Reconsidering Adaptive Industrialised Construction in Chinese Rural Areas: Responding to the Challenge of COVID-19

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Abstract

The spread of COVID-19 has caused an increasing demand for public medical rooms, especially in Chinese rural regions. Industrialised building techniques have been shown as capable of fulfilling this demand through the case of the Leishenshan Hospital. However, industrialised construction requires developed technologies and infrastructures, which are often non-existent in rural areas, thus making it difficult to replicate such a feat. Therefore, more suitable solutions for Chinese rural project delivery in the pandemic scenario are needed. Considering the constraints of pandemic prevention and rural applicability, the adaptive industrialised construction (AIC) method has potential as an alternative. This study evaluates the application of AIC by comparing simulated results using AIC and a conventional method, based on five evaluation indicators: construction speed, labourer distribution, material consumption, equipment utilisation, and cost. Taking an actual project as the sample building, the results indicate that the AIC method has several advantages. These include a shorter construction period, less labourer gathering onsite, and a lower cost, suggesting it may be an effective solution for rural project delivery during the pandemic. Architects and contractors could employ the same evaluation method to explore more solutions and optimise the construction schedule for future rapid construction needs in rural areas in a pandemic.

Keywords: COVID-19, Rural construction, Adaptive industrialised construction, Construction Simulation.

Introduction

The rapid spread and extreme transmission rate of COVID-19 have triggered a significant demand for medical wards and treatment rooms (Gbadamosi *et al.*, 2020). The normal level of medical resources cannot cope with the pandemic-fuelled rapid growth of patients, especially in developing countries (World Health Organization, 2021a). In Wuhan, China, for example, the number of visiting patients exceeded the maximum hospital load by 40% in the first month of 2020 (Cao et al., 2020), when COVID-19 was just reported and concentrated in a single city. A direct comparison of the infection ratio reveals the increasing demand for additional medical space: the rate escalated from 29 cases per 100,000 population (3,215 cases in 11.2 million citizens in Wuhan in 2020) to 2152 cases per 100,000 population (29,700,313 cases in 1.38 billion citizens in India in 2021) (World Health Organization, 2021b).

Existing solutions to this emergent situation include retrofitted temporary COVID-19 hospitals (e.g., the Nightingale Hospital in London, UK), temporary portable cabin hospitals (e.g., the USNS Mercy medical ship in the USA), and newbuild COVID-19 hospitals (e.g., Huoshenshan Hospital in Wuhan, China) (Gbadamosi et al., 2020). However, these approaches to provide more medical units within a short period rely on modern construction equipment and skilled labourers. For instance, the construction of Leishenshan Hospital took less than 12 days. During which over 1,500 workers and 800 construction machines were working day and night simultaneously (Luo *et al.*, 2020). It would be impractical to duplicate the same model in rural areas where both resources (Yuan *et al.*, 2021) and technologies are limited (Sun *et al.*, 2019).

Conventionally, rural construction achieves a similar construction speed as the industrialised construction approach by employing extra labour. The low-cost workforce in rural areas compensates for the low efficiency caused by insufficient construction equipment and makes construction projects labour-intensive (Mostafa *et al.*, 2016). However, a large number of labourers are not allowed to gather onsite due to the threat of COVID-19 (Johnson *et al.*, 2021). Therefore, there has been an urgent demand for exploring less labour-intensive rural construction methods to guarantee the rapid delivery of healthcare projects during the pandemic.

The adaptive industrialised construction (AIC) method (i.e., adjusting pure industrialised construction methods to the rural condition) has been claimed to be a practical method for bringing modern construction technologies to rural areas (Hsieh, 2016; Zhang, 2018; Zhu, 2011). Given that the industrialised-construction characteristic of replacing labour construction with equipment operation helps to realise safe and rapid project delivery (Chen *et al.*, 2021), the similar feature in the AIC method makes it a potential solution for rural construction during the pandemic. Therefore, a review and evaluation of previous AIC methods from the perspective of being applied during the pandemic could provide suitable solutions for rapid and safe rural project delivery. The suggested solutions could be applied rapidly and with a low development cost due to the use of existing products and technologies. Such solutions could also contribute to epidemic prevention in rural regions and promote worldwide COVID-19 prevention. Meanwhile, conducting a retrospective study helps to identify the potential value of existing AIC methods, accelerating advancements in the rural construction industry. Therefore, this study aims to explore suitable construction methods for rural project delivery during the spread of COVID-19.

Background

Rural Construction

Rural construction refers to construction projects in a non-urban environment, whether traditional or modern (Armesto González *et al.*, 2006). This covers diverse cultural and geographical features, economic levels, and available resources (Hu *et al.*, 2021), such as residences with masonry structures in central China (Zhang, Chen, Sun, *et al.*, 2019), stone corrals in the Adriatic-Ionian area (Picuno *et al.*, 2017), and houses with beamed drywall in Turkey (Sağıroğlu, 2017). Attempts have been made to classify rural construction. For example, Yuan *et al.* (2021) classified rural structural systems into traditional, early modern, and modern industrialised systems, identifying strengths and weakness of each in relation to convenience of materials and construction, cost , performance, and durability. Their conclusions are supported by other regional research in China (An, 2017; Qu, 2014), Nepal (Adhikari *et al.*, 2020), and Africa (Von Seidlein *et al.*, 2019).

Exploration of adaptive construction methods

A consensus exists on the idea that the modern construction mode entirely differs from the conventional handicraft process (Xu and Jin, 2019). The shortage of resources and capital prohibits the application of pure industrialised methods in rural regions, which demand large-sized construction machines and professional technicians (Sun *et al.*, 2019). To reconcile this contradiction, Sun *et al.* (2019) highlighted the importance of integrating modern construction technologies and rural workforce conditions. Technically, such integration achieves better adaptability by investigating alternative designs and delivering methods and materials for better adaptability (Adom-Asamoah *et al.*, 2017).

To that end, there are primarily two approaches. The first involves employing natural materials and traditional construction methods. For instance, Guan and Li (2002) constructed the foundation with local stones and filled the envelope with straw and bamboo to improve thermal performance. Yuan *et al.* (2018) explored the applicability of low-tech bamboo buildings in rural construction and ultimately recommended this structure for its technical simplicity because it is easy to learn and requires no professional operation skills. Other scholars have attempted to compensate for insufficient building materials in developing countries by integrating conventional materials with industrial products. For example, Liu and Huang (2020) studied the adoption of wood, straw, and loess-blended concrete in a Northwest Chinese residence. Adom-Asamoah *et al.* (2017, 2018) validated the engineering performance of bamboo-reinforced self-compacting concrete components. The findings from these studies showed that such components are available and are affordable alternatives for rural construction.

