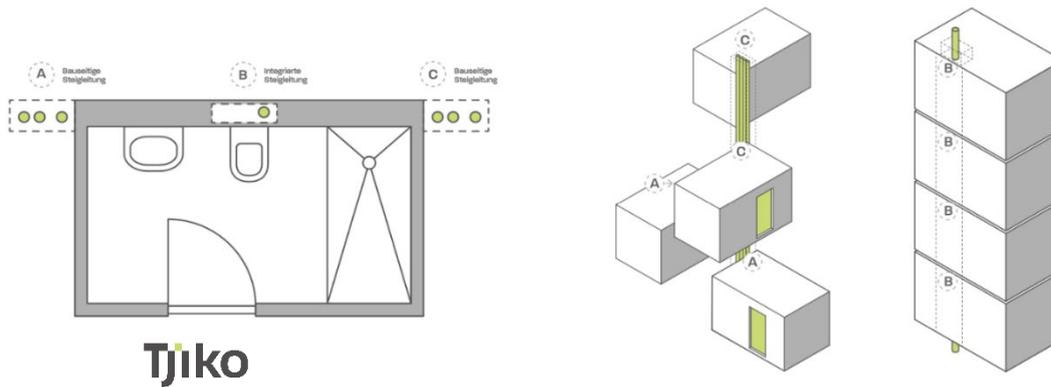


Figure 3.0.3: Tjiko System Integration. Das Tjiko Bad. (Images courtesy of Tjiko)

4. Proof of Concept

The POC called Degrees of Parameterization (also referred to as «D.o.P.» or «D.o.P. System») was carried out with Tjiko from June to December 2020. A strategy for product development was devised to respond to the challenges faced by Tjiko in the planning of bathroom modules for their small batch production. It was noted during the design and product development that offering standardized, partially customized, and fully personalized products was fundamental. According to Merriam-Webster, the definition of *parameterize* is simply «to express in terms of parameters»(10). When designing, determining which aspects or parameters of the product can be personalized by the customer is fundamental. This is a delicate step because every added customer input reverberates across the system and can seriously increase the scope of work. Therefore, maintaining a balance between the default inputs and the customizable inputs is key. In this context, products with a minimal amount of customization choices contain a high degree of parametric inputs that have been automated, or preselected, by the designer. In contrast, custom modules with more selectable variables, by default, have a lower degree of parameterization since those automated steps become manual inputs.

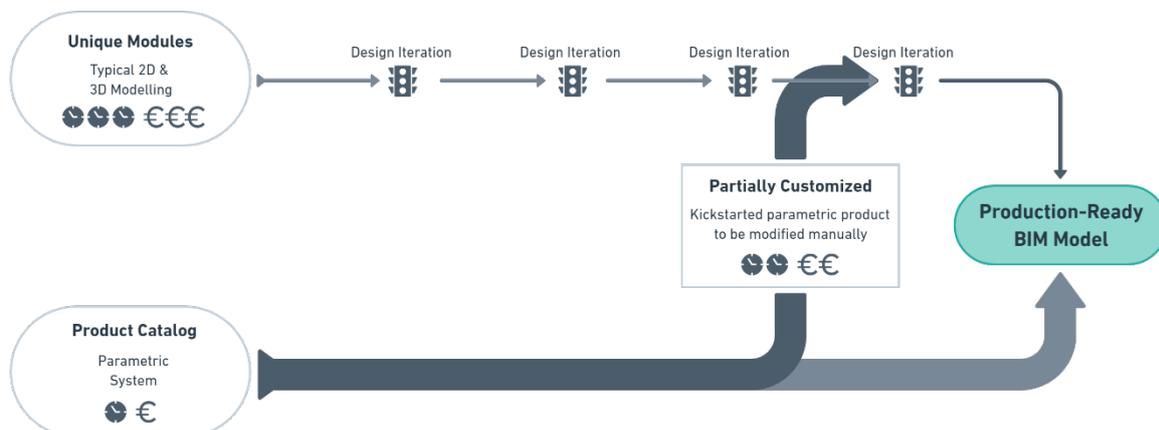


Figure 4.0.1: Tjiko Product offerings. (Diagram by Author)

This POC focused exclusively on the design, development, and execution of all products within the product catalog. Figure 4.0.1 illustrates the three product offerings and implies longer durations and higher costs for delivering small batches of unique bathroom modules compared to standardized modules.

