

# A SYSTEMATIC DESIGN FOR ASSEMBLY ASSESSMENT OF PREFABRICATED FACADE PANELS

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## ABSTRACT

Design for Assembly (DfA) is a key enabler of industrialized and off-site construction; however, its evaluation for building products remains fragmented and lacks sufficient structure. The existing literature examines several design factors in the assembly process and often employs qualitative methods. These methods usually lack the rigor needed for standardized assessment, highlighting the need for more practical and structured tools. This paper proposes a DfA-based systematic structure and practical evaluation tool tailored to prefabricated building products, with a particular focus on facade panels. Drawing on a Systematic Literature Review (SLR), relevant DfA factors and indicators are identified and organized into a Multi-layer Social Network (MSN) that links indicators, factors, and the overall DfA assessment at a high level. The proposed structure is applied to an industrial case study to demonstrate its applicability. The results highlight the potential of the proposed approach as a practical decision-support tool for improving assembly-oriented design and provide a transferable basis for evaluating other Design for Excellence (DfX) aspects.

## KEYWORDS

Design for Assembly, DfA assessment, prefabricated facade panels, Multi-layer Social Network.

## INTRODUCTION

The building industry is of significant interest compared to other industries (Taheripour et al., 2025). The growing demand for efficient building practices has led to industrialization (Taheripour et al., 2026). To support this transition, the building sector is increasingly adopting new concepts such as Design for X (DfX) (Hosnedl et al., 2016). DfX have become increasingly popular in the fields of production, research, and innovation. DfX is a method for creating products and processes that seeks to improve "X" across the product's lifecycle by focusing on the design phase (Ebikake et al., 2018). "X" stands for any aspect or phase of product, including assembly. Design for Assembly (DfA) is one of the most important methods in the large field covered by a large 'umbrella' of DfX. DfA has emerged as a prominent approach in the field of Off-Site Construction (OSC) (Nguyen et al., 2024), and arose in the early 1970s as a consistent process for developing products with ease of assembly (Ukala & Sunmola, 2020; Zhai et al., 2023).

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DfA was created to help designers by providing feedback on the influence of design decisions on product assembly (Shetty & Ali, 2015). Designers have traditionally separated design from production. However, this strategy necessitates redesigning the design after completion to address assembly concerns, which can be costly. DfA aims to prevent assembly errors by analyzing product assembly scenarios throughout the design phase (Jung & Yu, 2022). The goal is to assist the designer in producing an effective and economical design (Shetty & Ali, 2015). DfA is employed to reduce design complexity and minimize fabrication waste (Mehdipoor et al., 2025), and can guide building design decisions by analyzing assembly efficiency and controlling costs, thereby supporting industrialized construction practices (Boothroyd et al., 2010). These principles are closely aligned with lean construction and Target Value Design (TVD), as DfA emphasizes waste reduction, constructability, and early cost-informed design to ensure that project outcomes meet predefined value and cost targets. Numerous research has examined the factors and indicators that influence DfA in the building context. Among these is the research done by Matthews et al. (2018). They emphasized the reduction in the total number of product parts as a critical factor, which has been discussed by many other researchers (Tan, Lu, Li, et al., 2020; Tornow et al., 2015). Another important factor that contributes to assembly ease is the usage of symmetrical components in products (Go et al., 2015; Ukala & Sunmola, 2020). Many other factors have been investigated in the literature, the majority of which originated in manufacturing industries and were later adopted by the building sector. Factors identified in the literature are useful if they can be evaluated with precise indicators. In this regard, building products can be evaluated first using a set of factors and indicators and then improved depending on the results. However, research on DfA assessment for building products remains highly fragmented, with many studies focused on a single factor rather than an integrated view of many significant factors. For example, in research by Zhai et al. (2023), they created a DfA evaluation approach that incorporates formula design, the Delphi method, and the Analytic Hierarchy Process (AHP) method. This technique consists of two key components: the Assembly Efficiency Index (AEI) and the Assembly Design Index (ADI). This examination was completed using criteria such as component standardization, material diversity, the number of parts and connections, etc. Korean researchers (2024) developed an integrated OSC-Design for Manufacturing & Assembly (DfMA) assessment model that combines the OSC-DfMA production appropriateness assessment model and the OSC-DfMA production efficiency assessment model to assist decision-makers in selecting the optimum design option for an OSC project. They conducted this assessment using a checklist that included parameters such as the number of mold types, mold reusability, total number of modules, module size and weight, joint accessibility, and so on (Jung et al., 2024). The majority of research on DfA evaluation has been conducted in the manufacturing industries. Because DfA originated in the manufacturing industries and spread to the construction sector as a result of the development of industrialized construction methods. Building products differ significantly from industrial products in terms of assembly, including different factory work procedures, production scales, and product dimensions. The existing literature does not include a study that comprehensively compiles factors and indicators for evaluating DfA of building products. As a result, the current study addresses this gap by incorporating DfA-effective factors and their accompanying indicators into a cohesive structure. To achieve this, the research outlines the following objectives:

1. Identify the factors and indicators influencing DfA based on the literature
2. Develop a system for assessing the DfA
3. Implement the proposed system in a real-world case study

This study is part of an extensive research project that links university labs with industry partners and professionals in the design, production, logistics, and construction domains. The

following Methodology section provides a detailed description of the prefabricated facade panel that is the case study examined in this project. The next section highlights the research background by reviewing related factors and indicators. After that, it presents the results related to the implementation of the proposed system in a real case and a critical discussion of the results. Finally, the last section presents the conclusion, which includes the key results, research limitations, and opportunities for future research derived from these limitations.

## METHODOLOGY

Based on Figure 1, a multi-step research method consisting of SLR, creating a Multi-layer Social Network (MSN) structure, and implementing in a real case study is adopted in this study. First, an SLR was conducted, which concluded 123 relevant papers and documents.

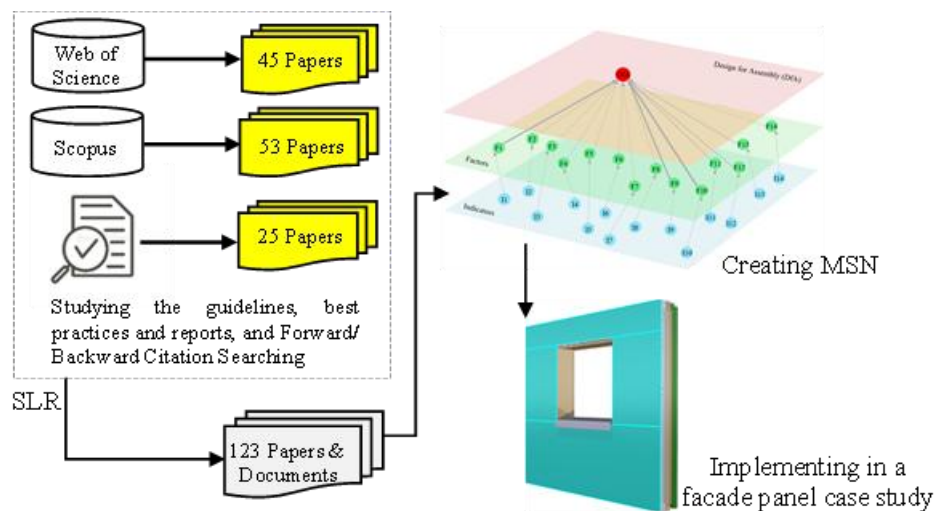


Figure 1: An overview of research methodology

Search strings containing keywords such as “Design for Assembly” OR “DfA” were searched across two databases: Scopus and Web of Science. The publications were filtered based on several criteria, including period (2015-2025), English language, research area, document type, subject area, Web of Science categories, publishing stage, keywords, and source title. The initial filter identified 565 papers. In the following step, 453 papers were rejected for being irrelevant based on their titles and abstracts. Finally, after eliminating duplicate publications, 98 relevant papers were identified. The next phase in the literature study was to conduct forward/ backward citation searches, as well as searches in guidelines, best practices, and reports, to ensure the comprehensiveness of the search results. This approach revealed an extra 25 papers. The indicators and factors presented in these 123 documents were extracted using NVivo software. 14 factors influencing DfA were identified, along with indicators for measuring these factors. The score for DfA was then established in connection with the specific characteristics of a case study using an MSN, which included layers for indicators, factors, and DfA. An MSN is defined as a collection of layers, where each layer consists of a unique set of nodes and edges. Unlike single-layer networks that consolidate all relationships into a flat structure, an MSN allows the distinct characteristics of each relationship type to be preserved within its layer. It enables the assessment of mutual interdependencies between different layers (Farooq et al., 2018), which is critical for understanding how effects or disruptions are propagated from one layer to another. Such a structure allows researchers to move beyond static properties and study system dynamics by simulating changes in nodes and edges, thereby uncovering how the performance of the entire system is influenced by interactions between different layers (Li et al., 2019). In fact, MSN is a structure that allows many relationships (edges) to connect two nodes from different