The second approach adopts domestic waste or industrial by-products for use as building materials. Temple and Rose (2011) packed car and truck tyres with dirt to create rammed-earth tyres as the frameworks of external walls. The researchers also employed inorganic-trash-packed plastic bottles to fill in the space between wall frames. Olorunnisola and Boboye (2016) used cement-bonded composite pipes (reinforced with natural fibre) for rural construction in tropical Africa. They finally replaced 50% ordinary Portland cement with carbide waste. In addition, this approach has also been adopted in rural road paving. For instance, Qiao *et al.* (2010) utilised sulphate-rich solid waste in rural road construction. The findings showed a reduction in project cost and no adverse environmental impact.

These studies promoted the implementation of industrialised construction methods in rural regions. Additionally, they provided general criteria of adaptive technologies evaluation, i.e., low-cost, material availability, a low requirement on labourer ability, and equipment independence. These demands will be considered in the AIC method evaluation in this paper.

Implementation of industrialised technologies

Generally, policy and emergency are two primary drivers of applying industrialised technologies in rural areas. The former is usually seen in the national rural construction campaigns, especially in developing countries like China (Gong and Li, 2013) and Vietnam (Thoa, 2019). These government-led projects aimed to improve the quality of rural residences and infrastructure by employing industrialised methods. Nevertheless, their neglect of local conditions led to poor practicability, low occupancy, and extensive resource waste (Zhang *et al.*, 2019). This mode is difficult to be replicated in areas without financial and policy support (Jin *et al.*, 2021; Wang *et al.*, 2020).

Research concerning emergency response is more in line with the objective of this study. Construction efficiency, material and equipment availability, and labourer ability are the most important considerations in these circumstances. Thus, there is a preference for prefabrication, especially the lightweight steel structures. Examples being a lightweight steel structure used to build two schools in the quake-hit area in Sichuan (Zhu, 2011). A similar approach was used as part of the 2015 Nepal earthquake relief (Hsieh, 2016). This structural system could also be combined with regional materials for better adaptability and a lower cost (Zhang, 2018). For temporary projects there is more choices, such as using shipping containers for a three-story temporary residence in Onagawa, Japan, and paper log houses in regions like Kobe, Turkey, India, and Taiwan since 1995 (Ban, 2017).

Although not being classified as adaptive construction (which focuses on the integration of rural and modern construction methods), Zhu (2011), Hsieh (2016), Zhang (2018), and Ban (2017)'s research incorporated adaptive thinking into technology application. These studies implemented industrialised technologies according to rural conditions, and thus they are examples of AIC application, which provides experience in rapid rural construction. However, none of them has considered the workforce restrictions fuelled by anti-pandemic measures and allow local labourers to gather during construction without social distancing (shown by their photographs). These labourer-intensive modes will cause unsafe conditions in the current environment where COVID-19 outbreaks continue to spread across the world.

Construction during the COVID-19 pandemic

As the largest industry in the global economy, construction has been significantly impacted by COVID-19 (Ribeirinho *et al.*, 2020). The coronavirus-induced recession resulted in cancelled projects and significantly delayed construction plans (Crain, 2020), causing, for example, a 975,000 job loss in the American construction industry in April 2020 (Currie, 2020). Meanwhile, the financial pressure forced construction employees to work without sufficient protection (Johnson *et al.*, 2021). Araya (2021) simulated the spread of COVID-19 among construction workers using agent-based modelling. The findings showed that the workforce would reduce by 30% ~ 90%, even with the most rigid management and prevention measures.

Since 2020, governments around the world have enacted rules and regulations to relieve such threats (Gostin and Wiley, 2020). Specific self-protection solutions suitable for the construction industry include 1) wearing masks, 2) staying a distance from others, and 3) avoiding crowds and poorly ventilated spaces (American CDC, 2021; Chinese CDC, 2020). However, implementing these solutions in construction is challenging due to the inherent labour-intensive nature of construction projects (Zheng *et al.*, 2021). Johnson, Hancock, and Matt (2021) reported how project managers gathered in site offices without adequate ventilation and self-protection, attributing the situation to the absence of adequate guidance.

That conclusion was supported by Zheng, Chen, and Ma's research (2021), which declared that Chinese labourers acknowledged COVID-19 and were willing to take preventive measures due to the government's continuous education. Nevertheless, it is still worth noting that 25% of the respondents reported not wearing a face mask and 16% reported not maintaining a sufficient social distance. Research on personal protective equipment provided another explanation for this issue. Chen *et al.* (2016) reported a higher breathing resistance with the N95 respirator and an increased respiratory rate after long periods of wearing a mask and walking. Smith, Whitelaw, and Davies (2013) indicated a significant increase in CO_2 rebreathing during a mask-wearing speech and work. Such conditions may contribute to mask-wearer discomfort and thus a wearing time reduction. As an industry requiring frequent communications and a heavy workload, the construction industry must consider effective labourer protections when operating in a COVID-19 environment.

Construction methods during the COVID-19 pandemic

Many researchers considered construction efficiency the most significant criterion to evaluate suitable construction approaches during this specific period (Gbadamosi *et al.*, 2020). Luo *et al.* (2020) made a detailed introduction of Leishenshan Hospital that outlined how BIM and the product, organization, and process model contributed to the ultra-rapid delivery of the project. A similar conclusion was drawn by Chen *et al.* (2021) in their analysis on the same project, highlighting the benefit of modular and offsite construction for rapid delivery. Gbadamosi *et al.* (2020) suggested these construction methods as well. However, the above approaches all heavily rely on a stable supply chain and transport system, which cannot be guaranteed during the COVID-19 pandemic. Considering the current situation in which the pandemic is raging in underdeveloped areas, research that focuses on an environment with limited resources deserves more attention.

