A Parametric Tolerance Model for Numerically Controlled Digital Fabrication

Adaptation of kit-of-parts components for a pre-manufactured WikiHouse scenario

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Numerically controlled digital fabrication (NC) encompasses precise toolpaths generated according to the predefined geometry, material characteristics, type of machining processes, and processing tools. This includes a definition of tolerances, necessary for a successful and smooth assembly process when dealing with component-driven assembly after the components were fabricated. However, the prototyping and assembly practice often encounters a variety of issues in real fabrication and assembly scenarios: humidity of the environment, specific material properties, such as the ability of the stock material to change its dimensions according to the unexpected environmental conditions, unexpected different dimensions of the stock material delivered from a factory or a producer, variety of fabrication producers with different machine types, or unique conditions of a production machine. Therefore, there is a need to adapt the geometry of components to different humidity scenarios and combinations of stock material properties or specific machine or production-related processes, which influence the dimensions, and the tolerances embedded into the process of toolpath generation. To address these, we introduce an adaptive parametric model. This has been created as an open-source and open-access algorithm within the Grasshopper environment to easily modify the dimensions of tolerances according to specific and unexpected conditions. The paper also elaborates on and discusses the limitations of such an approach and the scalability and extendibility of the proposed tolerance engine.

Keywords: *Tolerance Model, Digital Manufacturing, Intelligent Kit-of-parts Assemblies.*

INTRODUCTION

The tolerance engine was developed as a consequence of the challenges posed during the process of digital manufacturing and testing of a 1:1 scenario of the standard modular WikiHouse components - based on the 'Skylark 250' modules (Wikihouse Website, n.d.). This process of pre-fabrication and testing was executed in the workshop first before being sent to the fabricator for the final production.

The Wikihouse components by default already contain a certain tolerance range on the profile curves as well as inner slots. However, as observed during the on-site assembly process, the workshop conditions for testing differed significantly from the conditions in the workshop of the fabricator as well as on-site conditions respectively. Therefore, the 1:1

prototype of the modified WikiHouse scenario served as a test bed to experiment with developing the digital tolerance model, which integrates changing and uncertain conditions to positively influence the success of the on-site assembly.

While the presented methodology follows roughly those of Lin et al. (2021), the approach is much more pragmatic and suited to adaptability on-site considering differences in environmental conditions.

INFLUENCING FACTORS

We identified several influencing factors which influence the behavior of the material stock and kit-of-parts components before or after the pre-fabrication:

- humidity of the environment which affects the change of equilibrium relative humidity property (ERH) and swell of the material, e.g. the moisture content
- material properties of different types of wood species and fiber orientation of cross-laminated veneers used in the plywood which can affect the ERH ratios
- factory-based imprecisions related to the material thickness of the delivered stock material
- imprecisions related to the machining process or tools
- additional qualitative factors influencing the assembly process, such as proximity to the ground, machine calibration, quality of the base platform on which the house is built, design of the object itself, specific number of joints, level of skills of labor, and the level of mistakes they made during the process (try and error), location of the site in relation to a producer/factory
- assembly sequence (procedure) affecting the smooth process and eventual alignment of the entire assembly

The paper concentrates on the development of the tolerance model, which encompasses the properties related to the ERH ratios for the plywood (spruce) embedded into the computational model to modify the dimensions of the components.

Humidity of the environment

Based on the technical properties investigation (Performance panels Website, n.d.), (APA, 2010), the average coefficient of hydroscopic expansion or contraction in length and width for plywood panels (for spruce plywood) is about 0.0002 inches per inch for each 10% change in equilibrium relative humidity (ERH).

We used this factor in our calculation for the tolerance model to be able to modify the correct dimensions according to the measured environmental properties and the available stock material. The expansion (or contraction) across the width and length is also extended with additional swelling at the panels' edges, which is critical, especially when dealing with the slots of the Skylark components. According to the literature, the average coefficient of hydroscopic thickness-swell is about 0.01 inch per inch of original thickness for each 10 % change in equilibrium relative humidity. The relative humidity may vary between 40 and 80 percent, with corresponding equilibrium moisture content ranging from 6 to 14 % (Performance Panels Website, n.d.).

