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Research Article

An Integrated Analysis of Aluminium Formwork Systems in Non-Standard Floor Plan Construction: Defectology, Labour Productivity and a BIM-Based Cost Estimation Model

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Abstract: This paper presents a comprehensive case study of an 11-storey residential building constructed in Taipei, Taiwan, using an aluminium formwork system. The research establishes a detailed taxonomy of common concrete surface defects, quantifying their frequency and mapping their occurrence to specific structural elements. It was found that while defects are more prevalent in initial stages, a distinct learning curve leads to their reduction over successive floors. Secondly, this study analyses labour productivity, revealing that the Taiwanese construction team achieved an assembly rate of 5-7 m^2 per man-day, a figure that compares favourably with international benchmarks from India and Sri Lanka. Factors influencing this rate, including weather and geometric complexity, are examined. The primary contribution of this research is the development and validation of a novel labour estimation methodology. By leveraging Building Information Modelling (BIM), the study demonstrates that using a 'flat area' metric—the gross surface area ignoring openings—provides a more accurate prediction of labour requirements than conventional formwork contact area calculations. The findings confirm that despite higher initial investment and a steeper learning curve regarding defect control, aluminium formwork systems with BIM-automated drawings can reduce total construction costs by 31-53% compared to traditional timber methods.

Keywords: Aluminium Formwork; Concrete Surface Defects; Construction Productivity; Labour Estimation; Building Information Modelling; Green Building

I. Introduction

The construction industry is a significant contributor to greenhouse gas emissions, and a substantial amount of stored carbon, primarily in the form of concrete and steel [1], accounting for as much as 18% of carbon in Australia, for example [2]. Yet living under a roof is an unavoidable part of human existence, so it's not easy to decarbonise as compared to other industries where the demand could be reduced by changing consumer habits. A lot of focus on reducing building carbon footprint was on operational strategy, like reducing air-conditioning cost [3], but if this shift in operational strategy is done without corresponding architectural design changes (e.g. improved thermal insulation [4]), the result is only a building which is not usable, prompting people to use it less and the carbon embodied in it is wasted. Regarding design changes, one approach is to apply novel design principles [3] to make building projects more environmentally friendly. Another approach is to change the technology used to build existing designs, which can lead to faster emissions reduction, given the long timescales of building development and construction. One particular method is explored here, which is using aluminium formwork instead of wooden formwork. However, its implementation was slow as the change in the construction industry was slower than in other industries.

The accelerating pace of construction demands continuous innovation, with digital technologies such as Building Information Modelling (BIM) emerging as a key driver of efficiency and improved outcomes [5]. The potential of these tools extends beyond mere modelling, for example, Bukovics et al. [6] demonstrated a BIM-based framework for quantifying waste and managing deconstruction, highlighting how digital tools can optimize material reuse. Similarly, Károlyfi et al. showed how educational initiatives have successfully integrated

BIM to bridge the gap between architectural and structural engineering disciplines [5]. Most applicable to this paper's project location, BIM was shown to be a revenue driver and not a net cost in Taiwanese small-scale construction projects [7].

Despite these technological advancements, the industry continues to be heavily impacted by fundamental issues, particularly concerning poor quality in core building elements, which is documented to significantly increase project costs and cause substantial delays [8]. Therefore, while digital transformation provides powerful new tools for prediction, a critical need remains for integrated research that connects digital estimation models (like BIM-based cost planning) with the real-world operational factors of labour productivity [9] and the financial impact of construction defects.

The selection of a formwork system is one of the most consequential decisions regarding cost and duration of a concrete construction project. Comprising, on average, 30% of the total building cost [10] and significantly dictating the overall project schedule, formwork technology is a cornerstone of construction management. For decades, timber formwork has been the industry standard, prized for its low material cost and high flexibility, allowing for on-site modifications to accommodate complex geometries and design alterations. However, its disadvantages are equally significant: it is labour-intensive, has a limited lifespan, leading to considerable waste, and often results in surface inconsistencies that necessitate extensive and costly remedial work, such as plastering, to hide defects [11].

In response to these limitations, the construction industry has seen the rise of engineered, modular formwork systems. Among these, aluminium formwork has emerged as a leading alternative, particularly in the context of high-rise residential and commercial buildings. These systems consist of factory-made, lightweight aluminium alloy panels that can be rapidly assembled and disassembled, enabling the casting of a monolithic structure. The key technical advantages are well-documented. Ashiwin and Paul [12] highlight the system's high reusability, which can over 200 repetitions, amortising the high initial investment over multiple projects. Furthermore, the lightweight nature of the panels (approximately 20-25 kg/m^2) allows for manual handling, reducing reliance on cranes and accelerating assembly times. This acceleration is a primary driver of its adoption; research by Azharuddin and Anwar [13] demonstrated that aluminium formwork can cut a typical floor-to-floor cycle time in half, from 20 days down to 10 days, as compared to both wooden and steel formwork. Olanrewaju et al. [6] found that concrete floor and plastering defects occur extremely often – aluminium formwork often eliminates the need for plastering and allows for greater accuracy in slabs. While aluminium offers structural advantages, its surface characteristics and manufacturing quality are critical. Research by Stanojković and Radovanović [14] highlights how cutting parameters significantly influence surface roughness in aluminium alloys (6082-T6), which is directly relevant to formwork panel finish quality. Furthermore, numerical analyses by Salmi et al. [15] have provided deeper insights into residual stresses and defect formation in welded aluminium components, factors that ultimately determine the durability and lifespan of the formwork panels.

The actual labour productivity is notoriously difficult to predict due to variations in worker experience, weather, site conditions, and other factors. However, as digitalisation is penetrating the construction sector, numerous efforts have been made to collect long-term on-site statistics [9][10], as well as to make predictions using BIM methods [16].