Project management during the COVID-19 pandemic

Labour management has been mentioned as a significant issue during the spread of COVID-19. Scholars closely examined how personal monitoring could alleviate the risk of gathering. Araya (2021) suggested delaying the spread among labourers by maximizing the low-risk construction activities. However, the approach was limitedly implemented because it was difficult to determine the level of risk. Pavón, Alvarez, and Alberti (2020) used a mathematical model to simulate the occupant distribution throughout the building. By integrating BIM technology, the approach appeared effective for personnel density prediction. Although not construction-oriented, the model is a good example of simulating labour management. However, there seems to be a lack of objective criteria (e.g., a numerical criterion on the labour density onsite), and when accompanied by the absence of standard solutions, this may represent a high level of uncertainties and risks.

Problem statement

Previous studies have contributed to the understanding of the development of construction in either rural areas or during the spread of COVID-19. However, research concerning rural project delivery in a COVID-19 scenario and the practical methods to estimate construction method performance in this specific condition is rare.

The modern industrialised construction, which allows for rapid project delivery in an urban environment (Chen *et al.*, 2021; Gbadamosi *et al.*, 2020), has been partially realised in rural areas in the form of AIC (Hsieh, 2016; Zhang, 2018; Zhu, 2011), indicating that AIC could be a potential solution for delivering rural projects during the spread of COVID-19. Considering the continued impact of COVID-19 on construction speed, labourer safety, and resource supply, this research aims to estimate existing AIC methods from these perspectives to verify their application potential and to explore suitable solutions for current rural project delivery.

Method

This research conducts a comparative analysis between AIC and conventional construction methods to evaluate their performance in a COVID-19 scenario. The methodology employed in this study includes three steps: 1) determining design alternatives with different construction methods, 2) determining evaluating indicators that consider both the limitations of COVID-19 and rural project delivery, and 3) comparing and interpreting the performance of design alternatives concerning those indicators using simulation.

Determination of design alternatives

Sample building

As shown in Figure 1, a two-storey village centre with a total construction area of 574.44m^2 (319.29m^2 for 1F and 255.15m^2 for 2F) was selected as the sample building because the project represents the general demands of the rural medical facility (e.g., function, area, and spatial design).

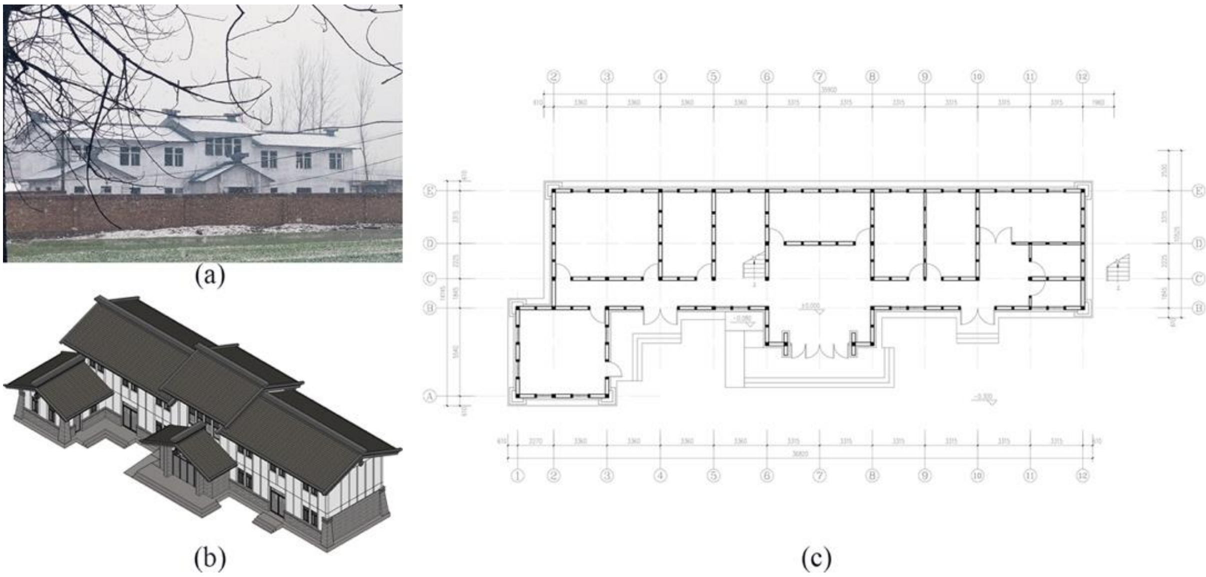

Figure 1. Photograph (a), 3D model (b), and the plan (c) of the sample building

The village centre was built from October 2019 to February 2020 in a rural district in Jiangsu province, China. The project employed an AIC method in the construction, of which a detailed description can be found in previous studies (Hu *et al.*, 2021; Zhu *et al.*, 2021). The building has a masonry structure with masonry walls and reinforced concrete floors. Specifically, the foundation was constructed using the roadbed construction method, as shown in **Error! Reference source not found.**. First, labourers excavated the earth to a depth of 750mm with a small-type excavator (8ton). The excavated soil was then mixed with the quick lime and curing agent by a retrofitted scarifier (**Error! Reference source not found.**-b). After that, the treated soil was stirred with cement and compacted to form the foundation. A 100mm cast-in-situ reinforced concrete was then constructed on the foundation layer.