layers. The current study models the bottom-up influence of indicators on factors and factors on DfA by defining DfA, factors, and indicators within separate layers. MSN has mostly been used to determine the most important nodes in a network. For example, Farooq et al. (2018) used MSN to identify prominent users across several Huawei platforms to improve their commercial strategies. In another study, researchers utilized MSN to simulate collaboration among several institutions, including emergency management, transportation, and flood control, in response to catastrophes such as hurricanes. Within this paradigm, each infrastructure system is regarded as a different "layer," and organizations are represented as "nodes" within these layers. By translating collaboration frequencies (e.g., daily, weekly, etc.) into statistical probabilities, the researchers simulated the coordinating process over a one-year cycle to find "bottlenecks" or communication flaws (Li et al., 2019). However, this system appears to have a limited application in building sector research. The use of MSN has various advantages over many other evaluation methods, such as factor checklists or AHP. The MSN takes into consideration the interrelated nature of DfA factors by mapping ripple effects, which occur when a single design factor (e.g., number of components) changes, affecting numerous factors at the same time, such as assembly time. Furthermore, MSN is mathematically organized to deal with large-scale factor sets, whereas typical evaluation methods become prohibitively difficult as the number of factors grows. Furthermore, while AHP is highly reliant on pairwise comparisons, which are prone to subjectivity, MSN makes use of the network's PageRank index. This allows for a more objective weighting based on a factor's "centrality" and "influence". Finally, applying MSN allows for the identification of bottleneck nodes in the assembly process, which immediately aligns with Lean principles by highlighting sources of waste that linear models may ignore. Although the proposed framework has only been used for one industrialized building product, as a facade panel, it has the potential to model other products, such as volumetric modules. This can be accomplished by replacing the nodes inside each layer based on the exact product being considered. In other words, the MSN architecture is intended to be product-agnostic while maintaining the ability to manage three-dimensional complexity. Each indicator node is directly connected to its associated factor node, which is then linked to the DfA node via weighted edges. In this study, three distinct scores were considered for each node: the ideal score, the acceptance score, and the current score. The ideal score is set to 5 for all nodes. The acceptance score for each indicator is either extracted directly from the existing guidelines, standards, and technical reports or was established, ranging between 60% and 100% of the ideal score. Indicators' current scores are determined using the equations and data provided in the next section. These values have been normalized on a scale of 0 to 5. The scores for the factors and DfA node are then determined by applying Eq. 1, derived from the previous node's score and its related weight. Eq. 1 is the computational core for aggregating scores from the indicator layer to the factors layer, and then to the overall DfA assessment. This algorithm accurately captures the ripple effects of each node by multiplying the scores of nodes from the previous layer by the weights of the current layer's nodes. While the weights are taken from the PageRank index, the scoring formula described in Eq. 1 is proposed as a novel development of this study to fill a gap in the existing MSN research. In contrast to traditional MSN models, which primarily focus on identifying key nodes, the current formula is intended to promote hierarchical performance propagation between layers. This methodological expansion enables a dynamic examination of how design indicators influence high-level DfA factors, which was not previously addressed in traditional network analysis.

$$S_i = \log \left( 1 + \sum_i^N (W_{i,l} \times S_{j,l-1}) \right) \quad (\text{Eq. 1})$$

$S_i$  = Score of  $X_i$  in layer<sub>l</sub>,  $W_{i,l}$  = Weight of  $X_i$  in layer<sub>l</sub>,  $N$  = Number of nodes connected to  $X_i$ , and  $S_{j,l-1}$  = Score of  $X_j$  in layer<sub>l-1</sub>