While the literature often focuses on buildings with identical, repetitive floor plans, this case study investigates a project where the floors are similar but not exact replicas. This demonstrates that aluminium formwork possesses a degree of adaptability sufficient for such semi-repetitive structures, challenging the notion that its use is confined to perfectly uniform designs. The economic viability of the system is also a key point of investigation. Typically, a project involves purchasing project-specific 'unique' forms while renting 'common' forms from the manufacturer. This study compares regular reuse as well as a worst-case scenario, which assumes that the entire formwork system is purchased for this single 11-storey building and subsequently discarded. The findings will show that even under this assumption, significant cost savings are achieved over timber, driven primarily by reduced labour and secondarily by minimised finishing work. The typical aluminium formwork assembly/disassembly workflow is shown in **Fig. 1.** While it's applicable worldwide, a particular difference of Taiwanese projects is that tie bars are left inside and forms are raised through special openings left in the floor, which are later filled in.

Despite its advantages, the system has its drawbacks. The high precision and smooth, non-absorbent surface of the aluminium panels, while often beneficial, can present challenges. The resulting concrete finish can be "too smooth" for certain applications, such as the adhesion of faux brickwork or some types of tile, which require a

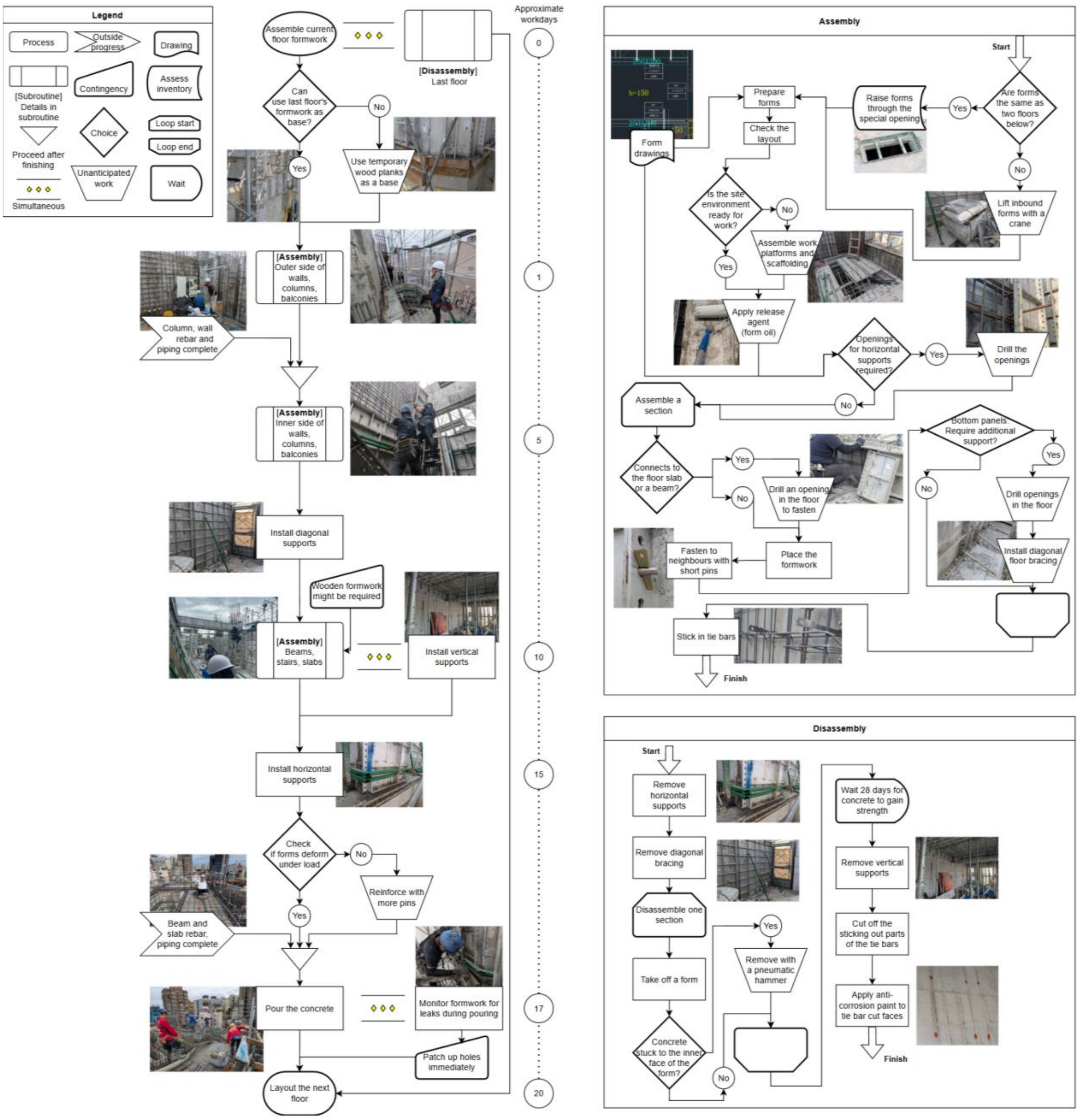

Figure 1. *Typical aluminium formwork workflow in Taiwan*

rougher substrate for effective bonding. This may necessitate additional surface preparation, such as mechanical abrasion or specialised primers, adding an unforeseen step to the finishing process. Furthermore, the system's manufacturing precision operates at a centimetre scale. This makes it difficult to form fine, millimetre-scale architectural details, such as inclined stair risers or custom-profiled windowsills. Consequently, such features often must be simplified to straight angles, representing a limitation in architectural expression. This rigidity makes late-stage design changes extremely costly. However, this same precision is what makes the system essential for achieving high-quality exposed architectural concrete.

The dependency on upfront 3D design is another critical factor. Unlike timber, which allows for improvisation, aluminium formwork requires a complete and finalised digital model well in advance, as panels are custom-manufactured. As shown in this paper, it was a major factor limiting the adoption of aluminium formwork before the automatic generation of 3D models became available very recently, as seen in the study by Chen [17]. The adoption is still slow and ongoing, particularly because software implementation has been slow in the conservative construction industry [18].