Stock material properties

For the tolerance model representation and calculation, it was necessary to measure the real thickness of the material as an input condition to calculate swelling and consequently the predicted or real thickness of the components. These affect the dimensions of the internal slots on the components, which width and length will slightly expand outwards.

The WikiHouse components by default contain pre-defined tolerances, which are already encapsulated in the Wikihouse shape files. There is a 0.25 mm offset on internal slots and holes and a 0.25 mm inset on the outer profiles of components (Wikihouse Website, n.d.). The tolerance model presented in this paper uses already pre-defined files with those tolerances and as such, does not require the additional definition of those in the parametric model. For the testing and manufacturing process, we worked with the standard industrial sheet plywood material (spruce) 2240 x 1220 x 18 mm delivered to the testing fabrication workshop.

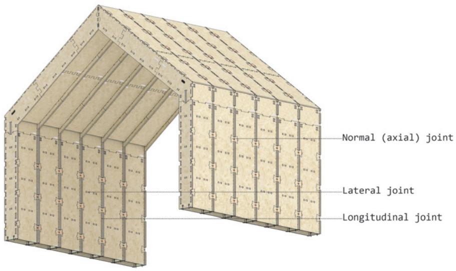

Figure 1
Type of joints of the WikiHouse Skylark 250 modules

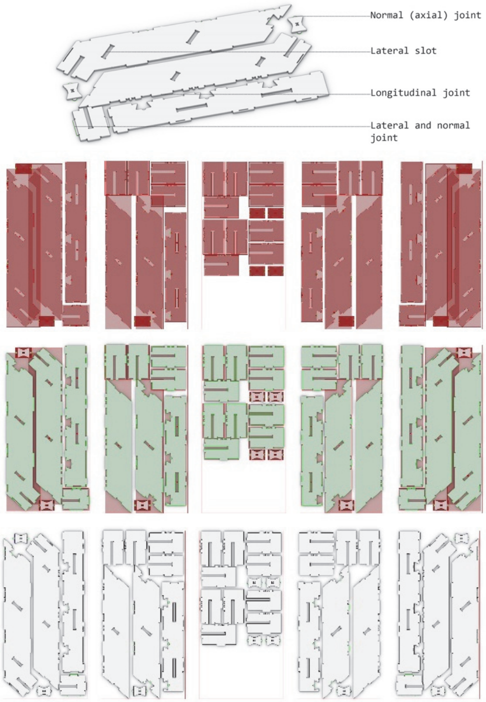

Figure 2
Modified geometry of the Skylark 250 Verge-G components according to the calculation of the tolerance model.

The assumed plywood equilibrium moisture content is 10 %. This value is set as an initial condition in the parametric model, however, this can be modified by the user according to the measured value in reality if the moisture is going to be changed rapidly, for instance for on-site assembly. This is significant, especially in subtropical or tropical environments, where there is a high difference between outdoor and indoor environments (e.g. warehouse, air-conditioned workshop).

This situation is further complicated by the need to determine the criteria for optimal fit, as the smart Wikihouse modules operate with joints in X, Y, and Z directions (see Figure 1). So how is it possible to achieve the perfect fit while allowing a smooth and straightforward assembly process?

Factory-related imprecisions

It is assumed that the delivered stock material is not precisely 18 mm due to a variety of factory-related imprecisions, that are not foreseen. For manufacturing, it is recommended to measure the delivered stock and find the imprecisions related to the thickness of the material, which will serve as an input parameter in the tolerance model. In the case of a large number of sheets ready to be milled, it is not possible to measure all sheets and individually set up the manufacturing process for each piece. One average thickness out of a certain amount can be taken as an input condition for the manufacturing setup.

The imprecisions related to the machining processes and tools cannot be predicted. It is necessary to test the first assembly of components at the beginning of the manufacturing process to set up and calibrate the tools properly. This was observed in the 1:1 scale prototyping process in the workshop setting before the on-site assembly. It is crucial to conduct these tests to avoid any manual assembly difficulties or use of wrong milling tools. For example, the process and the time length of manufacturing are also influenced by the sizes of the tools used in the process, as smaller diameters of the cutters require more time for the machining process. This can only be known by prior testing.

