**A Category and Index Hybrid (CIH) Approach to Measuring the Levels of Prefabrication**

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**Abstract**

Two generic approaches exist to measuring the Levels of Prefabrication (LoP) in construction. One is the ‘category’ approach to indicating which prefabrication type a building adopts. Another is the ‘index’ approach to measuring the ratio of prefabrication in the total construction volume. However, existing studies still face difficulty understanding the true picture of prefabrication in a project by adopting either category or index approach. To address this issue, this study aims to develop a ‘category and index hybrid’ (CIH) approach to measuring the LoP holistically. Firstly, a tentative CIH model was developed. Then, the model was used to measure 15 sizeable high-rise building projects in Hong Kong, which have adopted different prefabrication components. Finally, the approach was presented to industrial stakeholders for validation via interviews on its strengths, weaknesses, and prospective applications. A strong positive correlation was revealed between Levels 0 and 1 prefabrication usage based on Pearson correlation, *r*. It also found that the CIH approach’s ‘category’ component allows people to quickly grasp the prefabrication types a building adopts, while its ‘index’ component allows a numerical understanding of prefabrication in the entire construction. The interview results denoted that the CIH approach can enable a series of meaningful applications.

**Keywords:** Category and index hybrid approach; Prefabrication; Level of prefabrication; Prefabrication forms.

**1. Introduction**

The renaissance of prefabrication around the world is attributable to its various potential benefits. Prefabrication is widely considered a green production technology that causes less undesired environmental impacts (Choi et al., 2019). Using prefabrication, many construction components are manufactured in a controlled factory environment with a cleaner working environment and lower resource waste and consumption rate (Tam and Hao, 2014). Prefabrication could reduce time and labour investment by engaging fewer trade sub-contractors and reducing crowded construction sites during project peaks, thereby decreasing the idling and downtime (Lau et al., 2019). It is also amenable to massive manufacturing using machinery, production lines, and robotics (Bao et al., 2021). Currently, it is not uncommon for prefabrication to be moved to offsite or even offshore places in different countries. Construction internationalisation, convenient information and communication technologies, advanced construction technologies, and logistic and supply chain globalisation catalyse the booming of prefabrication (Lu and Yuan, 2013). In summary, prefabrication can largely shorten construction periods, increase cost-effectiveness, uplift productivity, and quality of works, enhance site safety, reduce wastage, and improve sustainability (Lu et al., 2018).

Alongside the globalisation of prefabrication, measuring and communicating the level of prefabrication (LoP) is becoming crucial. There are two generic approaches on the radar to measure the LoP adopted in a building project, namely: the category and the index approach. The category approach measures the prefabrication level based on the type/category of prefabricated components adopted in a project (Gibb, 2001). This approach has been reported to have the disadvantage of not telling exactly how wide or deep prefabrication has been implemented in a project (Gibb, 2001; Abosaod, 2010; Sierra and Zamora, 2013; Steinhardt et al., 2014), though it can link people’s understanding to a specific form of prefabrication. On the other hand, the index approach offers a numeric, indexed-style measurement in understanding the proportion of prefabrication in overall construction (Lu et al., 2018). This approach has been disadvantaged for informing the form of prefabrication adopted in a building project, although it accurately indicates the proportion of prefabrication in the total construction volume (CIDB, 2004; Alinaitwe et al., 2006; Wong et al., 2008; Hong et al.,2016; Shamsuzzoha et al., 2018). Other studies have also reported on its easiness for empirical tests such as the level of prefabrication and its performance measured by waste reduction (Tam et al., 2006), safety (Ahn et al., 2020; Mostafa et al., 2020), and so on. Measuring the LoP has been one-sided using either the category or index approach. Each approach is noted to be limited by its disadvantages in measuring the LoP. This does not give the full picture of prefabrication adopted in a project; hence, there is still a need for a comprehensive approach.

To claim the possible benefits of prefabrication, it is desirable to fully understand its utilisation, including the forms and proportion of prefabrication adopted in a project using a comprehensive approach. This can be achieved by combining the existing two approaches to form a hybrid approach, which harnesses the strength of the existing approaches (category and index). This concept of the hybrid approach has not been given much attention, though it has potential relevance in better evaluating the LoP in a prefabrication building project.