The weights of the edges connecting the indicators and factors are set to one. The weight of each edge connecting a factor to the DfA node is calculated using the PageRank index, which is impacted by the frequency of each factor in the literature. The unit of analysis is the product, specifically, industrialized building products. So, a prefabricated facade panel was selected, as it involves the simultaneous collaboration of multiple companies across design, manufacture, assembly, logistics, and construction. Convenience sampling was used to choose the product, mainly because of the availability of their technical data and the potential for several off-site inspections throughout the assembly period. In fact, this assessment was carried out on an experiment of an early version of the panel developed by the project teams, to guide design improvements for future iterations. The chosen panel, manufactured off-site and transported to the project site for installation. The panel comprises five layers. From the exterior to the interior, these layers include: the window frame and its outer sill, the facade cladding, the metal frame, and two insulation layers. The constituent materials for these five layers are, respectively: Galvanized steel sheet, Max Exterior panels, steel, and rock wool. Internally, the insulation layers and the metal frame are joined via a snap-fit mechanism, while the corners are secured using bolts, nuts, and fasteners. Data on the case study input into the code via a User Interface (UI) that includes an online survey. After that, the resulting DfA score is shown. To ensure the reliability of the results, a triangulation approach was employed. The required data was generated through a collaborative experiment. This approach integrated multiple data sources, including: (1) a direct assessment of the Revit models, (2) a comprehensive analysis of technical documentation from the design and assembly teams, (3) semi-structured interviews with key informants, and (4) direct field observations of the panel assembly process. To validate the DfA assessment of these panels, a focus group was held with five team members who worked in the panel assembly. The authors served as facilitators. All 14 factors were examined, and the panel assembly's scores were compared to their reality. Overall, the participants stated strong agreement with the score of assembly; in other words, they verified that the reported score reflects the real status of the panels from their viewpoint. The following section first addresses the factors and indicators identified from the literature and then presents the implementation results within the case study.

## ASSEMBLY INDICATORS AND FACTORS

This section introduces the factors and indicators identified from the literature that influence DfA. The factors and indicators are shown in Table 1.

Table 1: Factors and indicators identified from the literature

|                                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                                                                         |
|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Factor 1:</b> Minimize the number and type of connections (Nguyen et al., 2024; Shetty & Ali, 2015)                 | $\text{Indicator 1} = \left( \frac{N_A}{N_A + N_B} \right) \times \%100$ <p><math>N_A</math> = Total number of essential connections, <math>N_B</math> = Total number of non-essential connections (Construction Innovation HUB, 2022)</p> <p>This formula is used as a waste elimination indicator in Lean Production since non-essential components cause process complexity and result in longer assembly times.</p> |
| <b>Factor 2:</b> Simplify geometry and shape of parts to improve assembly and handling (Mesa, 2023; Zhai et al., 2023) | <p>A1: Asymmetrical with a non-uniform section (%35), A2: Asymmetrical with a uniform section (%40), A3: Symmetrical (%45), B1: Asymmetrical (%50), B2: Symmetrical with internal holes (%60), B3: Symmetrical without internal holes (%70), C1: Asymmetrical (%80), C2: Symmetrical with non-uniform section (%90), C3: Symmetrical with uniform section (%100)</p>                                                    |