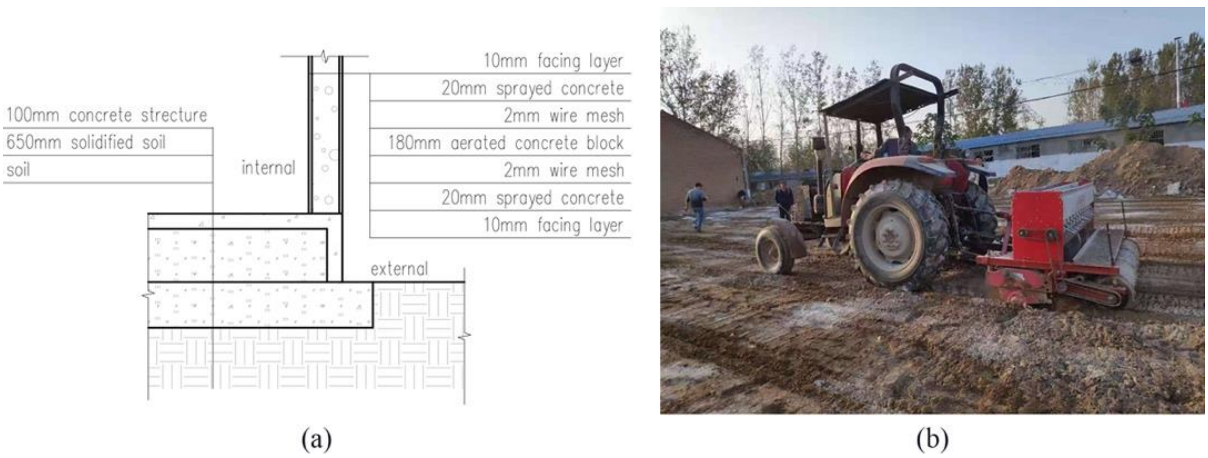

Figure 2. Design details (a) and construction process (b) of the foundation

Walls were constructed using structural columns and 960mm×180mm×600mm blocks, which were made of aerated concrete and straw, weighing approximately 25Kg per block (**Error! Reference source not found.**-a and **Error! Reference source not found.**-a). The spacing of structural columns was consistent with the size of the blocks (960mm). **Error! Reference source not found.**b - **Error! Reference source not found.**e illustrate the construction process of the walls. Before the construction, the reinforcement cages for the structural columns were prefabricated in the size of 130mm×180mm×3500mm. They were first welded to the embedded parts of the foundation. Next, labourers formed the wall with blocks and fixed them with steel bars (**Error! Reference source not found.**-b). After that, the 2mm bidirectional metal meshes were attached to both sides of a wall (**Error! Reference source not found.**-c). Labourers further poured the concrete following the sequence of the structural column, wall, and floor. Apart from the floor (which was paved by a pump truck), the other concrete was pumped and sprayed by a mobile concrete pump, as shown in **Error! Reference source not found.**-d. Finally, labourers polished the surfaces after concrete pouring and spraying (**Error! Reference source not found.**-e).

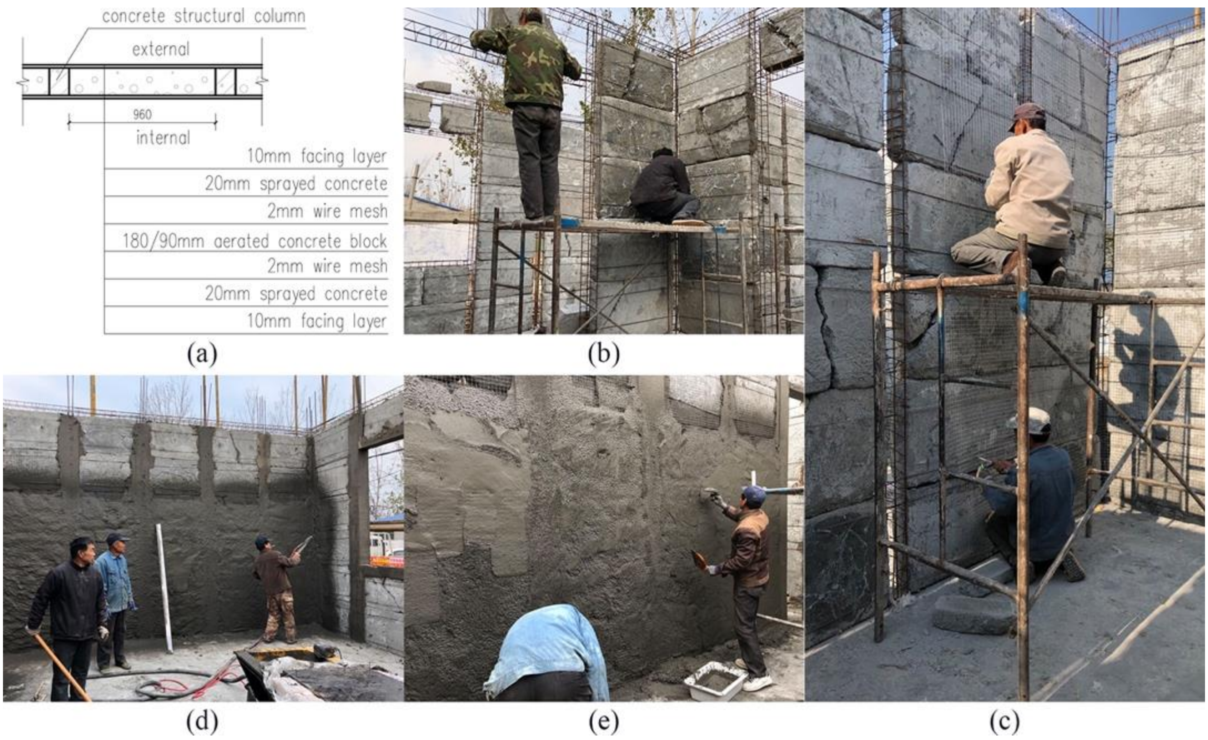

Figure 3. Design details (a) and construction process (b-e) of the wall

Design alternatives

Two design alternatives (A_1 and A_2) with the same geometric feature and different construction methods were generated based on the sample building. A_1 adopts the same structure as the sample building and applies the AIC method in the foundation and walls. A_2 adopts a conventional masonry structure with masonry walls, reinforced concrete floors, and a cast-in-situ reinforced strip foundation. This structure is the most comparable to the one used in A_1 because the original drawings of the real-world project was reviewed under the code for conventional masonry structures in 2019.

The masonry blocks used in A_2 are 240mm×115mm×63mm. Structure columns (240mm×240mm) are distributed every 4000mm. Apart from the difference in the structural system, A_2 employs the same equipment as A_1 in the commercial concrete pouring (i.e., pouring the concrete for the floor and foundation via a pump truck). Other cement-based materials would be prepared onsite using a cement mixer (see Figure 5).

Data Collection

Data collection for each design alternative comprised two steps: the content analysis of project files and the selection of construction parameters. Project files included design drawings and models, bills of construction quantity, the construction schedule, plans, and construction technology specifications. The project files for both design alternatives were checked for accuracy prior to starting the simulations.

Content analysis was followed by obtaining information concerning specific construction operations from actual construction practices and national codes. Table 1 lists the construction efficiency of each operation in A_1 and A_2, in which a day equals 8 working hours. The information was mainly sourced from the *Labour productivity standards for construction works* (MOHURD, 2009), a Chinese national quantity estimation guide providing average construction efficiencies for common construction operations. Measured values were used as alternatives for the efficiencies of some AIC operations that did not have a standard benchmark (marked by * in Table 1) (Hu *et al.*, 2021). The site record conducted during project delivery, from 29 October 2019 to 24 December 2019, was consulted to obtain the data.