The aim of this research is threefold: (a) to develop a category and index hybrid (CIH) approach to measuring the LoP; (b) to examine the LoP in projects using the CIH approach; and (c) to explore the strengths, challenges, and prospects of the CIH approach. It does so by adopting a mixed method of literature review, case study, and interviews. Aside the distinctive contribution of the CIH approach to knowledge, it can provide adequate results to fine-tune current incentive schemes to promote prefabrication adoption. It can also assist practitioners and policymakers to effectively track and understand construction waste generation and minimisation, carbon emission, and other possible key performance indicators of a project.

The remainder of this paper includes six sections. After this introductory section is a review of prefabrication technologies adopted in various countries. Section 3 reviews the prevailing approaches to measuring the LoP and identifying gap. Section 4 introduces the research methods, including the tentative CIH model developed in-house and a detailed description of the case study and interviews. Section 5 narrates the analyses and findings, and Section 6 finally discusses and concludes the study.

**2. Prefabrication in various countries**

Prefabrication has been unanimously promoted as a strategy for sustainable construction to alleviate the housing shortage problem in various countries, hence addressing the economic, environmental, and social aspect of sustainability (Jaillon and Poon, 2008). Other studies have also focused on quality and productivity (Blismas et al., 2006; Goodier and Gibb, 2007).

Prefabrication was widely adopted in Europe to rebuild the houses that were destroyed during World War II and accommodate the ‘baby boom’ that followed (Newton et al., (2018). Prefabrication has been exploited as a key technology option to materialise ambitious housing plans. Sweden became the most developed country for prefabricated construction globally, with 80% of its social housing sector using structures and elements prefabricated in factories, with a lesson learned on reducing construction time and reaping quality, safety and labour efficiency (McGregor, 2017). By enjoying a high penetration rate, its IKEA furniture has even been more effective than its construction counterpart in promoting the same underlying prefabrication philosophy. Also, prefabricated house production in Japan peaked at 18% in 1994 and stabilised since then at 15%, with an average of around 400,000 dwellings built per year (Jimenez-Moreno, 2017). In Singapore, prefabricated prefinished volumetric construction (PPVC) is mandatory in projects being developed on government land due to the saving labour force and improved work environment of workers (BCA, 2015). It could be inferred that various countries have also adopted the technology for addressing the social aspect of sustainability, including improvement in health and safety, more stable employment, and investment in machinery and skills development (Gorgolewski, 2004).

Also, in metropolitan cities such as New York, Tokyo, Hong Kong, and Singapore, people live a high-density urban life owing to the large population and limited land. Prefabrication has been widely adopted in high-rise buildings in these cities to save the environment (Jaillon and Poon, 2008). For example, prefabricated house manufacturers dominate the Japanese housing market due to the perceived advantages of producing high-quality buildings that are green to the environment and reducing construction time (Johnson, 2007). This proves that prefabrication has a positive impact on the environment, including the low construction waste and low carbon emission rate (Tam et al., 2006; Dong et al., 2015). Liu and Chen (2022) also added that the dust, noise, and sewage discharge of prefabricated buildings are greatly reduced, and the construction process can achieve environmental protection in line with the national energy conservation, emission reduction and green development goals.

In Hong Kong, half of the 7.5 million population is living in different forms of public housing, e.g., public rental housing (PRH) or subsidised home ownership scheme (HOS) housing (Hong Kong Census & Statistics Department, 2012), with advantages such as better-quality control, speedier construction and installation, relatively reduced costs, and improved resource efficiency. In China, prefabrication technology is noted to adopt the modern industrial production mode to replace the conventional manual production mode with the economic advantages of improving the quality of construction, improving production efficiency, shortening time, and energy-saving (Liu and Chen, 2022). Due to the potential economic benefits, various countries are up taking this technology along with other technologies such as building information modelling (BIM), etc.