This paper aims to bridge a gap in the existing literature by providing a multi-faceted analysis of an information-rich case study:

- To systematically catalogue and analyse the common surface defects associated with aluminium formwork.
- To benchmark the labour productivity of the aluminium system and investigate influencing variables.
- To develop and validate a rapid and reliable BIM-based methodology for estimating labour requirements.

II. METHODOLOGY

This study employs a quantitative, single-case research design, focusing on the construction of an 11-story above-ground residential building in Taipei, Taiwan. A key feature of this project is its hybrid formwork strategy: traditional timber formwork was used for the structurally unique basement (B2F, B1F), ground (1F), and mezzanine floors, while the aluminium formwork system was deployed for the residential floors from the 2nd floor upwards. Floors 3 to 10 comprise three typical floor groups, with minor differences within each group, as shown in **Fig. 2.** This setup provides a rare opportunity for a direct, on-site comparison of the two systems, controlling for variables such as project team, labour costs, and climate, which would typically confound a comparison between separate projects. Data was collected on-site in Taipei, throughout the construction of B2F to 7F, from November 2024 to August 2025.

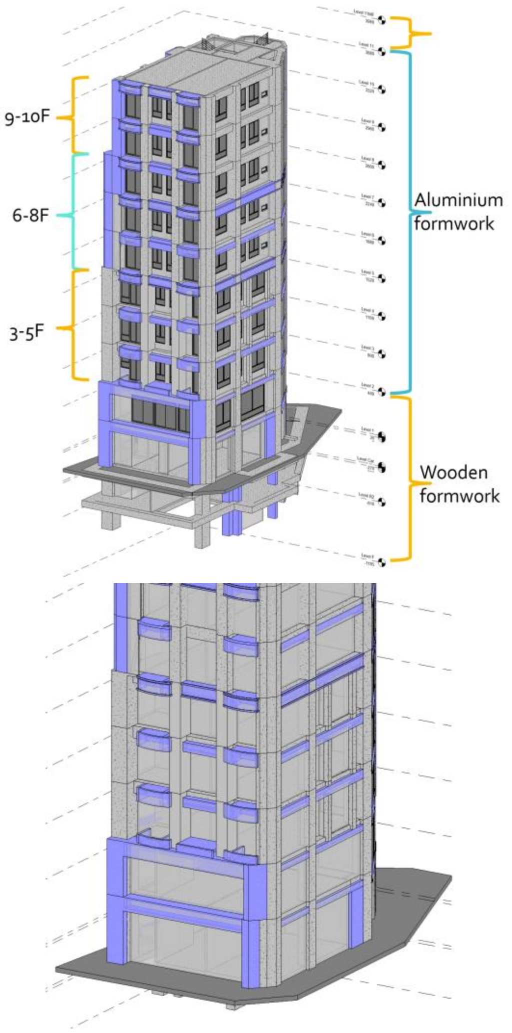

Figure 2. Whole building 3D model (top) and model for 'flat' area extraction (bottom).

Following the removal of the aluminium formwork on each floor, a comprehensive visual inspection was conducted. Defects on the concrete surfaces of all structural elements were identified, photographed, and categorised [11]. Typical examples are shown in **Table 1.** The classification system was developed based on industry-standard terminology and the specific issues observed on site, resulting in the following eleven primary defect categories:

1. Bubbles: Small, shallow surface voids.
2. Honeycombing: Coarse, stony surfaces where mortar has failed to fill the spaces between coarse aggregate.
3. Fractures: Linear fractures of varying depth and length.
4. Discolouration: Inconsistent colouring or staining on the concrete surface.
5. Corner damage: Spalling or chipping of external corners of beams, columns, or walls.
6. Protrusion: Unwanted materials, such as tie rods or styrofoam, embedded in and protruding from the surface.
7. Leakage: Fins or marks left by cement grout seeping through joints between formwork panels.
8. Unevenness: Deviations from a true plane, including both localised bumps/depressions and larger-scale differences in level.
9. Dirty formwork: Surface imperfections and textures caused by unclean formwork panels.
10. Missing paint: missing anti-corrosion paint on the metal formwork ties.
11. Not to drawing: construction not according to the drawing.

For each observed defect, its location, size, and severity were recorded. The frequency of occurrence was logged for each structural element on every floor to facilitate a quantitative analysis of defect distribution and trends.

Observed defects were further categorised according to the party responsible for them (formworkers, electroplumbers, pumpers, or general), but this paper primarily focuses on formworkers' defects.

To normalise the defect and labour data, precise area measurements of the building's structural components were required. A detailed 3D model of the building was created and analysed. For each floor, the formwork contact area was calculated for seven distinct structural element categories:

- Balconies
- Beams
- Columns
- Openings
- Stairs
- Walls
- Slabs/Ceilings

A hierarchical classification rule was established: if a surface belonged to more than one category, it was assigned to the more complex or dominant element in the order of openings, balconies, walls, columns, beams, and finally slabs. This ensured that each square metre of formwork was uniquely categorised. A representative floor, the 7th floor, was modelled in utmost detail to establish the proportional breakdown of these areas, which was then used as a baseline for the typical floors (6-8F).

In addition to the standard formwork contact area ('Normal Area'), this study introduces the concept of 'Flat Area'. The Flat Area is defined as the gross surface area of the walls and slabs calculated as if all window and door openings were filled in. This metric was calculated for each floor using the BIM model in **Fig. 2**. 7th floor formwork areas and connection lengths were also measured in situ with a ruler tape (**Table 2.**). Daily work records were maintained throughout the project, detailing the number of workers assigned to formwork assembly each day and the specific tasks they performed. This data was aggregated to calculate the total man-days expended on formwork erection for each floor. Worktime included assembling, disassembling, and moving the formwork. Defects were repaired by manual labourers, and the required time was measured separately.