|                                                                                                                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                    | - Options A1, A2, and A3 correspond to curve geometry, B1, B2, and B3 relate to rectangular geometry, and C1, C2, and C3 pertain to the flat geometry of the product.                                                                                                                                                                                                                                                                                                                                                                     |
| <b>Factor 3:</b> Label parts and materials for identification and handling (Mesa, 2023)                                            | Indicator 3 = $\sum_{i=1}^3 \text{Weight } I_i$<br>I1: Label's details on the components are understandable (%35), I2: The label is still readable after exposure to external factors (%35), I3: The font, colour, text size, and placement of labels are appropriate (%30).                                                                                                                                                                                                                                                              |
| <b>Factor 4:</b> Use standardized components (Nguyen et al., 2024; Roxas et al., 2023)                                             | Indicator 4 = ((The number of duplicates components)/ (The total number of components used in the product)) x %100                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>Factor 5:</b> Use modular design for parts and connections (Chang et al., 2017; Go et al., 2015)                                | Indicator 5 = $\sum_{i=1}^2 \text{Score } M_i$<br>M1: Are the dimensions of the product multiples of 1.2, 3, and 6 meters? (%50 (Yes), %0 (No)), M2: Is the width of the products a multiple of their length? (%50 (Yes), %0 (No))                                                                                                                                                                                                                                                                                                        |
| <b>Factor 6:</b> Reduce material diversity (Zhai et al., 2023)                                                                     | Indicator 6 = $(1 - (\frac{1}{1-H})) \times \% 100$ , $H = \sum_{i=1}^N c_i \log_2 c_i$ , $c_i$ = Percentage of each ingredient in the product, N = Number of different ingredients in the product<br>This formula quantifies the distribution of materials in the panel. A high score suggests lower material diversity, which simplifies logistics, lowers warehousing costs, and facilitates future disassembly process.                                                                                                               |
| <b>Factor 7:</b> Minimize tools, steps, and special procedures (Desai, 2019; Mesa, 2023)                                           | T1: Tool is not required; task is accomplished by hand (%100), T2: Common hand tool required (%66), T3: Special tooling/ equipment required, without time delay (%33), T4: Special tooling/ equipment required, with time delay (%0)                                                                                                                                                                                                                                                                                                      |
| <b>Factor 8:</b> Use dry, and reversible connections instead of permanent connections (Li et al., 2023; Tan, Lu, Li, et al., 2020) | Indicator 8 = $(\frac{\sum_{i=1}^N \text{Score}_i}{5N}) \times \%100$ , N = Number of connection type, Score of snap-fit/ plug-in (5), Score of standard bolts and nuts (4), Score of riveting (3), Score of industrial adhesives/ resins (2), Score of welding (1), Score of complex hybrid connection (0)                                                                                                                                                                                                                               |
| <b>Factor 9:</b> Consider for automated, parallel, and time-efficient assembly processes (Hein et al., 2018; Zhai et al., 2023)    | Indicator 9 = $(\frac{N_A \times T_S}{T_A}) \times \%100$ , $N_A$ = Number of essential parts, $T_S$ = Standard assembly time per part (s), $T_A$ = Actual assembly time (U.S. Department of energy, 2022)<br>This indicator shows the difference between standard and actual assembly time; a low score indicates the existence of non-value-added activities and unpredictability in the assembly line.                                                                                                                                 |
| <b>Factor 10:</b> Consider parts for easy manual handling, insertion, and alignment (Li et al., 2023; Nguyen et al., 2024)         | Indicator 10 = $\%75 ((H_A + H_B)/ 2) + \%25 H_C$<br>$H_A$ : Requires handling aids (%100), Requires one hand only (%75), Requires more than one hand or a grasping aid (%60), Requires a forklift, hoist mechanism or 2 people (%50)<br>$H_B$ : Slippery/ Difficult to Grip (%50), Fragile/ Delicate (%55), Sticky/ Adherent (%65), Sharp/ Abrasive (%65), Untouchable (%65), Severely Nest (%70), Flexible (%70), Tangle (%80), None (%100)<br>$H_C$ : Does the weight of the products comply with human standards? %100 (Yes), %0 (No) |

|                                                                                                                                                        | - Maximum 25 Kg for men, and 16 Kg for women<br>The goal of this indicator is to evaluate safety, guaranteeing that the panel design reduces worker fatigue and prevents pauses in assembly due to overly heavy or difficult components.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |           |                     |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|---------------------|--|-----------|--------|-------|----------|------|-----|---------------------|------|-----|-----|--------------|-------|-----|-----|-------------|
| <b>Factor 11:</b> Apply production-based tolerances (Nguyen et al., 2024; Zhai et al., 2023)                                                           | Indicator 11 is determined by comparing product tolerances to standard tolerances. <table><tr><th rowspan="2">Materials</th><th colspan="2">Tolerance (mm)</th><th rowspan="2">Reference</th></tr><tr><th>Length</th><th>Width</th></tr><tr><td>Concrete</td><td>± 13</td><td>± 6</td><td>(Long et al., 2023)</td></tr><tr><td>Wood</td><td>± 6</td><td>± 3</td><td>(ANSI, 2020)</td></tr><tr><td>Steel</td><td>± 9</td><td>± 3</td><td>(MCA, 2017)</td></tr></table> After evaluating the tolerance, one of the options will be chosen. Requires frequent adjustment (%20). It causes problems most of the time (%40). Sometimes minor problems occur (%60). Suitable in most cases (%80). Perfectly adequate (%100).                                                                                                                                                                                                                                                                                                              | Materials | Tolerance (mm)      |  | Reference | Length | Width | Concrete | ± 13 | ± 6 | (Long et al., 2023) | Wood | ± 6 | ± 3 | (ANSI, 2020) | Steel | ± 9 | ± 3 | (MCA, 2017) |
| Materials                                                                                                                                              | Tolerance (mm)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |           | Reference           |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
|                                                                                                                                                        | Length                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Width     |                     |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| Concrete                                                                                                                                               | ± 13                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | ± 6       | (Long et al., 2023) |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| Wood                                                                                                                                                   | ± 6                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | ± 3       | (ANSI, 2020)        |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| Steel                                                                                                                                                  | ± 9                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | ± 3       | (MCA, 2017)         |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| <b>Factor 12:</b> Use symmetry parts (Bielecki et al., 2021; Mesa, 2023)                                                                               | Score of completely symmetrical in all directions (%100), Symmetrical in 2 directions (%80), Only in one major axis (%60), Partially symmetrical (%40), Almost no symmetry (%20), Completely asymmetrical (%0)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |           |                     |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| <b>Factor 13:</b> Optimize part orientation to enable unidirectional assembly and efficient handling (Volotinen & Lohtander, 2018; Wasim et al., 2022) | Indicator 13 = (The number of parts usable inn multi orientation/ Total parts) x %100                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |           |                     |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |
| <b>Factor 14:</b> Facilitate positioning and alignment using self-locating parts and adjustable connectors (Bielecki et al., 2021)                     | Indicator 14 = (Σ Score (F1 + F2 + F3 + F4 + F5 + F6)) / (7+N), N = Number of connection type<br>F1 (Part placing processes): Self-locating (%100), Requires holding (%50)<br>F1 (Part fastening processes): Self-securing/ snap fit (%100), Screwing (%60), Riveting (%60)<br>F2 (Process direction fitting): Straight line from above (%100), Straight line from another direction (%60), Not in a straight line (multi-directional motion(s) required) (%50)<br>F3 (Process type): Single insertion (%100), Serial multiple insertions (%60), Multiple simultaneous insertions (%50)<br>F4 (Access fitting): Direct access, no visibility restrictions (%100), Restricted access and/ or visibility (%60)<br>F5 (Alignment fitting): Easy to align (%100), Difficult to align (%60)<br>F6 (Insertion Force): No resistance to insertion (%100), Resistant to insertion (%60)<br>The goal of Indicator 14 is to determine how adjustable connectors remove the requirement for manual holding or complicated alignment processes. |           |                     |  |           |        |       |          |      |     |                     |      |     |     |              |       |     |     |             |