Due to the technology’s perceived benefits, the developing world is also catching up in this prefabrication cause (Johnson, 2007). For example, rapid urbanisation in China and the housing shortage create a huge demand for new building construction (Lin et al., 2018). The Chinese Government, in its 13th National Five-Year Plan covering economic and social development from 2016 to 2020, tends to promote construction industrialisation and green building by targeting to achieve a 30% of newly constructed buildings being prefabrication rate in newly constructed buildings in 10 years (Chang, 2018). In Malaysia, a public project that costs over Malaysia Ringgit (MYR) 10 million or a private venture over MYR50 million is required to obtain a minimum Industrialized Building System (IBS) score of 70 (The Edge Property, 2016). By noticing these akin to a prefabrication ‘race’, Lu et al. (2018) called for a moratorium on this unhealthy ‘race’ and shifted focus to the proper LoP that fits into a nation’s political, economic, social, and technological condition.

In addition to the benefits mentioned above, prefabrication also has drawbacks. The technology is considered less stiff, less sound and waterproof than cast-in-situ construction (Hao et al., 2020). The technology is also known to face challenges such as limits of height for buildings projects, safety-related risks during the assembling/construction processes and bearing capacity of the frame structures, and durability (Ahn et al., 2020). To this end, the housing projects in Hong Kong and Singapore still adopt cast-in-situ in building the main structure parts (e.g., central cores, columns, beams, and load-bearing walls) while non-structural members are precast and installed into the positions (Hong et al., 2016). Against our orthodox wisdom, prefabrication is slightly costlier than traditional technologies due to high set-up costs and experiencing the learning curve (Zhang et al., 2018). Transportation cost becomes a new challenge that could be overwhelming, particularly for narrow streets and congested sites like Hong Kong. It is critical to source prefabrication within a certain range of distance to stable the supplies meanwhile reducing the transportation cost, e.g., Hong Kong’s access to the Pearl River Delta (PRD), China and Singapore’s access to the production and labour resources in its surrounding countries. The power and cost to hoist the precast components become another challenge that is yet to be fully solved. Prefabrication needs to fix its design to allow enough time for production; therefore, it is less preferred by real estate developers who often change designs and maintain their flexibility to the market needs (Jaillon and Poon, 2010).

Prefabrication also requires a different skillset from the traditional cast-in-situ construction (Rahman, 2014) and may not be readily available in a traditional construction market. The strategy to outsource many prefabrication works to offshore places will also add the cost of coordinating different stakeholders in different places, time zones, standards, and business cultures of doing business (Rotimi et al., 2022). Moreover, from a technical perspective, for many countries prone to earthquakes, prefabrication has faced damages and failures and is minimal since the technology related to prefabrication in those countries may not be matured yet (Arslan et al., 2006). Under these circumstances, it is critical to have a common language to measure and communicate different LoP.

**3. Existing approaches to measure the level of prefabrication**

The desire for a common language for LoP has motivated numerous researchers to develop approaches to measure it.

***3.1 The ‘category’ approaches***

The category approaches measure the LoP by proposing taxonomies/classifications based on the type of prefabricated components. These approaches were limited when adopted by studies (Table 1), thereby affecting the full picture of prefabrication in the case projects (Gibb, 2001; Abosaod, 2010; Sierra and Zamora, 2013; Steinhardt et al., 2014). This then informs the need for a method to address the limitations posed by the existing studies. Amongst the many ‘category’ approaches, Gibb’s (2001) seems monolithic, although it is not fundamentally different from others; hence, selected by the study.

Table 1 summarises the different category approaches explored in different countries associated with their limitations, as the LoP was examined by probing the forms of prefabricated components adopted.

**[Table 1 near here]**

***3.2 The ‘index’ approaches***

The index approach measures the proportion of prefabrication adopted in an entire project and presents it in numerical values/indices such as ratio, percentages, etc. Previous studies have adopted the index approaches in measuring the LoP in projects and have encountered limitations (CIDB, 2004; Alinaitwe et al., 2006; Hong et al., 2016). These limitations were mainly due to the inability of the approach to demonstrate the forms of prefabrication adopted in the project. Based on the index approach, other studies also raised the issue of “more effort needed in quantifying the prefabrications forms” (CIDB, 2004; Alinaitwe et al., 2006). These limitations call for an efficient approach to cater to limitations. This then study adopted the approach by Hong et al. (2016) due to the level of easiness, recentness and efficiency in computation compared with the other approaches.

Table 2 lists the major index approaches by studies as documented in the literature and the limitations of the study’s approach. Using ‘index’ to measure LoP has also been widely explored in various countries, irrespective of having different names, e.g., IBS score in Malaysia and PPVC in Singapore.

