# Applying the Concept of Selective Assembly to Modular Construction to Mitigate Impacts of Component Variability

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**Abstract –**

**As adoption of offsite methods of production continues to grow within the construction industry, optimization techniques from manufacturing are increasingly being utilized analogously for increasing productivity, reducing rework, and improving assembly processes. This paper demonstrates how the concept of selective assembly can be applied in modular construction as a potential assembly optimization technique. Rather than specifying and controlling tight fabrication tolerances, the selective assembly process groups components into bins or categories of compatible dimensional and geometric properties in order to find an optimal arrangement of interchangeable components in an assembly. This concept has traditionally proven to be more cost effective in certain manufacturing applications than using rigorous specification and control of tight fabrication tolerances. Using a laser scanner for as-built data acquisition, a modular steel bridge is analyzed as a case study to demonstrate how the concept of selective assembly can be applied in modular construction. The results of this case study show that selective assembly has potential to reduce rework in certain modular construction applications.**

**Keywords –**

**Selective Assembly; Tolerance Control; Modular Construction; Geometric Variability; Assembly Planning; Interchangeable Components**

## 1 Introduction

The paradigm shift in the construction industry towards offsite methods of production has raised the question about how to specify adequate component tolerances to ensure that fit-up and onsite installation are not met with serious challenges such as cost overruns, delays and extensive rework. While the traditional approach of benchmark tolerances has been used in stick-built construction [1], these same component tolerances are often not strict enough to ensure problem-free fit-up of components and modules in modular construction projects [2-4]. Dimensional coordination is thus a vital aspect of production in modular construction.

Two comprehensive approaches can be taken to develop adequate component tolerances for modular construction: (1) development of a new set of benchmark tolerances specifically for use in modular construction projects, or (2) creation of a systematic tolerance design through utilization of tolerancing theory employed in manufacturing (i.e., tolerance analysis, tolerance synthesis, vector loop models, etc.). These two solutions are non-trivial and can be very intensive to implement. Both of these approaches tackle the challenges faced in component fit-up and installation during the design phase by either proper selection or adequate design of critical tolerances. However a third approach is also viable, by solving component fit-up and installation challenges during the assembly phase through collection and analysis of 3D as-built data. This third approach uses a technique found in the manufacturing industry called selective assembly. The basic premise behind this technique is to measure and organize parts which are to be mated together into classes or bins of dimensional compatibility. Selective assembly is traditionally used to achieve tight clearance tolerances between mating parts that are manufactured using imprecise techniques; leading to high quality assembly using inexpensive techniques [5-7].

Modular construction has great potential for implementing selective assembly, since numerous components are often manufactured and assembled into repetitive modules. Even with the use of precise methods of dimensional control during production (i.e., framing tables, fixtures and jigs), offsite construction modules can experience geometric conflicts during fit-up and erection on site. Furthermore, not only are modular construction components often manufactured to be interchangeable (i.e., utilization of economies of scale), but fabrication and assembly processes themselves are also intrinsically highly repetitive. Process and product repetition are essential requirements for implementing selective assembly. Due to its intrinsic product and process repetition, modular construction has the potential to successfully use selective assembly to optimize assembly processes.

This paper investigates the use of selective assembly in an ad-hoc manner by optimizing the aggregation of mating parts in a small-scale modular steel bridge. The scope of this paper is limited to selective assembly on a simple 'bare-bones' structural assembly. However, the methodology can be applied to more general structural systems such as modular steel frames (Figure 1), where there is sufficient repetition of processes (e.g., cutting, fit-up, alignment, welding), and quantity of modules.

(a)

(b)

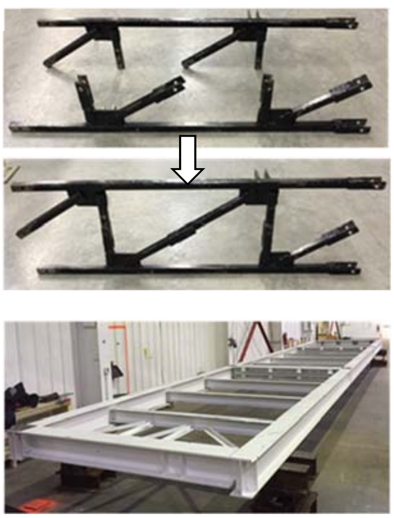

Figure 1: (a) case study in this paper examines the mating parts in modular steel bridge, (b) methodology can be generalized for mating parts in prefabricated steel systems such as modular steel frame assemblies.