PARAMETRIC MODEL

According to the above-mentioned parameters, the parametric model modifies the WikiHouse shape geometry (2D to 3D shapes from the WikiHouse library), aiming to find more appropriate tolerance dimensions related to the current conditions in the workshop or on-site environment and considering the material property of spruce.

The parametric model, implemented in the Rhino/Grasshopper environment, incorporates parameters such as:

- the measured thickness of the material,
- input geometries as separate entities, i.e. profile curves, internal slots and holes, and ½ thickness milling areas for milled pockets according to which the dimensions of particular components are extracted,
- components for butterfly-like connectors with those three layers,
- parameter of change of equilibrium relative humidity,
- hydroscopic swell ratio according to the change of ERH,
- expansion / contraction ratio according to the change of ERH.

The model operates with a more complex data tree to sort the particular data related to the extracted geometry from the provided WikiHouse shape files with different types of layers.

There are separate geometry types as user-defined inputs of the model (profile curves, internal slots and holes, and milling pockets). The butterfly connectors are embedded in a separate calculation algorithm for a better orientation in the GH definition (also with a separate geometrical layers) and for the later nesting customization of the distribution of the components on the stock sheet material.

The parametric calculation then contains two significant variables:

- Expansion (or Contraction) of length or width of the components (e),
- Swell thickness (s), expressed in following:

$$e = \left(\frac{q}{10} r_e\right) \times \left(\pm \frac{l}{25.4}\right) + l \qquad (1)$$

while q represents prametrically user-defined percentual change in equilibrium relative humidity, r_e is the hydroscopic expansion ratio (0.00508 mm for each 10 % change of q) and l stands for the length (or width) of the measured or proposed length of the component. And the swell calculation is expressed as:

$$s = \left(\frac{q}{10} r_s\right) \times \left(\pm \frac{t}{25.4}\right) + t \qquad (2)$$

while $s$represents the final swell thickness considering the measured component thickness t, and r_s represents the hydroscopic swell ratio (0.254 mm for each 10 % change of q). The numerical value of 25.4 is defined in mm (1 inch). $\pm$ value of the variable l/25.4 or t /25.4 represents the expansion or contraction, depending on whether the change in q increases or decreases.

At this stage of the report, the ratios are related to the spruce plywood, and different types of veneers may differ, such as birch plywood (Li at al, 2016). The ratio can be modified as a user-defined variable in the model. Bringing these calculations into the algorithmic definition to modify the given WikiHouse geometry, the maximum swell tolerance difference is calculated as $\pm$ 0.18 mm and the maximum expansion length difference is $\pm$ 0.45 mm based on the longest component, considering the q variable is 10%, and the r_e = 0.00508 and r_s = 0.254. This difference is evenly distributed through the component geometry according to the default geometry of the given WikiHouse files.

The internal slots, profile curves, and pockets have been modified according to those properties in their dimensions in the parametric definition (available via this link as an open source content: https://github.com/peterbus/Parametric-Tolerance-Model-for-Numerically-Controlled-Digital-Fabrication-.git) (Github, n.d.) (Figure 2). The output geometry can be further sent to post-process setup for the NC manufacturing via standard CAM tools, e.g. Autodesk Fusion 360 (Figure 3). The model has been tested using the data files for the Skylark 250 Verge-G components first, before being applied for a custom scenario for the customized WikiHouse scenario dataset.