Table 1. Parameters of the construction operations

Alternatives	Operation	Speed	Unit

A_1	Earth levelling	123.44	(m^2/person/day)
	Earth excavation	5.07	(m^3/person/day)
	Foundation construction	380.23	(m^2/day)
	Ground floor concrete pouring	4.52	(m^2/person/day)
	First-floor concrete pouring	5.41	(m^3/person/day)
	Foundation concrete curing	14.00	(day)
	Floor concrete curing	5.00	(day)
	Other concrete curing	0.42	(day)
	Column reinforcement assembly	340.00*	(m/person/day)
	Masonry assembly	12.86*	(m^3/person/day)
	Mesh attachment	135.00*	(m^2/day)
	Column formwork assembly	6.25	(m^2/person/day)
	Beam formwork assembly	6.85	(m^2/person/day)
	Column concrete pouring	0.95	(m^3/person/day)
	Beam concrete pouring	0.88	(m^3/person/day)
	Column formwork removing	23.75	(m^2/person/day)
	Beam formwork removing	20.88	(m^2/person/day)
	Plastering	29.55*	(m^2/person/day)
	Floor beam formwork assembly	11.75	(m^2/person/day)
	Floor surface formwork assembly	22.73	(m^2/person/day)
	Floor reinforcement assembly	39.00	(m^2/day)
	Floor formwork support removing	31.85	(m^2/person/day)
	Floor surface formwork removing	90.91	(m^2/person/day)
	Floor beam formwork removing	27.47	(m^2/person/day)
A_2	Earth levelling	123.44	(m^2/person/day)
	Earth excavation	5.07	(m^3/person/day)
	Foundation formwork assembly	11.40	(m/person/day)
	Foundation reinforcement assembly	25.00	(m/person/day)
	Foundation concrete pouring	1.47	(m^3/person/day)
	Foundation curing	14.00	(day)
	Floor concrete curing	5.00	(day)
	Other concrete curing	0.42	(day)
	Earth backfilling	14.08	(m^3/person/day)
	Soil tamping	27.18	(m^3/person/day)
	Ground floor concrete pouring	4.52	(m^3/person/day)
	Floor concrete pouring	5.41	(m^3/person/day)
	Masonry assembly	0.79	(m^3/person/day)
	Column reinforcement assembly	22.27	(m/person/day)
	Beam reinforcement assembly	20.94	(m/person/day)
	Column formwork assembly	6.25	(m^2/person/day)
	Beam formwork assembly	6.85	(m^2/person/day)
	Column concrete pouring	0.52	(m^3/person/day)
	Beam concrete pouring	0.51	(m^3/person/day)
	Column formwork removing	23.75	(m^2/person/day)
	Beam formwork removing	20.88	(m^2/person/day)
	Floor surface formwork assembly	22.73	(m^2/person/day)
	Floor beam formwork assembly	11.75	(m^2/person/day)
	Floor reinforcement assembly	39.00	(m^2/day)

Floor formwork support removing	31.85	(m^2/person/day)
Floor surface formwork removing	90.91	(m^2/person/day)
Floor beam formwork removing	27.47	(m^2/person/day)
Plastering	9.34	(m^2/person/day)

Determination of evaluation indicators

As previously discussed, project delivery in the age of COVID-19 demands fast construction speed, sparse labourer distribution, and independent resources. Meanwhile, rural construction appeals to strict limitations on the cost and equipment. Therefore, this study focuses on evaluating the construction from five aspects: 1) construction speed, 2) labourer distribution, 3) material consumption, 4) equipment utilisation, and 5) construction cost. These aspects are judged by the five indicators: construction duration, labourer density, material type and quantity, equipment type and quantity, and construction cost, respectively (as shown in Table 2).

Table 2. Indicators of construction performance evaluation

Perspective	**Indicator**	**Unit**
Construction speed	Construction duration	day
Labourer distribution	Labourer density	person/m^2
Material consumption	Material type	-
	Material quantity	m, m^2, m^3, and kg, respectively.
Equipment utilisation	Equipment type	-
	Equipment quantity	num*day
Construction cost	Construction cost	CNY or GBP

Labour density (LD) (i.e., the number of people per unit area) is the main indicator of labourer distribution because social distancing has been confirmed as an essential public restriction in many countries. LD is calculated with the following equation:

$$D_{i,j} = N_{i,j}/S_{i,j} \tag{1}$$

where $D_{i,j}$, $N_{i,j}$, and $S_{i,j}$ are the LD (person/m^2), the number of the labourers, and the area of the working place (m^2) in the working area j at the time i, respectively.

Araya (2021) claimed that limiting the number and duration of labour-intensive projects could reduce the infection risk onsite. Therefore, this paper statistically analyses the LD distribution during the entire construction process. The continuous density values are thus transformed into discrete numbers using the following equation:

$$N_i = \langle \frac{Dur_i}{\sum Dur_n} \times f \rangle \quad (2)$$

where N_i is the number of density values equal to i; Dur_i is the duration when the density value is equal to i; Dur_n refers to the duration of each single project n; f is a calculation factor to control the minimum sampling interval, which was less than 0.01 day in this study; and $\langle\ \rangle$ means to round the value in brackets to an integer.

To evaluate the labourer gathering, this study set two benchmarks for LD: 0.60 and 0.32 (person/m^2). The former refers to the requirements for the management of crowded places from the Chinese government, and the latter considers a 2m social distance (3.14m^2 per person).

Comparative analysis

The construction process is unique and non-replicable (Liu *et al.*, 2019) due to project-specific construction conditions (Biruk and Rzepecki, 2021). Therefore, it is not appropriate to directly compare actual construction processes (i.e., processes of constructing projects with the same design using different methods). To address this challenge, the current study conducts a comparative analysis on simulated construction processes, which are controllable and comparable (Song and Eldin, 2012).

$$construction\ efficiency = \frac{construction\ quantity}{labourer\ number \times construction\ duration} \quad (3)$$

Construction efficiency is calculated by dividing the construction quantity by the product of the number of labourer number and construction duration (equation (3)). Given the uniqueness of projects, it is challenging to determine the difference between alternatives with different labourer numbers and construction periods. Therefore, to create an objective comparison, this research compares A_1 and A_2 through scenario analysis. The comparison is conducted between two scenarios with the same construction period and between two scenarios with the same number of labourers.