4.1. Das Tjiko-Bad

The product catalog (aka «Das Tjiko-Bad») constitutes the backbone of information for the parametric framework. In short, a customer working with Tjiko can choose between different «models» (bathroom layouts) and «design lines». The design lines include functional and aesthetic items that include the sanitary assets along with the material and color palettes. Once the final dimensions, the design line, and the model type are determined, the documentation of customer inputs is done. From Tjiko’s point of view, this format enables the implementation of standards and helps reduce choice overload for the customer. Figure 4.1.1 shows some of the models offered in the product catalog and the «Zermatt» design line.



Figure 4.1.1: Das Tjiko-Bad. (Images courtesy of Tjiko)

4.2. Implementation

ModSpecs			
DIMENSIONS (mm)	Model Type	Select Design Line:	
Exterior Width	Product 'A'	Zermatt	
2425	Floor Panel Family	Door	WC
Exterior Length	CLT Type 1	Supplier9_model0001_R5wing_885x2032mm	Supplier24_model4321_400x600mm
3895	Wall A Family	Door Electrical Drilling Template	Radiator
Exterior Height	Wall Type 1	Supplier58_model1010_L1.3.2	Supplier36_model1551_1800x450mm
2350	Wall B Family	Washbasin	Tiles Family
	Wall Type 3	Supplier24_model1234_550x650mm	Supplier12_model54C_600x300mm
	Wall C Family	Shower or Bathtub	Lighting Concept
	Wall Type 2	Supplier22_model0987_1000x1400mm	Supplier62_LED001_AreaBased
	Wall D Family	Shower or Bathtub Fittings	Niche
	Wall Type 1	Supplier36_model17890_AP-ShowerSet	Supplier16_model8888_260x400mm
	Built-Up Floor Family	Washing Machine	Furniture
	Built-Up Floor Type 2	Supplier28_model5555_750x850mm	Supplier29_model4185_WM750x850mm
	Roof Panel Family	Washing Machine Electrical Drilling Template	
	CLT Type 1	Supplier58_model1010_SS_1.2	

Table 4.2.1: Left: Example drilling template. Right: Generic set of ModSpecs. (Table by Author)

Some of the programs used for this POC were already part of Tjiko’s technology stack. Such as Excel, Autocad, and hsbcad. Revit and Dynamo were chosen to implement computational design workflows. Dynamo is a plug-in that allows designers to create algorithms for a wide array of applications. From data processing to generating geometry (11). The term «ModSpecs» refers to the Excel spreadsheet with the customer inputs. This file is what tells the Dynamo graph what to generate in Revit. Table 4.2.1 shows an example set of ModSpecs. The inputs, in bold, are selected from dropdown menus while the rest of the data in the sheet auto-propagates based on the selected inputs. This format reduces naming variations and errors when running the Dynamo graph. Once the ModSpecs are completed and saved, the design team opens Revit and launches Dynamo. In essence, once the designer runs the Dynamo Graph, the functions specified in Dynamo are manifested in Revit. Figure 4.2.2 shows a screenshot of the Dynamo UI and the graph used to generate the bathroom models in this POC. The 3D model on the right is a .ifc model exported from Revit after running this Dynamo graph. This model is very basic but more than enough for early coordinating and estimating.