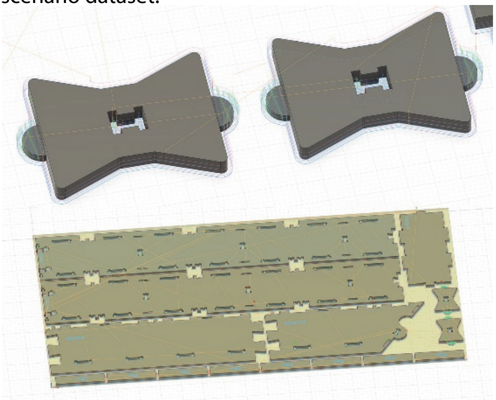

Figure 3
Manufacture setup and post-production to generate NC files for butterfly and standard components

Figure 4
Pre-prototype and assembly of the components to test the tolerances

Pre-prototype test and assembly

The standard WikiHopuse components were tested as a simple assembly first in the off-site workshop to test the default tolerances, without any considerations of the tolerance model being applied. The several components were milled utilizing a large-bed CNC machine.

The first test of the wall assembly was successful, with no specific difficulty during the assembly process (see Figure 4) from the delivered spruce plywood with an assumed standard moisture content of 6-14%, and with average environment humidity of around 50-60 %. The default tolerances defined by the WikiHouse files were acceptable.

According to this test, the final data were prepared for the pre-fabrication process, and the pre-fabricated Skylark modules as a kit of parts were delivered on-site for the final assembly.

ON-SITE DELIVERY AND ASSEMBLY 1:1

The tolerance model has been adapted and modified after the customised Wikihouse scenario had been assembled on the construction site in 1:1 scale utilizing the default tolerances. The location of the site was in a subtropical environment, where there is a difference between the air-conditioned workshop or a production facility and the outdoor environment.

On-site Conditions

The humidity of the selected urban site for the 1:1 scenario built project was higher as in the testing workshop or a main production facility, which was around 70-75 %. In addition, some days of the assembly process were rainy, which made the conditions even more humid and this had a huge impact on the components, stored on-site.

There were two crew groups involved in the assembly process onsite, which also brought certain embedded mistakes into the process of the assembly, as the second group continued working after the first group left. Neither group to precisely followed the recommended assembly sequence (Figure 5), both being less skilled at the beginning.

Figure 5
On-site assembly process and alignment of sections

This influenced how the partial sections of the assembly fit together and how they were eventually aligned.

Observations

It was observed during the assembly process that the fabricator delivered components that had been produced in different environmental conditions compared to the pre-prototype testing scenario. Additionally, the components remained for several days prior to assembly in the outdoor environment, with the relative humidity 75-85%.

From the perspective of the assembly, the most problematic on-site situation was the right and precise alignment of the particular sections of the assembly, when tightened together, such as pre-assembled wall assemblies.

The components themselves were fitting together well, however, the number of joints used in the assembly required a very high level of precision, including a flatter platform upon which the components were to be assembled. This means that if the platform or the first section of the assembly has a certain ratio of a difference in alignment, the mistake accumulatively exacerbates and the deviation of the non-aligned sections is tremendous.