***Table 1**. Concrete surface defect examples*

Bubbles	Honeycombing	Fractures
		
Discolouration	Corner damage	Rebar protrusion
		
Leakage	Unevenness	Unevenness
		
Dirty formwork	Missing anti-rust paint	Not to drawing
		

***Table 2**. 7th floor's formwork area sorted by structure type.*

	Balcony	Beam	Column	Opening	Stairs	Wall	Slab	**Total**
m^2	29.47	134.5	94.64	94.1	24.69	36.033	374.37	**787.8**
%	3.7%	17.1%	12.0%	11.9%	3.1%	4.6%	47.5%	**100.0%**

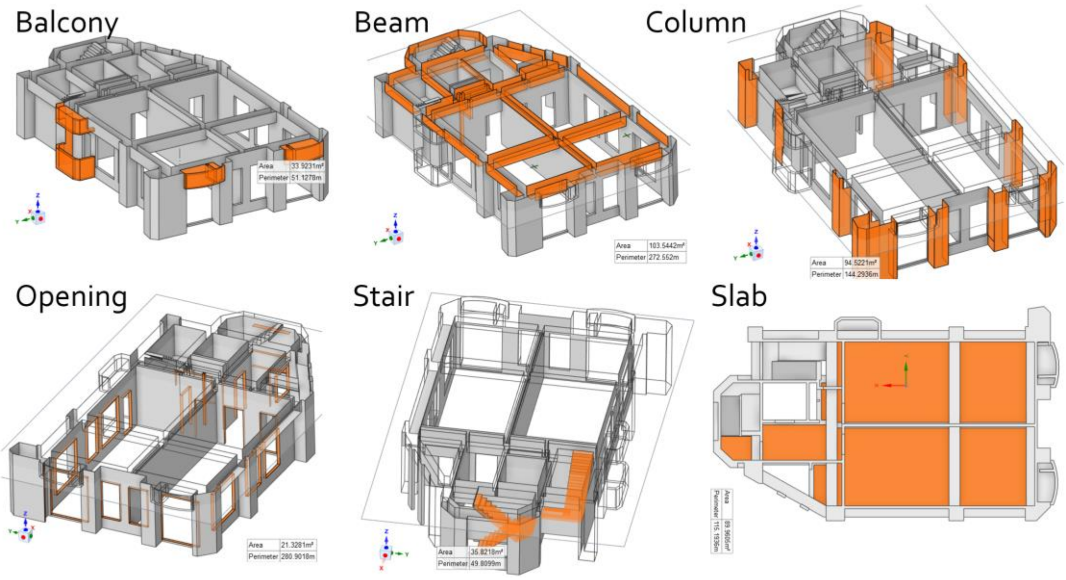

***Figure 3**. Visual representation of 7th floor's formwork areas by structure type.*

Weather data, specifically precipitation and temperature, were not collected on-site, and instead, local weather agency data are used [19][20].

To protect the confidentiality of the parties involved in the construction project, labour cost calculations were based on government statistics [19], which were then multiplied by an overhead coefficient of 1.5 to account for administrative expenses, resulting in the data presented in **Table 3**.

***Table 3** Daily wages for construction workers in Taiwan.*

Manual labourer	Carpenter (wood formwork)	Formworker (aluminium)	Engineer
1700 NTD/day	2850 NTD/day	3300 NTD/day	3954 NTD/day

III. Results and Analysis

1. Analysis of Concrete Surface Defects

One of the major advantages of aluminium formwork is that in theory, plastering is not required after removing formwork, as the surface finish is already very smooth and uniform. However, in practice there are surface defects, and the cost of their repair needs to be deducted from the cost savings from eliminating plastering.