Construction simulation

SimPy 4.0.1 was selected for construction simulation. It is a free process-based discrete-event simulation (DES) framework based on Python. In essence, SimPy is an asynchronous event dispatcher, generating and scheduling events at a given simulation time (Team SimPy, 2020). The programme shares the same simulation logic as construction simulations so that the general-purpose simulation software can be adopted (Bokor *et al.*, 2019). Although SimPy cannot extract the project data directly from design files and does not provide simulation visualisation, the programme allows for flexible process designs and parameter settings. Therefore, SimPy is especially suitable for the simulation of non-benchmarked processes, e.g., the construction process employing the AIC method.

The simulation considers construction operations as discrete events. They are sorted in the order of the construction process, as shown in Figure 5. The resource pool includes the labourer and formwork but excludes the construction materials, which are assumed to be infinite. The total amount of the formwork (resource capacity) is pre-determined in the simulation, which allows for formwork recycling. The manufacturing of formwork is deemed as an event, during which formwork is manufactured and added to the resource pool (with an initial number of 0). When the simulation begins, sorted events are processed sequentially. The event first requests resources (i.e., labour and formwork), and it will be processed if the requests are fulfilled. The event will release the resource to the pool once the process completes.

The simulation employs the parameters listed in Table 1. The outputs include information on the construction operation, schedule, location, LD, and so on. These outputs are exported to files with a suffix of '.xlsx' for further analysis. The simulation programme is pre-verified by comparing the simulated results of $A_1$with the onsite records. Although a difference exists in the total duration, the construction duration of each operation is satisfactory. The variance of the total duration stems from the fact that the concrete pouring is usually arranged at the end of the day to reduce the slack time. By curing the concrete at night (between working days), labourers could use their time for other tasks in the daytime. However, the onsite records neglected the curing duration as no labourer was working during these periods.

Establishment of scenarios

To compare the construction performance, this study established three scenarios: S_1, S_2, and S_3. S_1 is the baseline scenario. It corresponds to A_1 and is devised to represent constructing the project using the AIC method. S_1 employs the same labourers and construction equipment (number and type) as the actual construction. S_2 and S_3 are contrast scenarios. They are formulated to test the construction performance of A_2, which employs the conventional construction method. Specifically, the construction duration of S_2 is set to be the same as that of S_1, and the number of labourers of S_3 is the same as that of S_1.

As the construction process mainly differs in the foundation and structure components, this study excludes the construction procedures of stairs, roofs, doors and windows, and other facilities. All three scenarios employ a parallel construction approach, i.e., labourers conducted different projects in different regions simultaneously. The building is divided into several separate rooms, as shown in **Error! Reference source not found.**. The construction process in each room follows a standard workflow, as illustrated in Figure 5.

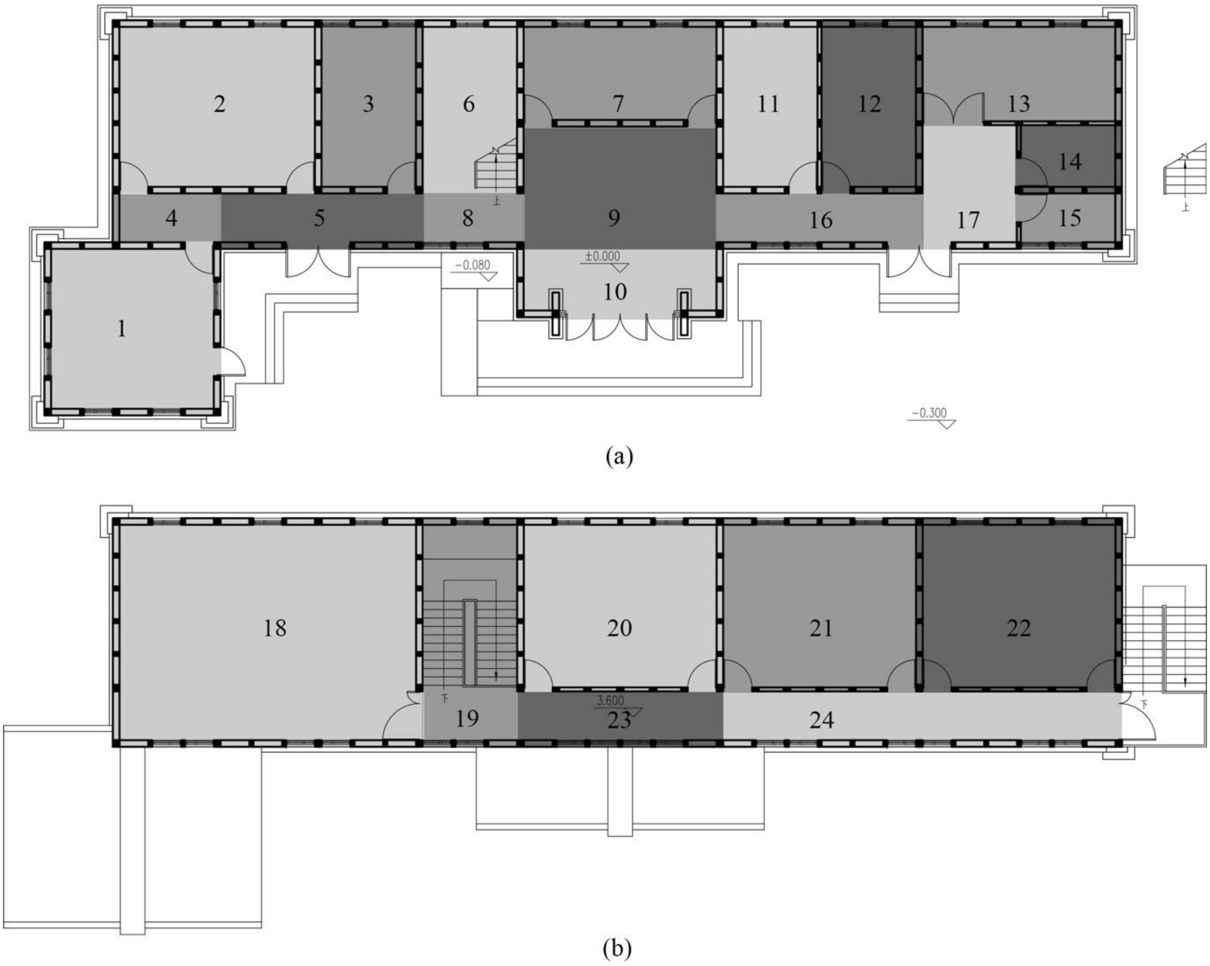

Figure 4. Room division of the ground floor (a) and the second floor (b)

Results

Comparison of construction processes

Figure 5 illustrates the construction operations and adopted products of A_1 and A_2. It highlights the significant difference by the red dash rectangles. The comparison of the foundation construction reveals that A_1 saves half the amount of earth excavation. Instead of digging down 500mm, to the depth of 800mm (relative to the ground floor), A_1 digs down 250mm, to a depth of 550m. Additionally, there is no artificial foundation in A_1, saving the time for formwork assembly, reinforcement assembly, concrete pouring, and concrete curing. Roadbed construction simultaneously finishes the earthwork backfill and soil tamping by forming the foundation using the solidified soil.