# 2 Background

## 2.1 Overview of Selective Assembly

The need for tolerances within the production of parts arises because variability is inevitable. Regardless of the amount of effort placed into controlling the dimensional and geometric properties of production processes, some degree of variability cannot be avoided. However, there are certain types of variability which have larger impacts than others on ease of assembly. These specified limits of variability, known as tolerances, are used to target critical sources of variability in order to control certain dimensional and geometric attributes of parts so that production goals can be met in way which balances cost, quality and customer satisfaction [8].

Production variability is an issue that emerges in many industries, including manufacturing. While the use of expensive equipment and precise production methods is a common approach for controlling critical variability in manufacturing, selective assembly is a valuable quality improvement tool which sidesteps the use of expensive equipment and precise production methods. Select assembly is a dimensional quality improvement tool used to determine optimal pairs of mating parts from stockpiles which are nominally identical [6,7,9].

One of the simplest examples used to demonstrate selective assembly is the aggregation of shaft and sleeve parts. In this example, the critical dimensions for aggregation are isolated (e.g., the radius of each part). Assuming the critical aggregation dimension of a given part can be modelled by a normal distribution with a certain tolerance threshhold (Figure 2-a), then sample distributions will vary within an allowable variability region (Figure 2-b). Then, as the stockpile for each part is populated, critical dimensions can be quantified and parts organized into bins which enable optimal aggregation. As seen in Figure 2-c, if four randomly selected sleeve and shaft parts are selected from their respective stockpiles, it is clear that based on their respective dimensional distributions, that an optimal set of best-fit pairs does exist.

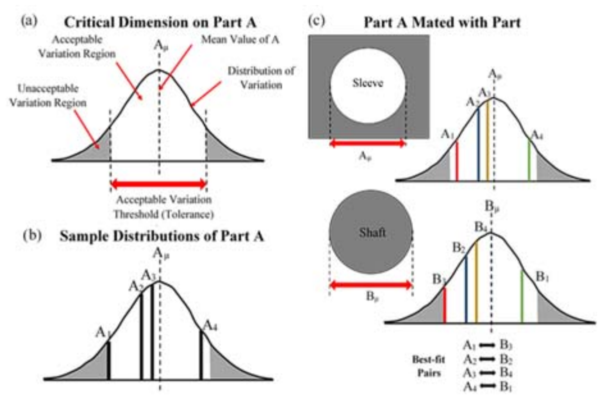


Figure 2: Demonstrating the concept of selective assembly: (a) dimensional distribution of critical feature for aggregation, (b) sample distributions of feature and (c) optimal matching of sleeve and shaft parts based on the distribution of critical aggregation features.

## 2.2 Current State of Selective Assembly

Selective assembly has been used in the manufacturing industry for years. Typical applications include the assembly of ball bearings and joints [10], production of pistons and cylinders [7], production of scroll compressor shells [11], and is still used in the assembly of engines, transmissions, and compressors [12].

The use of statistical selective assembly was introduced as a way of optimizing assembly based on the dimensional distribution of mating components, which for a number of years focused on parts with similar dimensional attributes that follow the Normal distribution [7]. In order to generalize statistical selective assembly, researchers began introducing novel grouping methods to reduce the dependency on the constraint that parts must have similar distributions [13,14]. The efforts to generalize statistical selective assembly opened a new area of research surrounding optimal binning strategies for a range of applications.

Binning strategies can either be designed before production, during production, or post-production (note that in the case of post-production, parts have been manufactured, but mating parts still await aggregation). Since selective assembly encompasses measuring part dimensions after they have been produced, it is often preferable to design the binning strategy after the design stage, in a prototypical manner. Performing selective assembly during production (before all parts have been manufactured), often utilizes a buffer system where bins are populated and depleted in real time [11]. In terms of the manufacturing environment, selective assembly is typically better suited for batch production rather than mass production, since the extra steps to utilize selective assembly in mass production can create congestion and bottlenecks, which is less likely to occur in batch production due to the lower production rate [9].