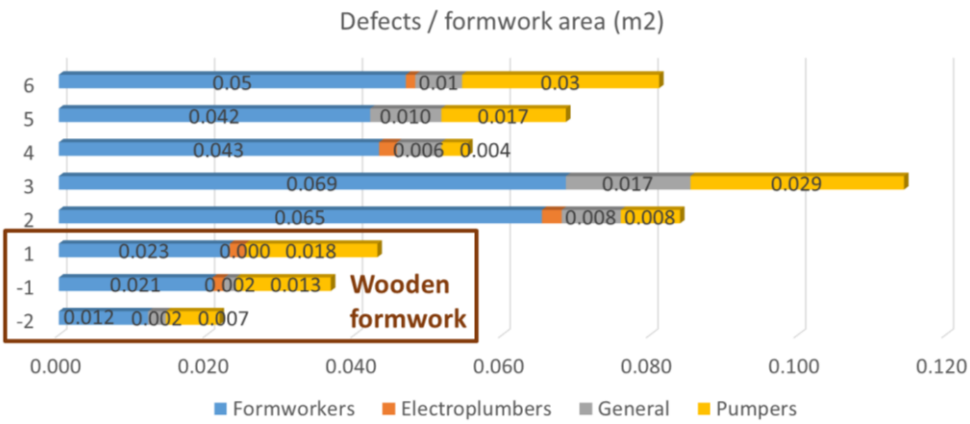

***Figure 4**. Defects density by floor.*

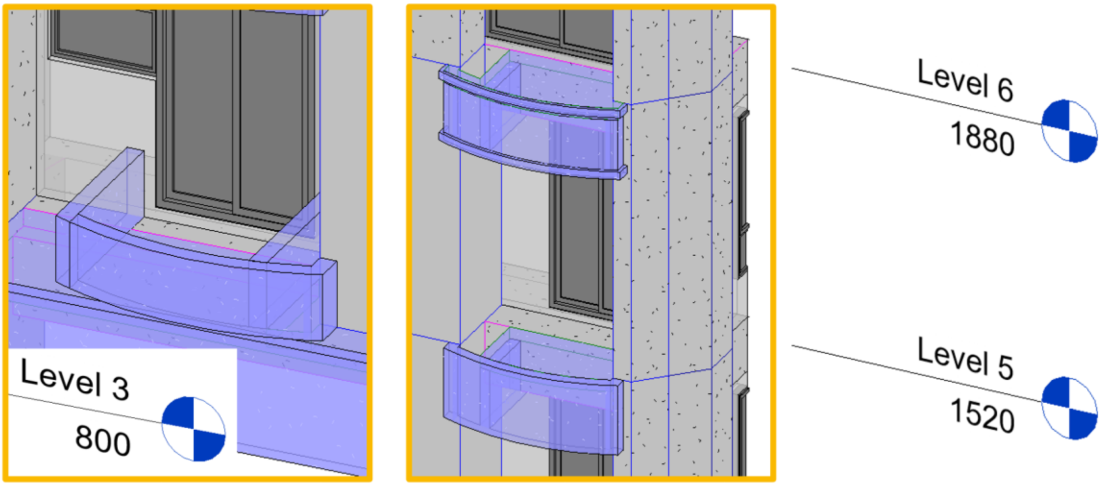

Figure 5. *Balcony shape becoming more complex.*

A systematic cataloguing of surface defects revealed a clear pattern of issues associated with the aluminium formwork system. The defects were not random but were concentrated in specific areas and their frequency evolved over the course of the project. For surfaces made with wooden formwork, there were also defects that require more than simple surface plastering to repair. The defects were caused by different parties as seen in **Fig. 4**; this paper focuses specifically on formwork-related defects from this point on.

The visual inspection across multiple floors led to the identification and classification of 11 distinct types of defects. Among these, some were primarily aesthetic, while others had structural implications. For instance, air bubbles were common but typically superficial, with depths ranging from 0.1 cm to 1 cm. In contrast, honeycombing represented a more serious defect, with some instances creating large voids that necessitated structural repair, indicating potential issues with concrete consolidation or grout loss.

Cracks were frequently observed around window openings and, in severe cases, were found to extend through the full 15 cm thickness of a wall, often resulting from stress concentration or grout leakage at formwork joints. Corner damage was another significant issue, with spalling depths of up to 10 cm on external beams, often occurring at the interface between aluminium and timber formwork elements.

Table 4 correlates defect types with structural elements, revealing that the most problematic areas were those with complex geometries. Balconies and stairs were identified as having the highest frequency of defects overall. Openings for doors and windows were also highly susceptible to issues, particularly corner damage and unevenness. This suggests that the complexity of assembling formwork around these features, with numerous joints and corners, increases the risk of imperfections.

When the frequency of major defects (corner damage, non-conformance to drawings, unevenness, and grout leakage) was plotted against the floor number, a distinct learning curve emerged. For most structural elements, the number of defects per square metre was highest on the initial floors (e.g., 2F, 3F) and steadily decreased as the construction progressed towards the upper levels. This trend indicates that the construction crew learned on their mistakes and improved upon the techniques.

Table 4. *Defects caused by formwork-related issues. Wood and aluminium formwork, all floors*

Defect	Balcony	Beam	Ceiling	Column	Opening	Stairs	Wall	Total
Bubble	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0%
Corner damage	3.8%	3.1%	0.2%	1.2%	33.1%	6.2%	0.5%	48%
Dirty formwork	0.0%	0.0%	0.0%	0.2%	0.0%	0.6%	0.3%	1%
Fracture	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0%
Honeycomb	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.1%	1%
Missing paint	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0%
Not to drawing	0.0%	0.0%	0.0%	0.9%	1.0%	0.0%	0.4%	2%
Leakage	6.6%	0.6%	0.0%	1.4%	1.0%	7.5%	0.2%	17%
Protrusion	2.8%	0.3%	0.0%	4.0%	1.0%	0.6%	1.1%	10%
Unevenness	1.9%	1.0%	0.0%	4.9%	6.0%	3.1%	1.4%	18%
Total	15%	5%	0%	13%	42%	19%	4%	98%

Table 5. *Major concrete defects number divided by respective structure's total area per floor (defects/m²). Brown floor colour stands for wooden formwork.*

Floor	Balcony	Beam	Ceiling	Column	Opening	Stairs	Wall	Total
6	0.034	0.015	0.000	0.159	0.265	0.056	0.029	0.047
5	0.231	0.060	0.000	0.030	0.149	0.056	0.028	0.042
4	0.033	0.034	0.000	0.070	0.335	0.196	0.019	0.043
3	0.165	0.060	0.000	0.141	0.409	0.168	0.033	0.069
2	0.061	0.070	0.000	0.079	0.529	0.254	0.039	0.065
1	0.000	0.013	0.000	0.074	0.000	0.096	0.017	0.023
-1	0.000	0.000	0.011	0.045	0.433	0.000	0.020	0.021
-2	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.012

However, this learning curve was not linear and was susceptible to disruption. A notable anomaly occurred with the balconies. The defect rate for balconies is spiking suddenly on the 3rd and 5th floors. Investigation revealed that the architectural design of the balconies changed at these levels, introducing more complicated geometries that the crew had not previously encountered, shown in **Fig. 5**. The same is true for the two columns that became inclined instead of vertical on the 6th floor. These design modifications effectively reset the learning process for that specific element, leading to a temporary surge in defects until the team adapted to the new configuration. This finding underscores the sensitivity of modular formwork systems to design variations and highlights the importance of consistent training when new elements are introduced.

2. Labour Productivity Analysis

The overall labour productivity for formwork assembly on this Taipei project was calculated to be between 5 and 8 square metres per man-day. Shown on a monthly basis in **Figure 6**, this rate is a measure of the total formwork contact area installed by a single worker in one day. This performance was benchmarked against data from three publicly available studies on aluminium formwork projects: two in India [21] [22] and one in Sri Lanka 0. A study in Korea [16] was excluded as an outlier, as the reported productivity rates were an order of magnitude greater than all other benchmarks. The comparison revealed that the productivity achieved by the Taiwanese crew was on the higher side, but all four projects had relatively similar productivity. Data from Taiwan confirms the previous findings from India, that the aluminium system, when implemented effectively, can yield significant labour savings and is at least twice as fast as conventional timber formwork methods.

The study investigated several variables that could potentially influence the daily productivity rate. A clear correlation was found between weather conditions and productivity, shown in **Fig. 7**.