Subsequently, the implementation results are presented.

## IMPLEMENTATION RESULTS

Table 2 shows the current scores derived from the indicators and their relevant factors during the case study implementation. For example, since the panel has 113 essential components and 96 non-essential components, the score for Indicator 1 (based on the Indicator 1 formula) is calculated at 54%, when normalized to a scale of 0 to 5, yields a value of 2.7. Based on this, the score for Factor 1 may be calculated using Eq. 1, which is obtained from the score of Indicator 1 and the weight allocated to Factor 1. The weight for Factor 1 is determined by the PageRank index formula, which performs sophisticated computations automatically. This method produced a score of 2.89. The scores for the other factors were calculated using the same method. Scores marked in red, orange, and green indicate a critical, warning, and acceptable status. The grey rows represent acceptance scores, while the colored rows indicate the current scores for indicators and factors.

Table 2: Acceptance and current score of indicators and factors of facade panels

| I1   | I2   | I3   | I4   | I5   | I6   | I7   | I8   | F9   | I10  | I11  | I12  | I13  | I14  |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 3.00 | 4.00 | 3.25 | 3.25 | 5.00 | 3.00 | 3.30 | 4.00 | 3.00 | 3.25 | 4.00 | 4.00 | 3.00 | 3.50 |
| 2.70 | 3.50 | 3.25 | 4.30 | 0.00 | 3.40 | 3.30 | 3.25 | 2.60 | 2.80 | 5.00 | 2.00 | 2.50 | 3.40 |
| F1   | F2   | F3   | F4   | F5   | F6   | F7   | F8   | F9   | F10  | F11  | F12  | F13  | F14  |
| 3.18 | 4.04 | 3.31 | 3.34 | 5.00 | 3.08 | 3.38 | 4.06 | 3.07 | 3.36 | 4.03 | 4.02 | 3.04 | 3.53 |
| 2.89 | 3.55 | 3.31 | 4.35 | 0.00 | 3.47 | 3.38 | 3.34 | 2.67 | 2.92 | 5.00 | 2.04 | 2.54 | 3.43 |

Figure 2 depicts the DfA assessment in the case study, which clearly displays which factors influenced the final score. The acceptance score for DfA was obtained as 3.64, while the current score for the evaluated panels was determined to be 3.20. This gap shows that the panels have not yet reached the acceptance assembly status; thus, panel design revisions are required.