While research on selective assembly has focused exclusively on manufacturing applications, the proposed methodology demonstrates how selective assembly can be used in modular construction. Reasons why selective assembly can be used as a quality improvement tool in modular construction include (1) the ability to achieve tight tolerance requirements without the use of a rigorous tolerance design, and (2) the use of production techniques currently employed in stick-built construction rather than adoption of highly precise equipment which can be very expensive. Modular construction also often resembles batch production manufacturing more so than mass production, making it very favourable for application of selective assembly.

### 2.3 Production Optimization Methods in Modular Construction

In the area of production optimization for modular construction, numerous methods can be employed. This section briefly introduces two production optimization techniques which achieve similar goals as the proposed methodology: application of lean principles, and design for manufacturing and assembly (DfMA).

Lean production principles, which first emerged in the Japanese manufacturing industry, are a collection of practices that aim to increase productivity, maximize value, and minimize waste [15]. While the application of lean principles in modular construction can significantly improve project performance [16-18], there still exists some key challenges with respect to the dichotomy between design and construction. For instance, Sarhan and Fox [19] found that in lean construction, there is often a conflict border between design and construction, resulting in inaccurate designs, rework, lack of constructability, and final products with significant variation from specified design values.

Design for manufacturing and assembly (DfMA) is a common design approach used in the manufacturing industry for optimizing production costs by addressing the trade-off between manufacturing and assembly that exists for various processes [20]. With respect to component tolerances, strict tolerances allow for easy assembly, however often come at an increased manufacturing cost. As such, DfMA is an effective design approach to evaluate tolerance decisions with respect to both manufacturing and assembly processes in order to determine an optimal component tolerance value. While DfMA is primarily only used in the manufacturing industry, recent efforts have been made to adopt its use for construction. Design for construction (DFC) is one of these efforts, and utilizes three key ideas: (1) design for manufacturing and assembly (DfMA), (2) lean production and (3) constructability [21]. DFC aims to capture tacit knowledge learned from previous production problems, so that unnecessary rework is minimized in future projects.

Some of the key goals of lean production and DfMA in modular construction are increased productivity, greater constructability and rework reduction. Current production optimization techniques in modular construction do not offer a systematic approach for managing problems that are often encountered in the assembly of modular components. To address this, selective assembly tackles the problem from a very unique perspective – by measuring and grouping components in order to optimize production processes.

## 3 Proposed Methodology

This paper demonstrates how the principles of selective assembly can be applied to modular construction to optimize the aggregation of repetitive pairs of components. Since selective assembly relies on sorting pairs of components based on the dimensional distribution of features that make up the physical interface between components, it is easier to develop an optimal strategy using as-built data rather than theoretical predictions. As such, the proposed use of selective assembly is applied after production has finished (i.e., parts are manufactured, but await aggregation). The proposed framework (Figure 3), is comprised of three key steps: (1) identify critical interfaces between components and tolerances, (2) calculate the minimum number of bins required, and (3) organize parts into bins based on a binning strategy.