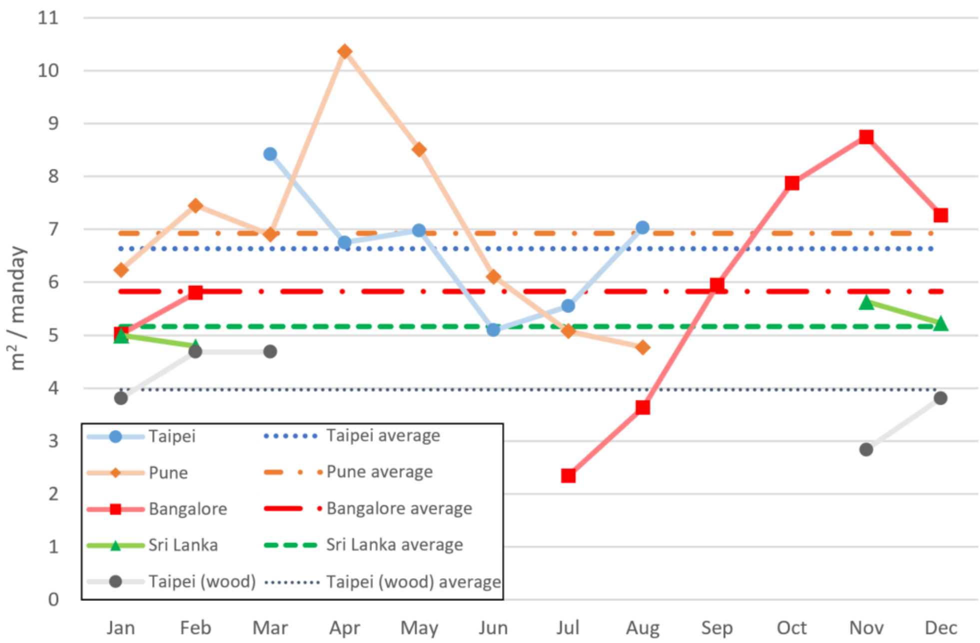

Figure 6. *Aluminium formwork labour productivity at 4 different locations*

Rainy days resulted in a significant decrease in the efficiency of the formwork assembly team. This is an expected outcome in construction, as adverse weather conditions hinder mobility, create unsafe working environments, and can completely halt the workflow. The impact of temperature, however, was inconsistent among the locations investigated and showed no clear trend. This can be understood as different populations have different temperature tolerance, and an increase in temperature does reduce workers' efficiency, but does not completely halt the work, as heavy rain does.

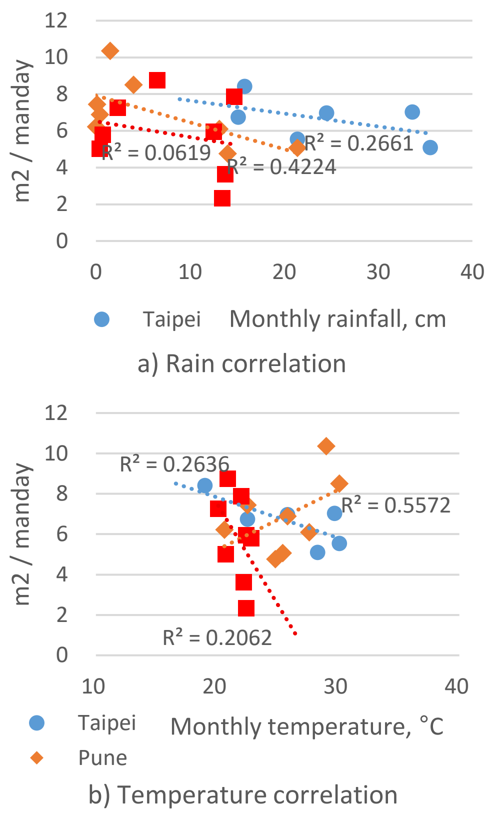

Figure 7. *Rain (a) and temperature (b) correlations with formwork productivity*

A key finding of the analysis was that the total surface area of formwork is not the sole determinant of the labour required for its installation. The complexity of the geometry, specifically the length of connections and joints between panels, plays a crucial role. To illustrate this, **Fig. 8** compares two scenarios with the same total formwork area (6 m^2). A simple, unbroken wall section has a connection length-to-area ratio of 1.16. A more complex section around an opening, with a smaller net area (4.1 m^2) due to the opening, has a much higher connection length and a ratio of 6.0. Assembling the latter requires significantly more time and effort due to the increased number of fittings, checks, and adjustments. This demonstrates that structures with a high degree of articulation (many corners, openings, and intersections) will have lower productivity rates (m^2 per man-day) than those with large, simple, planar elements.

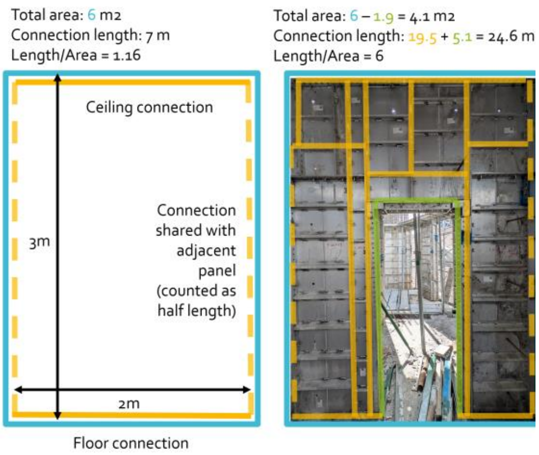

Figure 8. *Formwork areas (blue), lengths (yellow) and openings (green) definition. Wall segment (left) and door segment (right).*

3. Development of a Labour Estimation Model

Recognising the limitations of using a simple area as a predictor, the study aimed to find a more reliable metric for forecasting labour requirements.

In **Fig. 9**, three different metrics were evaluated for their ability to predict the man-days required for various structural elements. The results, visualised in a box-plot graph, showed a wide variance for 'Mandays per part' and 'Mandays per m^2 formwork'. This indicates that these metrics are unstable and unreliable for prediction; for example, the man-days per square metre of formwork for a ceiling are vastly different from those for stairs or a balcony. Moreover, there are many more factors influencing the assembly time of a particular section; they can be seen as “Choice” and “Contingency” elements in **Fig. 1**.