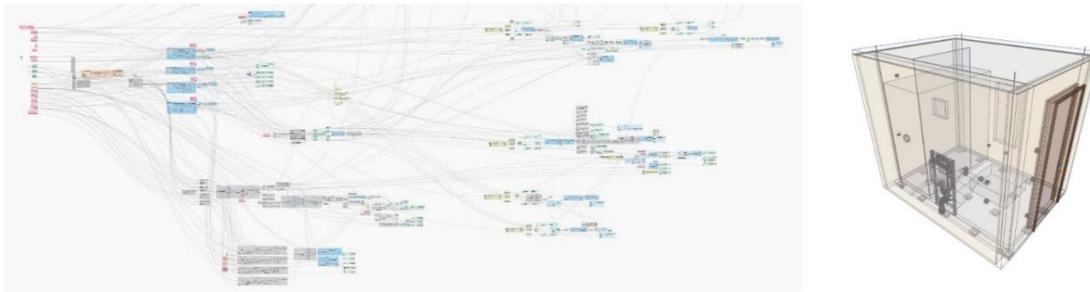


Figure 4.2.2: Left: Design Script 1. Right: .ifc export after running Script 1. (Screenshots courtesy of Tjiko)

Because a project flows from general to specific, subcontractors avoid overinvesting in schematic proposals. Understanding that design is an iterative process, spending too much time on a solution that will likely change, or be replaced by another idea, is unproductive. However, if the Dynamo script could consistently build accurate 3D models in a fraction of the time, then delivering a quick turn-around without overextending resources during the estimation phase could be achieved. If a customer changes the specifications of a product, the team could quickly generate a new one instead of manually editing the previous one. Significantly cutting back on manual 3D modeling.

Only until a letter of intent or a contract is signed, would the Project Manager run a separate sequence of Dynamo graphs that read the existing model's geometry and parameters to apply the corresponding hsbcad TSLs. For example, LED lights, electrical outlets, and asset mounting patterns are translated into box-cuts and void drills and applied to the CLT panels and sheathing layers on the wall elements. In addition, these scripts kickstart the documentation process by creating a set of cross-sections and sheets, placing those sections in the sheets, and populating the Titleblock based on the inputs in the ModSpecs. Seriously reducing tedious and repetitive tasks with a workflow that minimizes mistakes.

Unfortunately, at the time of this POC, hsbcad had not released its hsbStickFrame package for Revit. Therefore, the near-finished Revit model was exported with the hsbcad exporter tool and imported into Autocad with the *HSB_IMPORTMODELX* command. Afterward, a series of manual steps convert the walls and the stick-frame spacing logic is applied. At this point, the project manager can switch into «default mode». Meaning that the process to complete the product and take it to «production-ready» status was carried out by typical 3D modeling in Autocad. Figure 4.2.3 shows a typical WC drilling pattern that would be applied with hsbcad as 'void drills' via Dynamo. The 3D image is from the .ifc model exported from Autocad. This model is shared with the leading party and other technical partners to check for collisions and the integrity of all MEP connections. Lastly, the figure shows a sheet kickstarted with Dynamo.



Figure 4.2.3: Left: Mounting pattern translated to hsb drills. (Image courtesy of hsbcad and Geberit, n.d.)

Middle: .ifc export from Autocad. Right: Revit sheet kickstarted by Dynamo. (Screenshots courtesy of Tjiko)

4.3. Results

The D.o.P. System provides a delivery model for standard products that begins in the sales phase. However, the team decided to first test the effectiveness and reliability of the Dynamo graphs on an ongoing project with good fit. Figure 4.3.1 illustrates the start of the POC with the rhomboid labeled ModSpecs and ends with the production data milestone.

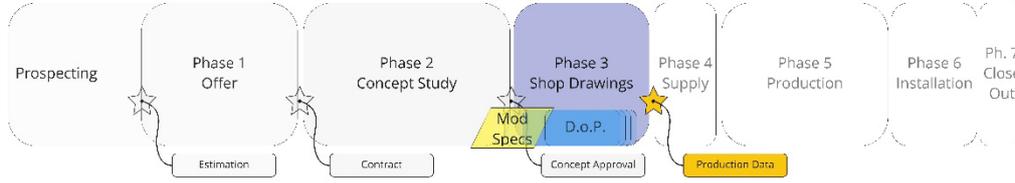


Figure 4.431: POC tested within Phase 3 of the Tjiko PCP. (Diagram by author)