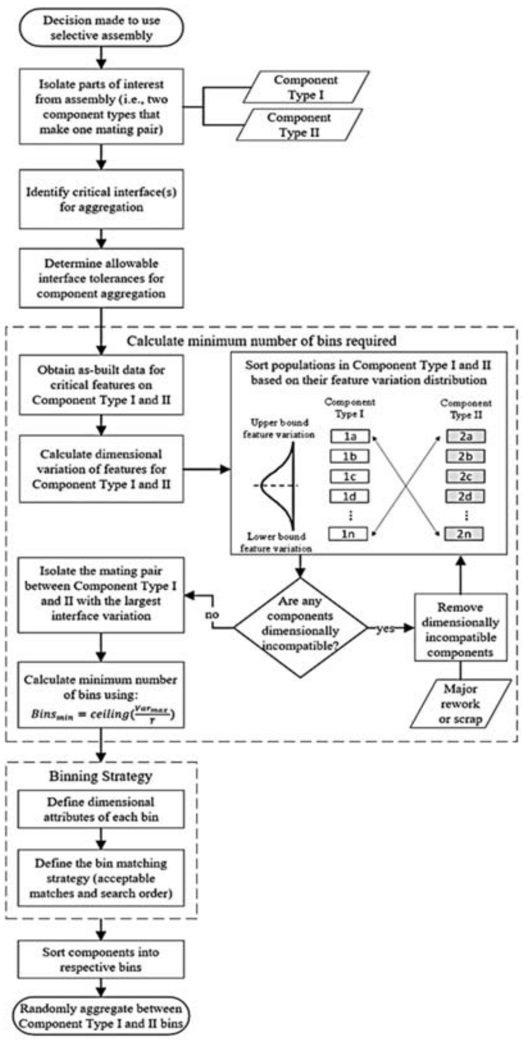


Figure 3: Framework of proposed methodology

## 3.1 Isolating the Critical Interfaces and Determining Aggregation Tolerances

The critical interfaces between components are the physical regions or points on components in direct contact with each other. The dimensional variation of features that make up the critical interfaces on the as-built components must be determined. Laser scanning is proposed for this purpose based on its ability to yield rich and accurate data [22]. One of the most challenging aspects of applying selective assembly lies with determining tolerances that govern adequate component aggregation. For this purpose, three approaches can be taken: (1) measure variation on prototyped pairs (2) use previous experience or benchmark tolerances, or (3) conduct a systematic tolerance analysis.

## 3.2 Calculating the Minimum Number of Bins Required for the Binning Strategy

Before calculating the minimum number of bins required in a binning strategy, it is important to ensure that all components are dimensionally compatible based on the allowable aggregation tolerances. For checking dimensional compatibility, each isolated component must have at least one possible mating component, otherwise it will not be able to aggregate properly. In the event that dimensional incompatibility exists (i.e., the geometry variability of a particular component is such that it cannot connect with any other component), major rework or component scrapping is required (depending on which option is least expensive or time consuming). Finally, the minimum number of required bins ($Bins_{min}$) is calculated using:

$$Bins_{min} = ceiling(\frac{Var_{max}}{T}) \quad (1)$$

where $Var_{max}$ is the maximum measured interface variation between all possible pairs, $T$ is the allowable aggregation tolerance and $ceiling$ is a function that rounds up to the nearest whole integer. Although the minimum required bins is calculated here, a larger number may be used, depending on desired accuracy. In general, increasing the number of bins decreases assembly variations, but also increases the likelihood of having surplus parts, disproportional bin populations, and decreased overall effectiveness [11]. Selective assembly in manufacturing usually aims to achieve low assembly deviations since most mating parts are moving (i.e., pistons in automotive engines). However for modular construction, the level of assembly deviations only needs to ensure adequate component aggregation, and parts are typically not designed to experience movement after aggregation. As such, it is preferable to minimize the number of bins for selective assembly in modular construction.

## 3.3 Developing the Binning Strategy

The next step for applying selective assembly is determining the binning strategy, which outlines how components are organized into bins and how bins are matched together. Two common ways to partition the dimensional attributes of bins are (1) equal dimensional width or (2) equal probability. Equal width partitioning divides the total interface variability equally between bins, while equal probability partitioning ensures that each bin has equal populations of components [5]. Matching criteria defines how components are matched between bins. Traditional methods include one-to-one matching (each bin has exactly one other matching bin), or one-to-three matching (each bin has one matching bin but can pull from adjacent bins to the matching bin if need be) [11]. The methodology for developing the a binning strategy is outside of the scope of this paper, however based on the results of the case study, the authors recommend using equal probability bin partitioning and one-to-one matching due to its simplicity. Since modular construction typically has a lower number of mating pairs of components than in manufacturing, and since part inventories are not common, everything should be matched on each project. These factors lend themselves to have equal probability bins (avoiding surplus parts), and one-to-one matching (to ensure that every part is matched). After the binning strategy has been determined, components between matched bins can be randomly aggregated.

# 4 Modular Bridge Case Study

A 6 m long modular steel bridge designed and built by the University of Waterloo Steel Bridge Team is examined. The bridge is comprised of hollow steel section members, and has five types of assemblies or modules that are bolted together (Figure 4). As part of a modularization strategy, 24 assemblies were designed as interchangeable top and bottom pairs (A2 and A3 in Figure 4-c). During construction, selective assembly was utilized as an approach for mitigating the impact of fabrication error (accumulating effects of cutting, milling, fit-up, measurement, welding distortion, and inspection). Selective assembly was applied for the aggregation of the top and bottom pairs.