**[Table 2 near here]**

***3.3 Strengths and weaknesses of existing approaches***

From reviewing the existing studies with the adopted approaches, the study summarised their strength and weaknesses (Table 3). One observation is that the approaches’ strengths and weaknesses can largely supplement each other. For example, the category approach is easy to use; one can easily examine the components or even drawings of a project and understand which category of prefabrication has been adopted (Gibb, 2001; Shamsuzzoha et al., 2018). However, it is not intuitive how much the prefabrication is proportioned to the total construction volume (Alinaitwe et al., 2006). By contrast, the index approach can provide such information (Hong et al., 2016). Nevertheless, it needs extra effort to collect the data, e.g., total numbers and construction volumes of certain components, to have the index (Alinaitwe et al., 2006; Lu et al., 2018).

**[Table 3 near here]**

Another observation is the potential yet unknown link between the two measurements. Theoretically, it might be the case that only Level 1, e.g., precast slab, is adopted, but it still has a higher index if all the slabs in a building project are precast. It might also be the case that a high Level 3, e.g., volumetric kitchens, is adopted, but the overall prefabrication index is low if only this form is adopted in a project. In real-life practices, these two extreme scenarios are unlikely the case. The proposition is that a certain range of prefabrication index can be mapped to a certain category of prefabrication and vice versa. Having the two in one approach will provide a rounder picture of LoP adopted by a project.

**4. Research methods**

The CIH approach to measuring the LoP in this study is developed using a mixed method. A literature review is embarked on to review the existing approaches to measuring the LoP and identify the research gap. The following activities are then embarked on to realise the CIH approach:

***4.1 Modelling the Category and Index Hybrid (CIH) Approach***

The CIH approach is developed based on a mixed prefabrication level measurement system; hence, being a hybrid of the mixed approaches (i.e., category approach and index approach). The data from the category and index approaches become interdependent in addressing the common question of measuring the LoP. The CIH model (Figure 1) advocates that the LoP should be measured in a 2-way system that considers the type and the volume of prefabrication components in a project, attaining a volume of prefabrication by category. The CIH approach harnesses the strengths of the existing approaches (i.e., the category approach and the index approach) to address the limitations encountered by the studies reviewed (Table 1 and Table 2).

**[Figure 1 near here]**

The category component in the CIH model measures the LoP in a typical project by mainly considering prefabricated components. Specifically, Gibb’s (2001) taxonomy is adopted given its wide acceptance by researchers and practitioners in the industry 4.0 era without modification. His taxonomy classifies the building components used for a project into levels (i.e., 0, 1, 2, 3 and 4), as described previously. In real-life practice, a project may adopt different levels of prefabrication ranging from full cast-in-situ to complete prefabrication. Designers often prefer a combination thereof depending on several factors such as site condition, supply of different technologies, and their experiences.

The index component in the CIH model measures the volume of prefabricated components used in the building project by referring to the three dimensions, namely length, width, and height. In a typical project, the indices display the percentage volume of prefabricated forms concerning cast-in-situ construction or total construction volume. Hence, adopting the index approach by Hong et al. (2016) due to its recentness, easiness and efficiency with computation.

***4.2 Case Study***

A case study is then conducted to (a) illustrate how the CIH model can be applied; and (b) to understand the internal link between the two measures in prevailing prefabrication practices.

*4.2.1 Background of case study*

The case study is contextualised in Hong Kong, which has achieved world-renowned development in prefabrication construction. The history of prefabrication can be traced back to the massive public housing programmes since the 1950s. Owing to the limited land supply for residential purpose, any housing must go upward. Hence, the housing buildings are commonly up to 30 to 60 floors in Hong Kong. The industry has developed an international reputation for applying prefabrication in high-rise buildings. A strategic development was to relocate the supply of prefabrication in the adjacent PRD, China, to exploit the relatively cheaper labour, materials, and spacious space there. The building industry in Hong Kong has thus also developed an international reputation in managing design locally and manufacturing offshore and cross-border logistics and supply chain.

*4.2.2 The sample projects*

A total of 15 high-rise sizeable building projects in Hong Kong were chosen. Table 4 illustrates their basic information. The projects are quite sizable in terms of floor area and contract sum. They are all built in the 2010s. Ten of them are public housing projects, and five are private. It is known that prefabrication has been adopted in these projects, but it is unclear how it has been used.