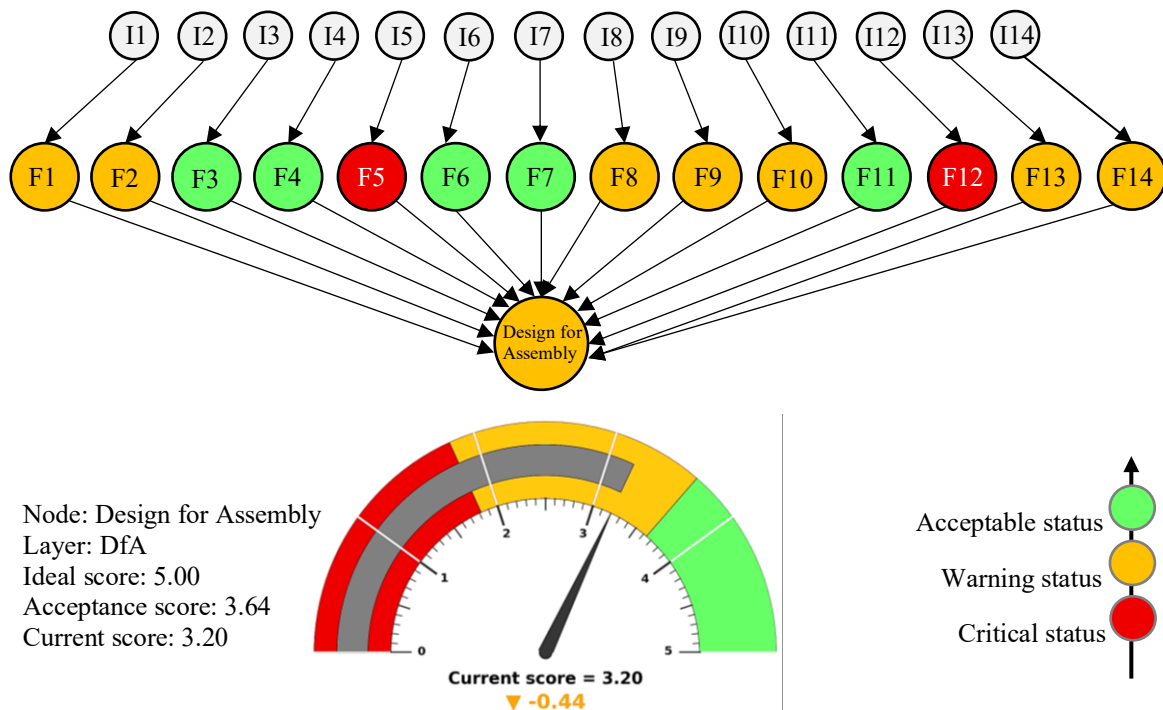


Figure 2: DfA assessment of facade panels

As seen in Figure 2, factors 5 and 12 are in a critical status. Factor 5 represents the failure to incorporate modularity into the panel design. In this case study, the facade panels are installed on the exterior of an existing building. The lack of modularity in panel dimensions could be

attributed to the fact that the window openings in the current building envelope do not have modular dimensions, requiring the panel sizes to be designed based on these constraints. This problem is clearly present in renovation projects. Factor 12 indicates the asymmetry of the panels. The panels consist of five layers. Each layer is composed of several distinct components that are asymmetrical and have different dimensions. These factors cause assembly complexity and require more time for the assembly process. The second priority factors include those outlined in warning status, which also have not acceptable status. Factor 1 refers to the large number of components used in the design of a single panel. Factor 2 refers to the geometrical configuration of the panels; while they are rectangular, the corners have multiple chamfers to facilitate structural connections. Furthermore, the second layer (the steel frame) is made up of many U-shaped steel profiles of various sizes and orientations. Factor 8 is another crucial factor that has been identified in the warning status. It can be noted that, in addition to dry connections such as snap-fits, bolts, and nuts, welding and riveting are also employed in the panel assembly, which reduces the ease of assembly. Factor 9 evaluates the assembly status in terms of the time consumed during the process. The actual time spent on panel assembly exceeds the standard time, leading to its current unfavorable score. Furthermore, Factor 10 (ease of manual handling and insertion) is also in an unacceptable state, which appears to be due to the high weight of the panels. Considering Factor 13, results indicated that only two of the five layers can be oriented and assembled in two different directions. The score of Factor 14 is due to two reasons: the require holding to engage the insulation layers with the steel frame, and the screwing procedures required to attach the external cladding to the panel structure. The need for holding and screwing, rather than more efficient techniques such as snap fits, makes assembly more complex. The remaining factors present an acceptable status. These include readable labeling of panel components (Factor 3), the usage of repeating components with uniform size (Factor 4), low material variety (Factor 6), low diverse tools for assembly process (Factor 7), as well as the adherence to acceptable tolerances (Factor 2). From the standpoint of Lean Construction, stakeholders, including designers and assemblers, can discover aspects that impact waste reduction and value improvement during the design process by using visual dashboards (Figure 3). For instance, low scores in Factor 1 (Minimize number and type of connections), Factor 6 (Reduce material diversity), Factor 8 (Use dry, mechanical, and reversible connections instead of permanent or chemical bonding), and Factor 9 (Consider for automated, parallel, and time-efficient assembly processes), are unmistakable signs of non-value-added operations that increase waste during panel assembly in factories. Additionally, the suggested MSN transforms from a qualitative evaluation into a proactive decision-making tool for TVD by quantifying acceptance and current scores. A key practical application of the proposed MSN is its potential integration as a plugin for BIM tools like Revit. This would enable stakeholders to directly visualize the impact of design changes on the product's assembly. The integration of Large Language Models (LLMs) is another important implication of the suggested structure. LLMs can offer practical solutions to improve product design and ultimately optimize the assembly operations by utilizing the evaluation results and particular product specifications. This is accomplished by combining specialized domain expertise with the wide general knowledge of LLMs, which have developed into potent decision-support assistants.