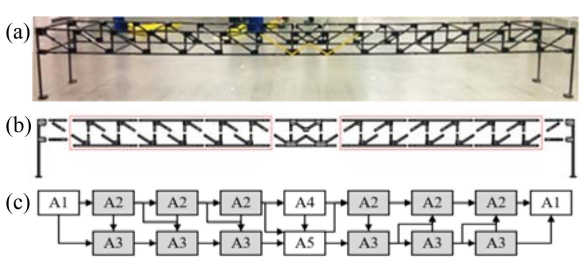


Figure 4: (a) Fully assembled steel bridge, (b) deconstructed single truss, (c) assembly diagram of single truss showing the five main assembly types.

## 4.1 Critical Aggregation Interfaces

For each top and bottom assembly pair (A2 and A3), there are three direct contact points that make up the aggregation interfaces. Of these interfaces, two critical dimensions are extracted: (1) an angular dimension, ϴ, and (2) a linear dimension, X, as illustrated in Figure 5. Aggregation between top and bottom pairs is assumed to rely on the compatibility of these critical dimensions.

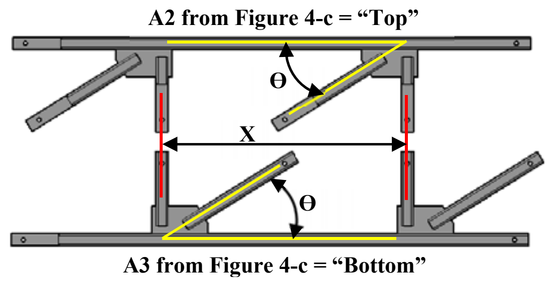


Figure 5: Repetitive assembly pair in case study, with critical interface dimensions as ϴ (yellow) and X (red).

The as-built data of the critical interface dimensions were obtained by conducting coordinate probing using a laser scanner (Faro Edge Arm). This device has an accuracy of 0.024 mm for the working length employed [23]. Coordinate probing was used since each part can be reduced from its as-designed model into a centreline model, and then to a series of critical coordinates at the interface points (Figure 6).

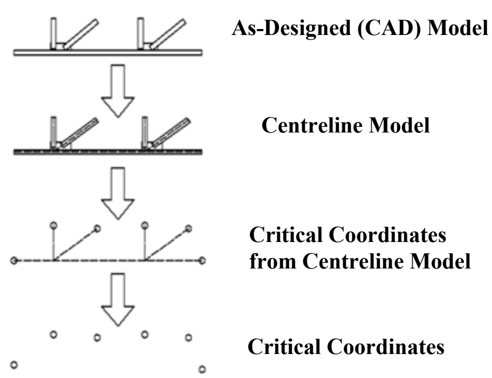


Figure 6: Process of Extracting Critical Coordinates from Original As-Designed Model

Selective assembly in this case study depended solely on the centreline alignment of the physical interfaces for top and bottom pairs. Rework during aggregation is assumed to be constrained to shimming (i.e., extending the length of a member at an interface) and grinding (i.e., reducing the length of a member at an interface). This type of rework is much less intensive than having to cut, realign and weld a member into proper position (which does not necessarily eliminate the need for grinding and shimming at interfaces). After critical interface coordinates were obtained, populations of top and bottom components were sorted based on the distribution of each critical dimension (Table 1).

Table 1: Sorted Populations of Top and Bottom Components based on Distribution of Critical Aggregation Dimensions

| Dim Θ (degrees) | | | | Dim X (mm) | | | |
|---|---|---|---|---|---|---|---|
| ID | A2 (top) | ID | A3 (bot) | ID | A2 (top) | ID | A3 (bot) |
| 10 | 30.67 | 1 | 31.44 | 8 | 393.17 | 6 | 392.48 |
| 6 | 31.62 | 8 | 31.88 | 9 | 393.35 | 9 | 393.79 |
| 9 | 31.67 | 3 | 31.95 | 11 | 393.53 | 8 | 394.58 |
| 2 | 31.90 | 11 | 32.02 | 2 | 395.06 | 12 | 394.58 |
| 5 | 31.94 | 7 | 32.21 | 12 | 395.27 | 11 | 394.82 |
| 7 | 32.29 | 4 | 32.33 | 4 | 395.59 | 1 | 395.32 |
| 4 | 32.32 | 12 | 32.37 | 6 | 395.62 | 4 | 395.44 |
| 12 | 32.51 | 5 | 32.55 | 10 | 395.66 | 5 | 395.97 |
| 11 | 32.97 | 2 | 32.58 | 5 | 395.71 | 10 | 396.04 |
| 8 | 33.07 | 9 | 32.80 | 1 | 396.07 | 2 | 396.97 |
| 3 | 33.51 | 6 | 33.09 | 3 | 396.26 | 3 | 397.10 |
| 1 | 33.60 | 10 | 33.40 | 7 | 398.89 | 7 | 399.37 |
| Nominal Dim – 32.9 | | | | Nominal Dim – 396.88 | | | |