**[Table 4 near here]**

*4.2.3 Data collection*

Three steps were involved in the data collection. Firstly, the construction floor plans, particularly the standard floor, of the selected projects, through which prefabricated components involved were further identified. This requires considerable domain knowledge to know the components and the LoP they belong to. The next step extracted the dimensions of the prefabricated components using the standard floor plans by considering the length (*L*), width (*W*)/ Thickness(*T*) and Height (*H*) of the components. The volume of prefabricated components was computed using appropriate formulae based on their form/shape. This was done in parallel with the extraction of the cast-in-situ elements’ dimensions, creating the possibility of computing the total construction floor volume. Lastly, different colour pens were used to mark directly on the floor plans to ensure easy visualisation of the prefabrication components and the cast-in-situ parts (See Figure 2).

**[Figure 2 near here]**

There is a caveat that some of the precast components in the non-standard floor (usually the first three floors) and the rooftop (e.g., some parapets or water tanks) are omitted from the data collection. However, these components in the non-standard floors take up a small, negligible portion in a high-rise building with 30~60 standard floors. The data collection process was rather time-consuming and tedious. One author conducted the data, and another validated it independently to enhance the inter-rater reliability. Finally, all the data, including specific levels and types of precast components, prefabrication volumes, and cast-in-situ volumes, were tabulated in a spreadsheet for further analysis (as reflected in Table 6).

***4.3 Interviews***

A series of semi-structured interviews with selected industrial stakeholders mostly related to the 15 selected projects were conducted to review the strengths and weaknesses of the proposed CIH approach and its prospective applications. This is purported to add to the validation of the CIH approach. Questions are organised under the following three topics:

* What approach to measuring LoP do you use in your projects or during your works? What are the strengths and weaknesses of these approaches?
* The Category and Index Hybrid (CIH) approach needs to identify the precast components category and their ratio in the total construction volume. What are the advantages and drawbacks of using the approach, particularly compared with previous category and index approaches?
* What are the potential uses of the CIH approach?

The interviews were conducted from 2020 to 2021 in Hong Kong and the PRD regions. A typical interview is often started with some background discussion, general comments on existing prefabrication practices, and so on, to warm up and “enter the mood”. Then, some questions in the first category are asked. Extra questions were asked when there was an area the interviewer needed to tease out more information from the interviewee. It needs to point out that not all the interviews followed a strict protocol. Some of them happened on a site, in an office, or even in a car to the factory. Later stage, owing to the social distancing caused by the COVID-19, some of the interviews were conducted by phone, Zoom, or email, depending on the availability of interviewees. Six interviews were conducted, with some information as listed in Table 5.

**[Table 5 near here]**

**5. Analyses and Findings**

***5.1 Gibb’s Taxonomy-Based Classifications***

This study classified the prefabricated components adopted in each case study based on Gibb’s taxonomy, as indicated in Table 6. Furthermore, the study investigated the usage of prefabricated components per standard construction floor in Hong Kong. It inferred that both public and private building projects in Hong Kong have actively involved the use of prefabricated in recent years. Project clients tend to adopt cast-in-situ technology for the structural parts in these projects; meanwhile, adopt almost every level of prefabrication technology. Level 4 prefabrication, consisting of complete well-furnished modules, is also emerging in Hong Kong, but no project data has been collected for this study yet.

Inferring from Table 6, public projects engage high volumes of precast façades, followed by full precast slab and precast bathrooms, while the private projects make use of a high proportion of non-structural prefabricated external walls, followed by precast façades and the precast structural wall. Particularly, precast façade (i.e., Level 2 prefabrication) was adopted in an impressive proportion across all the sampled projects. The findings show that the Hong Kong construction industry uses a significant amount of prefabrication, yet on-site construction is also prevalent in the projects studied. Such prevalent on-site construction elements include the internal wall structure and the slabs.

The study further investigated the usage of prefabrication components per standard floor in Hong Kong in response to the taxonomy developed by Gibb (2001). The results in Table 6 depicted that Hong Kong adopts different kinds of prefab components characterised, except the Level 4 prefabrication. The case projects did not use any elements characterised by Level 4, and it consists of a complete well-furnished module.