In contrast, the 'Mandays per m^2 flat' metric showed significantly less variance across most structural categories. This metric, calculated using the gross area of a surface as if there were no openings, proved to be a much more stable and consistent predictor of labour effort. The underlying logic is that the labour saved by not having to place formwork in an opening is roughly offset by the additional labour required to form the complex edges and sides of that same opening. The 'flat area' metric effectively averages out this complexity, providing a robust basis for estimation.

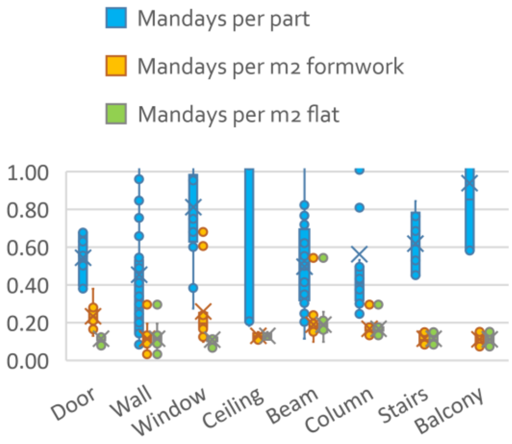

Figure 9. *Comparison of estimation metrics*

A predictive formula for estimating the number total man days required (TMD) was developed in Equation 1. The model uses the 'flat area' of different structural components, multiplied by empirically derived coefficients, seen in **Fig. 9**. The coefficients need to be derived based on a particular project's crew and site conditions, but the coefficients provided here can be used for a rough estimate. The analysis yielded the following coefficients (in man-days per m^2 of flat area): C_{infill} = 0.11. C_{slab} = 0.125, $C_{structural}$ = 0.17.

$$TMD = C_{infill}\left(A_{walls} + A_{openings} + A_{stairs} + A_{balconies}\right) + C_{slab}\left(A_{slabs}\right) + C_{structural}\left(A_{columns} + A_{beams}\right) \quad (1)$$

This model was validated against the project's actual data and demonstrated a predictive accuracy of within 10% in this case. For the reason of business confidentiality, the detailed manhours table for the floor areas cannot be disclosed. It should be noted that this approach can be applied anywhere; however, the coefficients must be adjusted based on the actual crew and site conditions. Its primary advantage is its speed; given a 3D BIM model, the flat areas can be extracted and the total man-days for a floor can be calculated in under five minutes, providing a powerful tool for early-stage planning and bidding.

IV. Discussion

1. Overall Cost-Effectiveness and the Role of Automation

The conclusion from the studied project is that aluminium formwork is unequivocally cheaper than timber formwork when considering the total project cost. The analysis suggests that, depending on the number of reuses, the total cost for the concrete frame using an automated aluminium system can be between 31% (for disposable forms) and 53% (for maximal reuse) lower than with traditional timber. In the first case, it is assumed that wooden formwork is reused 5 times and aluminium 12 times; in the latter, wooden formwork is reused 10 times and aluminium 200 times, based on practical experience and manufacturer recommendations. This cost saving is a composite of several factors, as seen in **Fig. 10**. While the material cost of aluminium is higher, this is offset by drastic reductions in other areas.

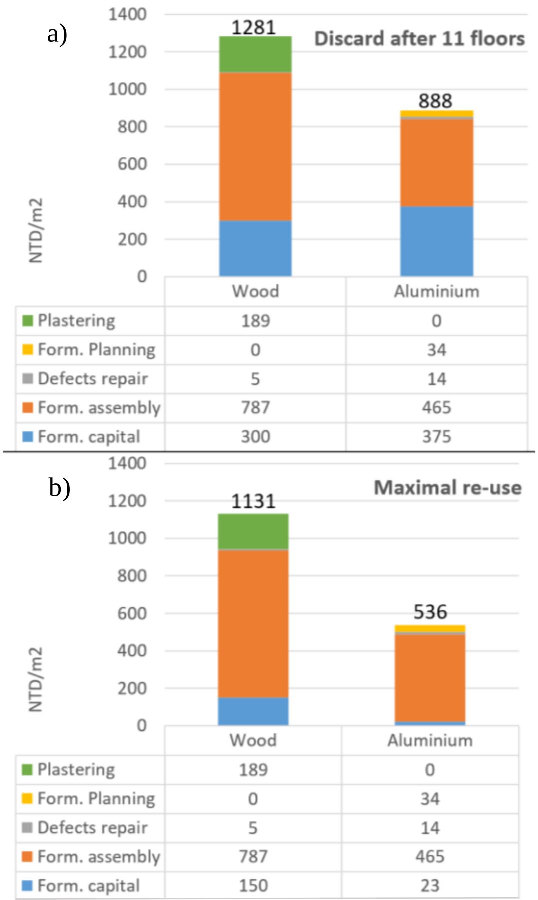

Figure 10. *Aluminium vs. Wood formwork cost Comparison per m², NTD – New Taiwan Dollar. a) assume both formwork materials are discarded after 11 floors; b) assume both are re-used to their practical re-use limit.*

The most significant saving comes from speed. Aluminium formwork is simply much easier to assemble; workers describe it as assembling LEGO blocks. Moreover, a two-fold increase in construction speed reduces project overheads and shortens financing periods. The direct cost reduction from these factors has not been considered in this comparison; however, they are critical financial considerations in large-scale property development.

The second key factor is the elimination or reduction of plastering. Timber-formed walls have rougher surfaces that require a thick plaster coat (1-2 cm) to achieve a smooth finish. Aluminium forms produce a much smoother surface, allowing for direct application of paint or the use of a simple metal trim to cover insulation and minor imperfections around windows, representing a substantial saving in both labour and materials.

However, the cost-effectiveness is highly dependent on design automation and surface requirements. The main historical barrier to aluminium formwork's adoption was the time-consuming nature of producing the detailed 3D drawings required for formwork manufacturing and assembly on-site. As shown by Chen [17], the development of automated and semi-automated software that can generate these drawings rapidly has been a game-changer.