## 4.2 Binning for Critical Angular Dimension

Using the sorted populations of top and bottom components, the first iteration of binning was carried out for the critical angular dimension, Θ (Figure 5). Since the allowable tolerance for this dimension was not specified in the design, it was determined through prototyping. The maximum angular discrepancy between Θ values of top and bottom components for a successfully aggregated pair was measured as 2.72° from testing all possible component pairs. Since all possible top and bottom pair combinations result in angular discrepancies equal to or less than 2.72°, a single bin can be used for each top and bottom population for aggregation based on Θ. As such, a binning strategy was not required for the critical angular dimension, since random aggregation can proceed between all possible top and bottom pairs.

## 4.3 Binning for Critical Linear Dimension

Using the sorted populations of top and bottom components, the second iteration of binning was carried out for the critical linear dimension, X (Figure 5). The allowable tolerance for this dimension was specified in the design as +/- 1/16” (1.588 mm), since the bolt hole diameters are 1/16” (1.588 mm) larger than the bolt diameter used. As such, the tolerance range is equal to 1/8” (3.175 mm) to account for the case where an upper bound deviation is matched with a lower bound deviation. One final check was performed before determining the minimum number of bins to ensure that no components would be rejected based on dimensional incompatibility: for every bottom component there is at least one top component that does not exceed the allowable tolerance, and for every top component there is at least one bottom component that does not exceed the allowable tolerance. This check yielded no dimensionally incompatible components. Using the largest deviation between critical linear dimensions for all possible pairs (6.41 mm) and the tolerance (3.175 mm), the minimum number of bins was calculated using (Equation 1): $Bins_{min} = ceiling\left(\frac{6.41\ mm}{3.175\ mm}\right) = 3$. Since the minimum number of bins is greater than 1, random aggregation cannot proceed between all top and bottom pairs, and a binning strategy is required.

The binning strategy uses a one-to-one strategy, where every bin for top components has exactly one matching bin for bottom components. Furthermore, equal probability partitioning is employed to avoid having surplus components. Since the combined width of all bins (3 x tolerance = 9.525 mm) is larger than the largest deviation between all possible pairs (6.41 mm), several bin arrangements are possible. A script was compiled in MATLAB to find that there 8 possible bin arrangements (Figure 7).

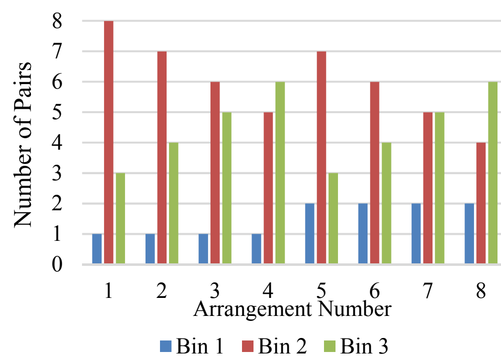


Figure 7: Bin Populations for all Possible Bin Arrangements Based on the Critical Linear Dimension

## 4.4 Selection of Optimal Bin Arrangement

While each of the 8 possible bin arrangements yield dimensionally compatible component pairs, there exists a specific arrangement with a statistically optimal amount of rework avoidance. There are two approaches for selecting the optimal bin arrangement in this case study: (1) absolute rework avoidance or (2) least expected rework. Absolute rework avoidance finds the pairs of components in each bin with the largest possible deviation. Then, these values are summed together and used for comparison to find the bin arrangement with the least overall deviation (Table 2).