**[Table 6 near here]**

# ***5.2 Percentage (%) Volume Computation***

The volume of construction works done offsite (Table 7) was computed in relation to the volume of works done on-site using *Equation 1* based on Hong et al.’s (2016) approach. Attention was paid to construction floor volume, where a typical standard floor was considered among all the floors for a particular high-rise project.

*Index Approach =*$ \frac{Volume of Prefabrication}{Total Construction Volume }\* 100\%$*…… (Equation 1)*

**[Table 7 near here]**

Finding the percentage of prefabrication in the 15 case projects roughly denotes, as stated earlier, the proportion of prefabricated components being engaged in each project. Per table 7, the lowest prefabrication volume was obtained by P11 (71.426m3) with a prefabrication proportion of 46.968% of the entire project, whilst the highest prefabrication volume was obtained by P6 (503.627m3) with prefabrication percentage of 33.854%. This vividly demonstrates that higher prefabrication volume does not guarantee a higher prefabrication ratio in the entire project. It depends on the size of the project. The highest prefabrication index was obtained by P14 (67.696%), showing that a high volume of prefabricated components was involved.

**[Figure 3 near here]**

By comparing the prefabrication volume to the forms of prefabrication, the stacked column (Figure 3) demonstrated the possibility of better measuring the prefabrication rate simultaneously. “Level 0” was the highest across all projects, and this is because Hong Kong makes use of cast-in-situ in the construction activities among both the private and public projects. The finding again confirmed that prefabrication components are engaged in all projects in Hong Kong, from a simple geometrical form (“Level 1”) to a more complex geometrical form (“Level 3”).

The Pearson correlation, *r,* was then adopted to examine the correlation between the prefabrication forms (Levels 0,1,2,3) using the index data following the correlation threshold (Ratner, 2009)*.* The finding indicated a strong positive correlation between the use of Levels 0 and 1 prefabrication (0.799) across the sampled projects (Table 8). Prefabrication in the form of components and assemblies is often used in conjunction with cast-in-situ parts. Hence, compared to Levels 2 and 3, Level 1 is easier to integrate into in-situ construction (Level 0). This is parallel with the hybrid concrete construction concept, which integrates precast concrete and cast-in-situ to take advantage of their inherent qualities (Glass, 2005; Zhang et al., 2021).

**[Table 8 near here]**

***5.3 Strengths and weaknesses of the CIH Approach***

An analysis of the interview data shows that the strengths of the CIH approach are derived from individual category and index approaches by keeping their strengths and covering each other’s weaknesses, as listed in Table 3. For example, the CIH approach can provide a clear-cut measurement of the categories of prefabrication while showing the percentage of prefabrication adopted in a project. It is thus easier for communication and enables one to have a rounder understanding of the prefabrication type and ratio adopted in a project. Interviewee E commented that the CIH approach

*“provides a clearer prefabrication-level breakdown structure”.*

This is echoed by Interviewee F, who reflected that the CIH approach

*“makes the measurement of prefabrication finer by combining qualitative and quantitative measurements”.*

Meanwhile, interviewees also reflected on some weaknesses of the CIH approach. The first type is related to the methodology, mainly the data collection part. For example, Interviewee B mentioned that collecting the data, e.g., the prefabricated components, their geometries and volumes (Section 4.2.3), requires considerable domain knowledge and meticulous efforts. The second type of weakness, as commented by the interviewees, is the potential oversimplification of the approach. Interviewee F suggested that

*“It is difficult to tell which form of prefabrication falls into the ‘category’ as adopted in your approach. There is no clear industrial standard. Ultimately, such difficulty may lead to inaccurate calculation of the prefabrication index”.*

Interviewee C commented that there are numerous methods for calculating the prefabrication index,

*“The CIH approach only counts precast concrete volumes. Meanwhile, you need to consider the steel rebars, windows, doors, and other prefabricated components. The regulations also stipulate different terms such as prefabrication ratio, on-site assembly ratio, etc. Your CIH approach seems incapable of differentiating these”.*

It is not surprising that the interviewee from Mainland China had such comments. After the national target of prefabrication adopted was set in China, various provinces had devised their targets and incentive policies. To have a solid measurement does matter to measure the progress and allocate incentives. The differences in the targets and incentives have led to sheer definitions of LoP and measurement methods.