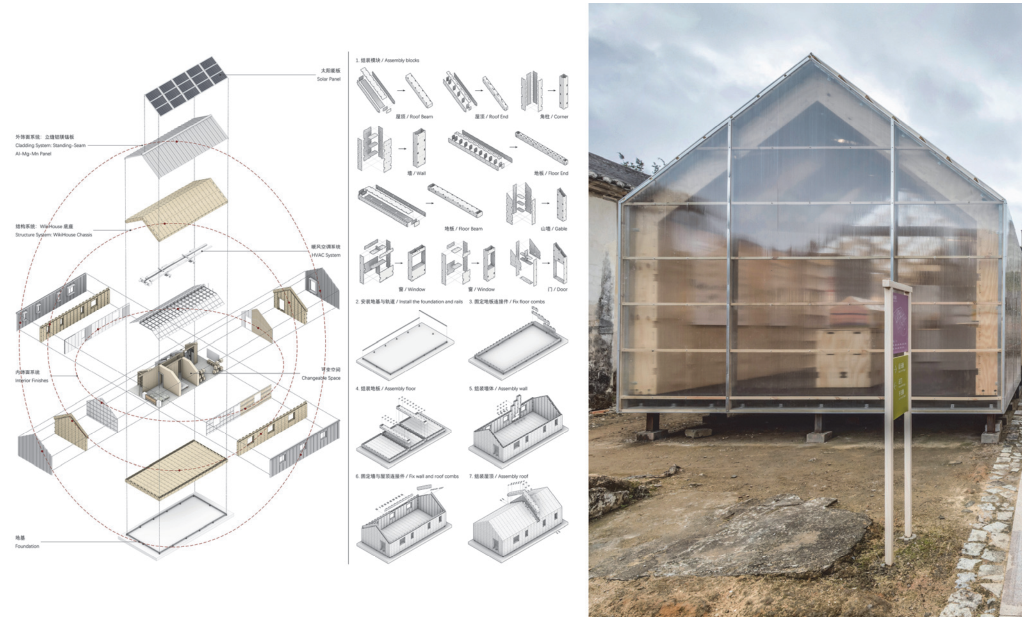

Figure 6
Assembly diagram of the scenario and the 1:1 scale prototype (authors & students: Jixuan Bao, Wenqi Wang, Xiaoyue Qiu, Qi Wang, Ruojun Ren)

Apart from the alignment of the particular sections, the butterfly joining components had to be slightly adjusted (1 mm sand off) to perfectly align the walls components when joining and aligning them together.

After the rain had occurred and the moisture content raised, the assembly process of the kit of parts was more problematic, as the edges of the slots and profile outlines swelled.

However, the minor alignment issues were addressed and the assembly utilizing manual tweaking and standard tools was successfully erected in 1:1 scenario of the pre-fabricated housing prototype (see Figure 5 and 6).

DISCUSSION AND LIMITATIONS OF THE PROPOSED TOLERANCE MODEL

Although the model has not been fully tested and verified in different climate zones, weather conditions in different scenarios, and using a variety of production facilities, the authors argue the proposed tolerance engine may serve as an initial platform to be applied when dealing with unpredictable situations in terms of weather changes during the process, building in a subtropical climate, especially where there is a big difference in temperature affecting the moisture content, differences in outdoor and indoor environments (off-site and on-site) in terms of the large variation of humidity.

Additional differences in the machining processes of a testing facility and other factory-related conditions of a fabrication facility are not specifically included in the model, however, it is necessary from case to case to test the machining process first before the final production and address all differences. The model can be also used in situations when the delivered components are stored temporarily in the outdoor environment where the relative humidity can be higher.

From the perspective of the authors' previous experience, it is advisable to operate with fewer joints (for instance butterfly joints can be reduced from 5 to 3 in the assembly of walls should the structure permit) to address the alignment problem easier. It should also be noted that the design of the object itself also significantly influences how smooth the assembly process will be.

CONCLUSION

The paper introduced a parametric tolerance model for a customized WikiHouse prefabrication and delivery scenario, which can be implemented in the production workflow to deliver kit-of-parts components. It implements a variety of parameters that influence the dimension of tolerances to compensate for the moisture-driven dimensional stability of a species-specific plywood sheet material, in this case, spruce.

The tolerance model as an open-source system for geometry modifications is available for designers and experts as a scalable and extendable computational framework with additional options to be enhanced with different material scenarios (embedded hydroscopic ratios for different plywood types or timber) via (the link will be added in the camera-ready paper).

For successful implementation, it is necessary to test the simple assembly of components first, before the final production, and tweak necessary parameters or imprecisions.

In general, there is a systemic embodiment of certain types of factors that affect the imprecisions of the components, that are supposed to be assembled after the fabrication and production. This model aims to address some of those. However, more qualitative factors were observed during the production and assembly process in real conditions onsite, which affect the success of the final assembly.

There is also an argument related to the location of the production delivery, whether the production of the components has to be available on-site. It was observed that this is very individual as some of the given conditions do not allow the manipulation and production on-site due to a variety of practical and space-related limitations, however, this argument requires deeper study and understanding of a variety of situations, including other options to locate the manufacturing (production) facility nearby the site location in a same or different environment in terms of humidity or temperature, which, in fact, influences the moisture content in the material.

The proposed engine can be a starting point to understand more deeply the aspect of tolerances and how the tolerance model can be embedded within the production workflow of architectural or another kit of parts-driven scenarios.

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