Table 2: Maximum Deviations for Critical Linear Aggregation Interface for all Possible Pairings in Each Bin Arrangement (all deviations in mm)

| Arrangement | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Bin 1 | 0.48 | 0.48 | 0.48 | 0.48 | 3.11 | 3.11 | 3.11 | 3.11 |
| Bin 2 | 2.04 | 1.83 | 1.51 | 1.48 | 1.91 | 1.70 | 1.38 | 1.35 |
| Bin 3 | 1.41 | 2.58 | 2.79 | 3.11 | 1.41 | 2.58 | 2.79 | 3.11 |
| Sum | 3.93 | 4.89 | 4.79 | 5.07 | 6.43 | 7.39 | 7.29 | 7.57 |
| Average | 1.31 | 1.63 | 1.60 | 1.69 | 2.14 | 2.46 | 2.43 | 2.52 |
| Std. Dev. | 0.64 | 0.87 | 0.95 | 1.08 | 0.71 | 0.58 | 0.75 | 0.83 |

Least expected rework associates a probability of selecting a random pair with its deviation value. As such, this approach finds the most probable deviation to be expected between pairs in each bin. The expected deviations for each bin are summed together and compared to find the bin arrangement with the least expected overall deviation (Table 3).

Table 3: Expected Deviations for Critical Linear Aggregation Interface for all Bin Arrangements (all deviations in mm)

| Arrangement | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Bin 1 | 0.48 | 0.48 | 0.48 | 0.48 | 1.56 | 1.56 | 1.56 | 1.56 |
| Bin 2 | 0.79 | 0.72 | 0.65 | 0.66 | 0.67 | 0.59 | 0.51 | 0.52 |
| Bin 3 | 0.85 | 1.01 | 1.08 | 1.14 | 0.85 | 1.01 | 1.08 | 1.14 |
| Sum | 2.11 | 2.20 | 2.21 | 2.28 | 3.07 | 3.15 | 3.14 | 3.21 |
| Average | 0.70 | 0.73 | 0.74 | 0.76 | 1.02 | 1.05 | 1.05 | 1.07 |
| Std. Dev. | 0.16 | 0.22 | 0.25 | 0.28 | 0.38 | 0.40 | 0.43 | 0.43 |

As seen from both approaches, bin arrangement 1 is optimal since it has the least absolute rework and least expected rework. As such, it was selected for as the bin arrangement for this case study.

## 5 Discussion

The binning strategy in this case study was conducted by isolating repetitive pairs of component in a modular assembly, classifying them by distinct dimensional attributes and sorting them into bins that yielded component pairs that could be correctly assembled. Laser scanning was employed for as-built data collection primarily for its ease of capturing rapid and accurate data. Currently, the method of determining critical aggregation interfaces, and tolerances is manual and requires proper user judgement. Although the critical angular dimension was not directly used in this case study, it should be noted that a binning strategy needs to incorporate all critical dimensions. For instance, the ID numbers shown in Table 1 do not match up for a given component between each dimension. The distribution for the angular dimension does not match with the distribution for the linear dimension. This means that as the number of critical dimensions increases, it becomes increasingly more difficult to decrease the minimum number of possible bins.

As a result of the binning strategy shown in this case study, the component aggregation of mating pairs in the modular steel bridge proceeded with no major rework or wasted components. Before applying selective assembly, the fabrication team of this bridge attempted to apply random aggregation of top and bottom components without a binning strategy. Due to compounding effects of fabrication error, there were two instances of extensive rework, where members had to be cut, realigned and welded into proper alignment. While the exact quantitative impact of this rework is unknown, the team found the results of binning components to yield component pairs that could be successfully aggregated.

The primary limitation of this case study lies in the assumption that component aggregation is solely based on the three direct contact points between top and bottom components (Figure 5). In this regard, the binning strategy finds optimal pairs locally, but does not consider the impact that a given assembly has on its adjacent neighbours (i.e., assemblies on either side).

## 6 Conclusions

This paper demonstrates how selective assembly can be used in modular construction to reduce the adverse effects of component variability. Variability is an unavoidable aspect of component manufacture and if not controlled properly, it can lead to severe conflicts during component aggregation. This was observed by the fabrication team in the case study, but also occurs in modular construction projects. Instead of conducting comprehensive tolerance designs, which is one approach used in manufacturing, selective assembly is a technique that can be applied during fabrication to avoid aggregation conflicts. The proposed binning strategy is shown to yield an optimal set of component pairs based on least overall deviation. It is reasonable to assume that rework is directly related to the amount of deviation between components, which means that the proposed framework for selective assembly results in an optimal rework mitigation strategy.

Future work of this research aims to extend selective assembly to include a more systematic approach for optimal assembly planning.

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