The contracted design was very similar to a standard model. And began by generating the model in Revit and exported it to Autocad. This model ended up substituting the original model used in estimation. Then, the new model went through a typical course of clash detection and MEP updates. Once approved, it was exported as an .ifc file and sent to Tjiko’s suppliers (Phase 4). A few weeks later, Tjiko’s production received the components and assembled the parts (Phase 5). Figure 4.4.2 shows the stick frame walls and the drilling patterns for the washroom assets, on the left. The middle picture highlights the operations done to the CLT roof panel. And on the right, the pre-assembled modules are split into batches and finished out.



Figure 4.4.2: Prefab walls, CLT panels, and assembled modules from the POC. (Pictures courtesy of Tjiko)

Because this was a partially customized product, it still took the project manager a considerable amount of time to coordinate and finalize the planning. Overall, implementing the D.o.P system just reduced the workload by approximately 15 hours. Nothing revolutionary. However, those 15 hours - that would have been spent manually building the 3D model - were replaced by a workflow that lasted 35 minutes. Approximately 24 times faster. Figure 4.4.3 provides a table, on the right, that delineates the durations of each step in the POC. The bar graph and pie-chart illustrate how despite contributing up to 15% of the total workload, the D.o.P. System took less than 2% of the total planning duration.

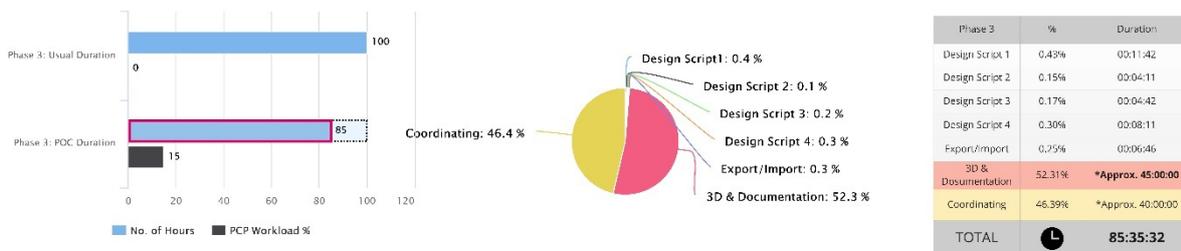


Figure 4.4.3: Step durations in POC. (Tables and charts by author)

5. Analysis

The impact on the total planning time was low. But it was expected. Transferring to AutoCAD and making it unique really slowed down the team. However, if standard products could be sold instead of customized modules, this solution offered great potential. With tools like Dynamo and Grasshopper, developing a highly flexible and customizable product is possible. It's just a matter of proficiency with computational design tools, good systems thinking, and a highly motivated and organized team.

When working with unique product variations, using AutoCAD with hsbCAD allows for the highest range of customizability. But it comes at a cost determined by the feasibility of developing these unique solutions in relation to the batch size in production. Knowing that not all projects consist of low variations and high volumes, improving the feasibility of small batches for production is key for a small organization like Tjiko. A 60% reduction of total planning time was predicted if a standard product was left unaltered. Translating into quicker turnarounds for smaller batch sizes.

5.1. Rewiring

In many cases when a project is completed, its information is archived and forgotten. By comparison, this system is designed to salvage and repurpose the knowledge gained in a project cycle. Figure 5.1.1 shows a rewired L3 model. Which was repurposed from the I3 model used in the POC. The time spent readapting the workflow took approximately 15 hours.