Nevertheless, the measurements become too diverse to comprehend, and there is little consistency in the methods across different jurisdictions. Interviewee A resonated with our argument,

*“There is a rule-of-thumb formula to convert the volume and weight of concrete and other materials in one region, as they often adopt the same building codes, e.g., concrete and rebar ratio”*

Interviewee D further added,

*“In the upper storeys of a high-rise building, the walls, regardless of being cast-in-site or precast, are thinner. This is allowed by building codes. Shall we also consider this in calculating the prefabrication index? My opinion is not to. In understanding level of prefabrication, we don’t need it as accurate as rocket science”.*

Therefore, we argue that the CIH approach provides a reasonable degree of precision in measuring LoP without losing its strengths for easy communication.

**5.4 Prospective applications**

By analysing the interview data, it can be deduced that the CIH approach can have three prospective applications: (a) enabling a series of empirical tests; (b) benchmarking LoP across different countries; and (c) gauging or fine-tuning public policy incentives to promote prefabrication.

Firstly, rather than harvesting the propagated benefits straightforwardly, the promotion of prefabrication has experienced a winding path. Stakeholders are deeply tangled with the material implications of adopting prefabrication, e.g., cost-saving, productivity enhancement, building time saving (Zhang et al., 2018), or the like. These examinations have later been extended to some non-monetary benefits, e.g., saving carbon emissions, OHS hazards (Ahn et al., 2020), construction waste minimisation (Tam et al., 2006; Lu et al., 2021), and so on. Nevertheless, none of the research studies has measured the LoP quantitatively as a dependent variable for more precise examinations. The CIH approach can provide such quantitative variables. However, a word of caution is that the prefabrication indexes should be measured in a large scale and constant fashion. The correlations between the LoP and its impacts are normally confounded by many other factors (e.g., project complexity, site constraints) that need to be “controlled” in regression or correlation analyses.

Secondly, the CIH approach provides an opportunity to benchmark the LoP across different regions or against their past. As shown in Section 3.2, countries all have their respective definitions of the LoP and measuring methods. There is a tendency to benchmark across different countries and learn from each other’s good practices with the globalisation of construction and prefabrication. Nevertheless, current definitions and measurements of the LoP without any sense of standardisation are hurdles to cross-region benchmarking and learning. We argue that the CIH approach used as a standard across these different countries’ prefabrication practices would provide an easily accessible yet powerful tool for benchmarking and learning. The CIH approach can also gauge the LoP change over time, as it provides a consistent method that allows longitudinal comparisons.

Lastly, the CIH approach can also be used to gauge or fine-tune current incentive schemes to promote prefabrication adoption. As mentioned above, prefabrication has not always been preferred by clients. Governments have devised many schemes to incentivise the adoption of prefabrication. For example, in China, developers adopting prefabrication can enjoy all kinds of incentives varying from one province to another. In Shanghai, a client can enjoy a monetary subsidy of CNY100/m2, totalling up to several million of CNY (Lin et al., 2018), if a project meets a certain LoP criterion. Counting the prefabrication index matters to decide whether it meets the pre-set LoP criteria. Hong Kong counts it as green building technology, so clients can enjoy exemption of sellable floor area, which is the most expensive commodity in this compact city. The CIH approach proposed in this study can provide an easy-to-use, yet consistent measurement of the LoP, although, as above mentioned, some interviewees think it is somewhat oversimplified.

**6. Discussion and Conclusion**

Prefabrication is increasingly utilised as a modern construction strategy to source construction resources from offsite or even offshore places worldwide. Under these circumstances, a common language to measure and communicate the LoP become a particularly urgent need. Recognising the shortcomings of using the existing individual approaches by previous studies across different countries, there is still a need for a comprehensive approach to understanding the true picture of prefabrication in a project. This study, therefore, developed a CIH approach by understanding the need to combine the existing two approaches to form a hybrid approach, which harnesses the strength of the existing approaches to meet the limitations addressed in the literature. It determines the categories of prefabrication and the prefabrication index adopted by a project and explores their inherent internal nexus. An interview was conducted to understand the CIH approach’s strengths, weaknesses, and prospects.