## CONCLUSION

This study contributes to the body of knowledge by introducing a novel structure for evaluating DfA. The proposed structure employs an MSN to establish interconnectedness among the influencing factors and indicators. This method derives the DfA score at the higher level from the factor scores, which are computed based on the related indicators. Information about a prefabricated facade panel was incorporated into the MSN. According results, the panels do not generally demonstrate a suitable status of assemblability, and design changes are necessary to

make their assembly easier. Panel modularity and symmetry were found to be the weakest factors. The panels received the highest scores for production tolerance compliance and standardization. Also, the implementation of the proposed structure in the case study revealed its efficiency and industry-wide applicability. By implementing this approach, design companies can streamline the assembly process through product design optimization, resulting in significant benefits for assemblers. Furthermore, other stakeholders can directly benefit from this study. For example, using the proposed system to analyze design for installation or design for safety could result in significant benefits for project site contractors. This indicates that, using a similar methodology, factors originating in the design phase and influencing the construction phase can be used as the foundation for evaluation DfA in other industries. Finally, this methodology can be used to evaluate other DfX. The framework for analyzing other DfX aspects has already been developed by the research team, albeit the results have yet to be published. For example, in terms of Design for Installation, various factors such as “compatibility with lifting point of equipment on site”, “Considering crane lifting capacities as a design constraint for panels”, and “Installation time” can be incorporated into the framework as relevant nodes. The proposed MSN structure is more than just an assessment tool; it also provides an operational framework for tracking lean production metrics throughout the assembly process. The identification of bottleneck nodes is an important feature, as it is directly related to the reduction of assembly variability. For example, optimizing factors like Factor 12 (Use symmetry parts) and Factor 14 (Facilitate positioning and alignment using self-locating parts and adjustable connectors) reduces fluctuations caused by human errors. Furthermore, by improving factors such as Factor 1 (Minimize number and type of connections) and Factor 9 (Consider for automated, parallel, and time-efficient assembly processes), the production process turns toward Work In Progress (WIP) reduction. This quantitative technique bridges the gap between design and production in the TVD framework, guaranteeing that wastes are reduced or eliminated before the assembly phase. Nonetheless, making changes to specific factors and re-evaluating the DfA score could help quantify the influence on lean production measures, which is suggested for future research. One of the current study’s limitations is that only one indicator was linked to each factor; thus, future researchers could improve the dependability of the results by generating a more thorough set of indicators. Another limitation of this study is the acceptance score developed for this assessment. While these acceptance thresholds were developed based on technical needs, they require additional validation through a larger multi-expert agreement to improve their reliability and overall assessment tool robustness. Additionally, weighing the factors based on expert judgment or other methods can be suggested as a future research direction. Future research could focus on comparing DfA evaluations before and after factor modification. This approach would allow for a sensitivity analysis to discover the most successful factors in the assembly process. Furthermore, the identified factors and indicators were specifically tailored to building products. As a result, extending the proposed system to evaluate products from other industries will necessitate the adaptation and customization of both factors and indicators. Nonetheless, this study establishes a practical and academic base for future applications.

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