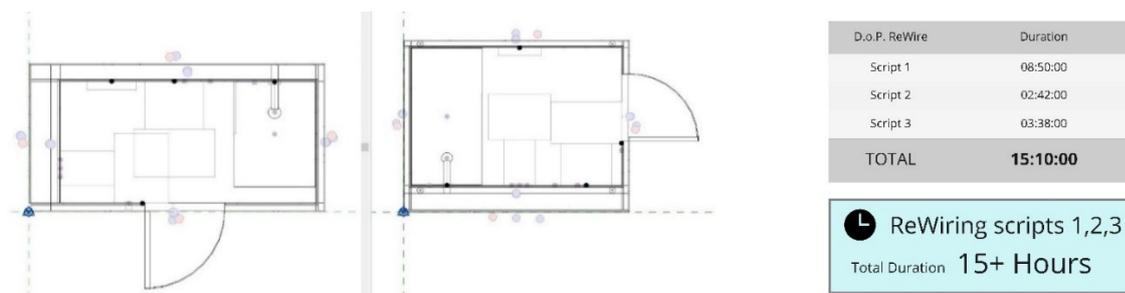


Figure 5.1.1: Left: L3 Model. Right: I3 model. Rewiring duration. (Screenshot courtesy of Tjiko)

If a unique project were to meet certain benchmarks – such as volume and technical recurrences – rewiring the scripts for a personalized solution might make sense. In turn, this new script could be offered as a new model type in the product catalog.

6. Conclusion

This thesis argued that the planning stages themselves, have become the bottleneck for new construction. For companies going through a digital transition, implementing computational design strategies could become the difference between stagnation and growth. According to Bernstein, regardless of how much architects and design professionals are criticized, or wrongly accused, for never stopping the design, the profession will remain at the center of construction. «Design operates at the headwaters of the entire building enterprise, and design information – no matter who might create it – is still the necessary lifeblood of construction. Understanding, controlling, and coordinating how the information assures that a design converts into a built artifact will be our central challenge in a world where digital modeling, machine expertise, high resolution data sets and algorithms become part of the modernized building industry. The tools are certainly available and at our beck and call, we only have to decide to use them (12).»

7. Outlook

In the end, the POC was meant to demonstrate how computational design tools can be utilized by small specialty contractors to increase their quality and productivity while exerting less effort. After completing the Masters in Holztechnik, the author joined Timberlyne Group as Director of Innovation. As a growing design-fabrication company specializing in heavy timber and engineered wood structures in the United States, Timberlyne's projects have grown in scale and complexity. By implementing design automation and workflows that extend past product design and into rigging and logistics, the company is improving the speed and clarity of their planning processes and deliverables.

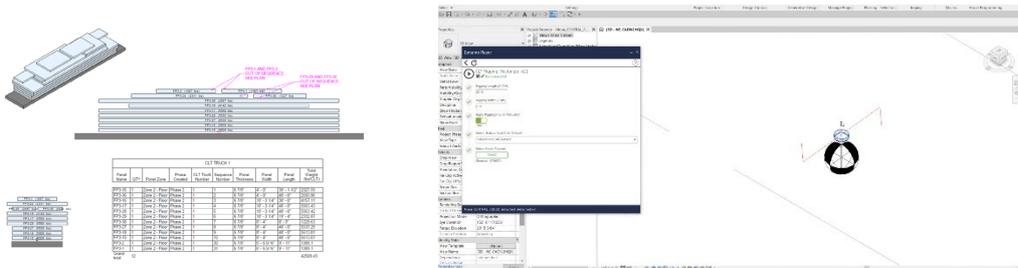


Figure 7.1.1: Left: Kickstarted CLT Shipping Plans. Right: «Locator» milling at center of gravity on a CLT panel

Figure 7.1.1(left) provides an example of a CLT Truck plan kickstarted by a workflow involving a couple of Dynamo graphs and Excel Sheets. On the right, a screenshot shows the center of gravity of a CLT panel – revealed by an hsbcad tool in Revit – with a shallow drilling that indicates its location to the rigging and construction teams on site. In both examples, the number of manual steps to complete the task were reduced significantly. Whether they were through clicks or actual pencil marks and measurements on a part. Adding ground to the argument that automating complex, and redundant workflows increase efficiencies, reduce human error, and empower rising companies to reach their goals.

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