Regarding the masonry wall, differences exist in the masonry blocks and reinforcement. The larger-size masonry blocks in A_1 increase the construction speed from 0.787m^3 to 12.86m^3 per person a day. In addition, the employment of reinforcement cages requires no stirrup forming and binding, causing a 14-time efficiency growth (from 22.27m to 340m per person every day).

Adaptive construction equipment includes a tipper for foundation construction and a mobile concrete pump for column concrete pouring and plastering. The equipment provides a higher construction efficiency than manual work (e.g., the concrete pump increases the plastering speed from 9.34m^2 per person/day to 29.55m^2 per person/day).

Comparison of construction durations

The construction schedule (Figure 6) objectively compares the construction duration between A_1 (S_1) and A_2 (S_2 and S_3). The construction processes of both A_1 and A_2 are divided into eight categories: earthwork, foundation, ground floor, masonry, reinforcement, concrete, formwork, and plastering, each taking a row in the graph with a unique colour and corresponding labour amount. Table 3 illustrates the detailed classification of the construction projects.

Table 3. The classification of the construction projects

Category	Content
Earthwork	Earth levelling, excavation, backfill, and soil tamping
Foundation	Foundation reinforcement assembly, formwork assembly and removing, concrete pouring and curing
Ground floor	Ground floor concrete pouring
Masonry	Masonry assembly
Reinforcement	Structure column reinforcement assembly, mesh attachment
Concrete	Other concrete pouring
Formwork	Formwork assembly and removing of the structure column, beam, first floor
Plastering	Plastering the internal and external surface of the wall

In the baseline scenario S_1, the construction lasts 65 days (8 working hours per day). During the construction, the foundation is built in the first 10 days. After a 14-day curing, the structure on the ground floor is constructed from the 25th day to the 46th day (22 days). The construction of the first floor takes another 17 days after a 3-day cure from the 49th day to 65th day. The durations of the eight projects are 5, 4, 1, 5, 19, 18, 30, and 22 days, respectively. In contrast, the construction duration for S_3 expands to 119 days when employing the same number of labourers as in S_1. The eight projects take 16, 16, 1, 52, 28, 21, 26, and 21 days respectively, causing a 54-day longer construction duration than S_1.