The CIH approach revealed the true picture of prefabrication in a project, including the type/forms of prefabrication adopted and the corresponding volume percentages based on their geometric forms. This could assist in benchmarking the effect of prefabrication in a building through an empirical test on understanding the waste minimisation from prefabrication project (Tam et al., 2006; Lu et al., 2017), cost and time saving (Zhang et al., 2018), carbon emission reduction to the environment (Dong et al., 2015), etc. The CIH approach could serve as a powerful tool to easily gauge and access a country’s performance regarding prefabrication technology and its effect on the environment. It provides a consistent standard method that can allow longitudinal comparison between the percentage volume and forms of prefabrication in projects. This then proceeds to help in fine-tuning incentive schemes to promote prefabrication. For instance, the adoption of building modular units, the highest level of prefabrication, has helped drastically minimise waste, construction schedule, etc. (Lu et al., 2021; Olanrewaju and Ogunmakinde, 2020). Effectively tracking the cost, time, and waste performance on related projects with the CIH approach could push policymakers to fine-tune current incentive schemes to promote prefabrication adoption (Lin et al., 2018) from the simplest to the highest form.

The CIH approach identified visually the apparent relationships among the prefabrication levels and enabled a better understanding of the bigger picture of prefabrication adoption. It revealed a strong positive correlation between Levels 0 and 1 prefabrication usage across the Hong Kong prefabrication construction projects. It implies that high-rise building clients and their designers prefer non-structure components such as slabs, façades, partitioning walls, and sometimes, volumetric kitchens/bathrooms to be precast while remaining the structural parts as cast-in-situ (Hong et al., 2016). This is also consistent with the hybrid concrete construction concept, where precast concrete elements are combined with the in-situ concrete elements to take the best advantage of their different inherent qualities (Glass, 2005). The accuracy, speed and high-quality finish of precast components can be combined with the economy and flexibility of cast-in-situ concrete (Burridge, 2021). Also, the study revealed that when facades and non-structure external walls are chosen for prefabrication projects, they are often bulky in volume, and the LoP measured by index can be 50% or even higher (Jaillon et al., 2020).

The CIH approach developed in this research is advanced to measure the category and prefabrication index. It provides a much rounder measure of the LoP and facilitates communication among stakeholders. It enables many theoretical and practical contributions. Theoretically, the study makes a distinctive contribution to knowledge as it does not only propose the CIH approach to measure the LoP, but also identifies its strengths and weaknesses to enable its improvement in evaluating the LoP in a project. Furthermore, the index component of the CIH approach can provide a numerical independent variable for empirical studies, whilst the category component can help researchers delve into more detailed effects caused by different types of prefabrication. On the practical side, the CIH approach can provide adequate results to fine-tune current incentive schemes to promote prefabrication adoption due to its holistic ability to unify index and category data to understand the full picture of prefabrication usage in a project. For example, construction clients in different economies often enjoy incentives (e.g., sellable floor area exemption, green building certification) by adopting prefabrication technology. The index component of the CIH approach can help scrutinise whether they are *bona fide* subscribers of prefabrication or just superficially tasting the green construction technology. It thus can help fine-tune current public policies to incentivise the adoption of prefabrication properly. It also has a significant influence on assisting practitioners and policymakers in effectively tracking construction waste generation and minimisation, carbon emission, and other key performance indicators of a prefabrication project.

Nevertheless, the CIH approach needs extra effort and domain knowledge, e.g., to recognise different precast components and their portions in the total construction volume. The taking-off process is by researchers based on the drawings, which is a limitation of this study. It may involve some level of subjectivity or even mistake. Hence, future research is then urged to integrate the concept of BIM technology and construction 4.0 into the CIH approach to automate the processes involved and better evaluate the LoP in a prefabrication building project. Also, this study’s result is based on historical data; therefore, future research could implement the CIH approach in future buildings to understand the building’s performance concerning the prefabrication technologies adopted, and also to ensure its validity and reproducibility in producing generalised results. In the specific construction industry, there are often “rules of thumb” to convert the two measures (volume indices and forms) quickly. Hence, future research is also encouraged to codify such rules, even for laymen, to allow rapid measurement of both category and index of prefabrication to harness the power of the CIH approach.

**Data Availability Statement**

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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