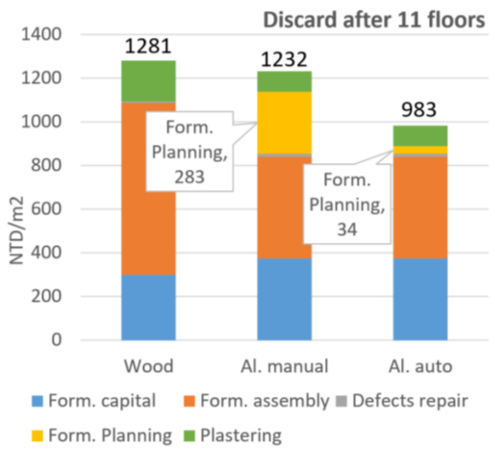

Figure 11. *Formwork cost comparison considering wet brickwork façade and manual drawings.*

A second limiting factor is that the smooth surface achieved by aluminium formwork is not always what's needed. Particularly in East Asia including Taiwan, the most popular façade finishing technique is wet brickwork, i.e., sticking faux bricks to wet plaster or concrete. For the brickwork to stick, the surface needs to be rough, which is easy to achieve by raking wet plaster, but not hard, settled concrete. In the latter case another layer of plaster still must be applied and raked while gluing the brickwork. Considering that brickwork is only applied on the façade, **Fig. 11** shows that aluminium formwork with manually drawn assembly drawings costs almost the same as wooden formwork. Considering that learning to use a new work method is challenging, it is easily seen how aluminium formwork was not popular for a long time after its invention, until automated 3D BIM assembly drawings were generated, as well as finishing techniques other than wet brickwork became more widely adopted.

2. Managerial Considerations

The case study concludes with several pertinent questions and suggestions from the site director and engineers, which point towards areas requiring further management attention and research.

Flexibility and Design Changes: The director's primary concern revolves around the system's inflexibility. "If the owner's drawings are not good, and are constantly changing, what is the effect on the aluminium formwork?". This is the system's Achilles' heel. Late-stage design changes are extremely difficult and costly to accommodate, as they necessitate the remanufacturing of panels. This places immense pressure on finalising the architectural and structural design much earlier in the project lifecycle than is traditional. Project managers must implement strict design freezes and robust change-management protocols.

Durability and Tolerances: A question was raised about the robustness of the aluminium panels against damage. While durable, panels can be damaged by improper handling, leading to dents that translate into surface imperfections on the concrete. This requires careful site logistics and worker training. Furthermore, the tight tolerances and precise nature of the system mean that correcting deviations, such as bulging (which is relatively simple with timber by adding more bracing), might be more challenging with aluminium formwork.

Environmental Factors: The potential impact of temperature differences on the expansion and contraction of the aluminium panels, and thus on the gaps between them, was raised as a concern. This could potentially impact the incidence of grout leakage and the overall dimensional accuracy, suggesting that environmental conditions should be considered in quality control planning.

This discussion illustrates that the successful implementation of aluminium formwork is a socio-technical process. It requires not only the right technology and automated design but also a well-trained workforce, adapted construction methods, and a project management framework that embraces early design finalisation and rigorous on-site quality control.

V. Conclusions

This research provided a data-driven analysis of an aluminium formwork system applied to a residential construction project in Taipei, Taiwan. By integrating a study of concrete surface quality, labour productivity, and BIM-based cost estimation, the paper offers several insights for the industry.

Defectology and the Learning Curve: The study established a taxonomy of common surface defects associated with aluminium formwork. While the system is capable of producing high-quality finishes, the results indicate that defects are not random but are concentrated in areas of geometric complexity, such as balconies, stairs, and openings. Crucially, a distinct learning curve was observed; the frequency of defects diminished significantly as the construction progressed to upper floors. This underscores the necessity for intensive initial training and the retention of experienced formwork crews to maximise quality control.

Productivity and Influencing Factors: The recorded labour productivity rate of 5–7 m^2 per man-day compares favourably with international benchmarks. However, this productivity is highly sensitive to external variables. The analysis confirmed a strong negative correlation between precipitation and assembly efficiency. Furthermore, productivity is intrinsically linked to the articulation of the structure; elements with high connection-length-to-area ratios (such as complex walls with openings) require disproportionately more labour than simple planar elements.

A Novel Labour Estimation Methodology: A primary contribution of this work is the validation of a 'flat area' metric for labour estimation. The study demonstrated that calculating the gross surface area—ignoring openings—provides a more stable and accurate predictor of labour requirements than traditional net formwork contact area calculations. This logic posits that the labour saved by not shuttering an opening is offset by the additional effort required to form its perimeter. The proposed formula (Equation (1)) allows for rapid estimation using BIM data, facilitating more accurate bidding and planning.

Managerial Implications and Implementation: The economic viability of aluminium formwork is substantial, with significant potential cost savings, provided that automation is leveraged for design and assembly drawings. However, successful implementation requires a shift in project management strategy. The system's rigidity is its "Achilles' heel"; late-stage design changes are prohibitively costly as they require the remanufacturing of panels. Therefore, project managers must enforce strict design freezes and ensure architectural and structural drawings are finalised significantly earlier than is typical for timber formwork projects.

Limitations and Future Research: It must be noted that these conclusions are drawn from a single, detailed case study. As pointed out by the limitations of case study research, the specific labour productivity values derived here reflect the specific conditions, crew proficiency, and climate of this Taipei project. Practitioners should view these values as a baseline to be calibrated against their own historical data. Future research should aim to validate the 'flat area' estimation model across a broader range of building typologies and geographical locations. Additionally, while this study focused on production, further investigation into the lifecycle environmental impact—comparing the high embodied carbon of aluminium manufacturing against the forestry impact of timber usage—would be valuable to fully understand the sustainability credentials of the system credentials.

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Authors contributions

G. Ivanov: Conceptualisation, data collection, manuscript writing and revising.

Disclosure statement

At the time of data collection, the author worked at He Xing Smart Engineering as a Site Engineer Intern.

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