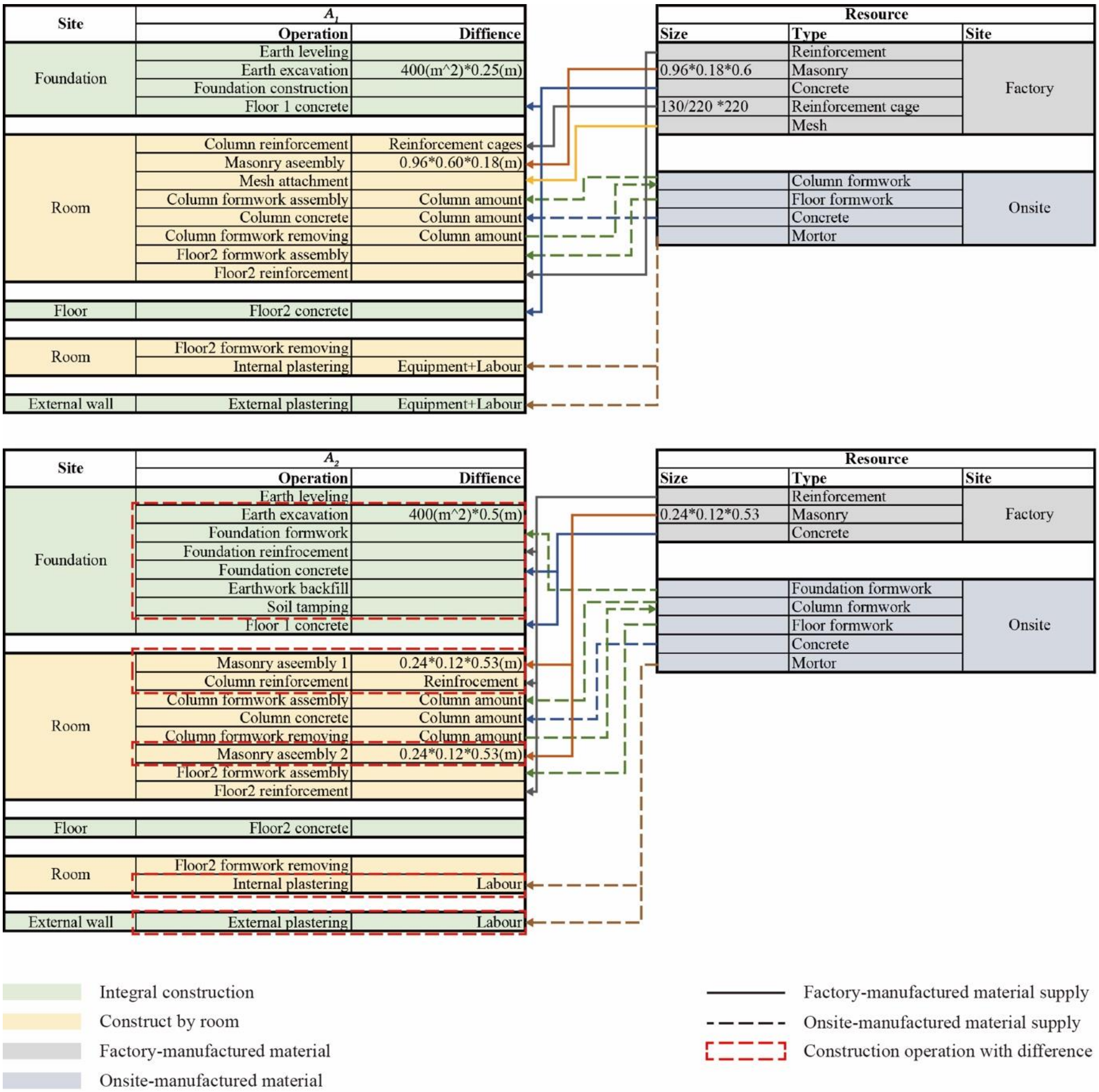

Figure 5. Flowchart of construction processes of A_1 and A_2

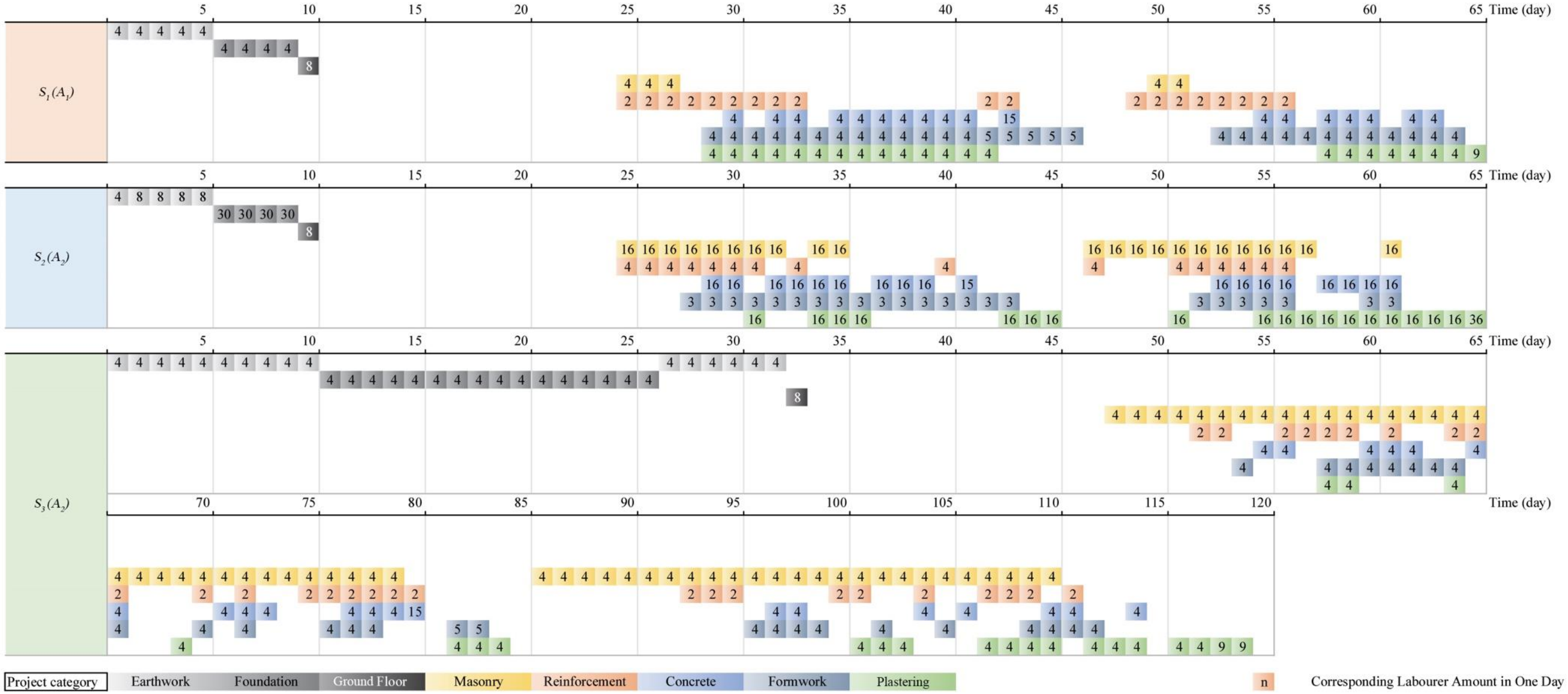

Figure 6. Gantt chart of the construction schedule.

Comparison of labourer density

As Figure 6 shows, the contractor needs to employ more labourers in S_2 to finish the project within the same period as S_1. S_2 employs twice the number of labourers (8) in the earth excavation due to a deeper foundation pit. The foundation takes 26 more labourers to complete it, approximately seven times the workforce of S_1. Adopting a smaller masonry block and excluding the mobile concrete pump in concrete pouring and mortar spraying increases the labourer number from 4 to 16 in masonry, concrete, and plastering projects. Transforming the reinforcement cages to conventional reinforcement requires another two labourers for the reinforcement assembly. However, in the formwork project, S_2 employs 25% fewer labourers (number of 1) than S_1 because of fewer structure columns (the column interval is 960mm in the A_1 and 4000mm in A_2).

Figure 7-a and Figure 7-b provide information on the variation of LD in S_1 and S_2, respectively. In general, LD stays below 0.6 and even 0.32 most of the time, which means both approaches are not labourer intensive. However, the value is high in some periods, risking the health of labourers through closer and more frequent contact.

In S_1, LD is at the lowest level in the first 24 days, during which only 4-8 labourers are working on a $400m^2$ area. After that, the values of most rooms stay between 0.1 to 0.3 during the construction of the main structure (from the 24^{th} to the 65^{th} day). There are some significant peaks between the 39^{th} and the 45^{th} day because labourers are working within the narrow space of rooms 14 and 15 (approximately $7.27m^2$). As for S_2, LD varies with a similar characteristic to S_1. There are more peaks in S_2 than in S_1 from the 30^{th} day to the 45^{th} day. These peaks are concentrated in rooms 14 and 15 due to their small area. Another peak appears on the last day of the project because 36 labourers are plastering the external walls.

Figure 7-a and Figure 7-b are superimposed (Figure 7-c) to give a direct comparison. Generally, the LD of S_1 (red area) is smaller than that of S_2 (blue area). The first distinction appears between the 5^{th} day and the 9^{th} day. 30 labourers construct the artificial foundation of S_2 during that period, while the labourer number of S_1 is only 4. On the 30^{th} day, the LD of S_2 in rooms 14 and 15 is approximately three times that in S_1 due to employing more labourers. The same reason also contributes to a higher density in S_2 than in S_1 from the 47^{th} day to the 65^{th} day (constructing the structure on the first floor).

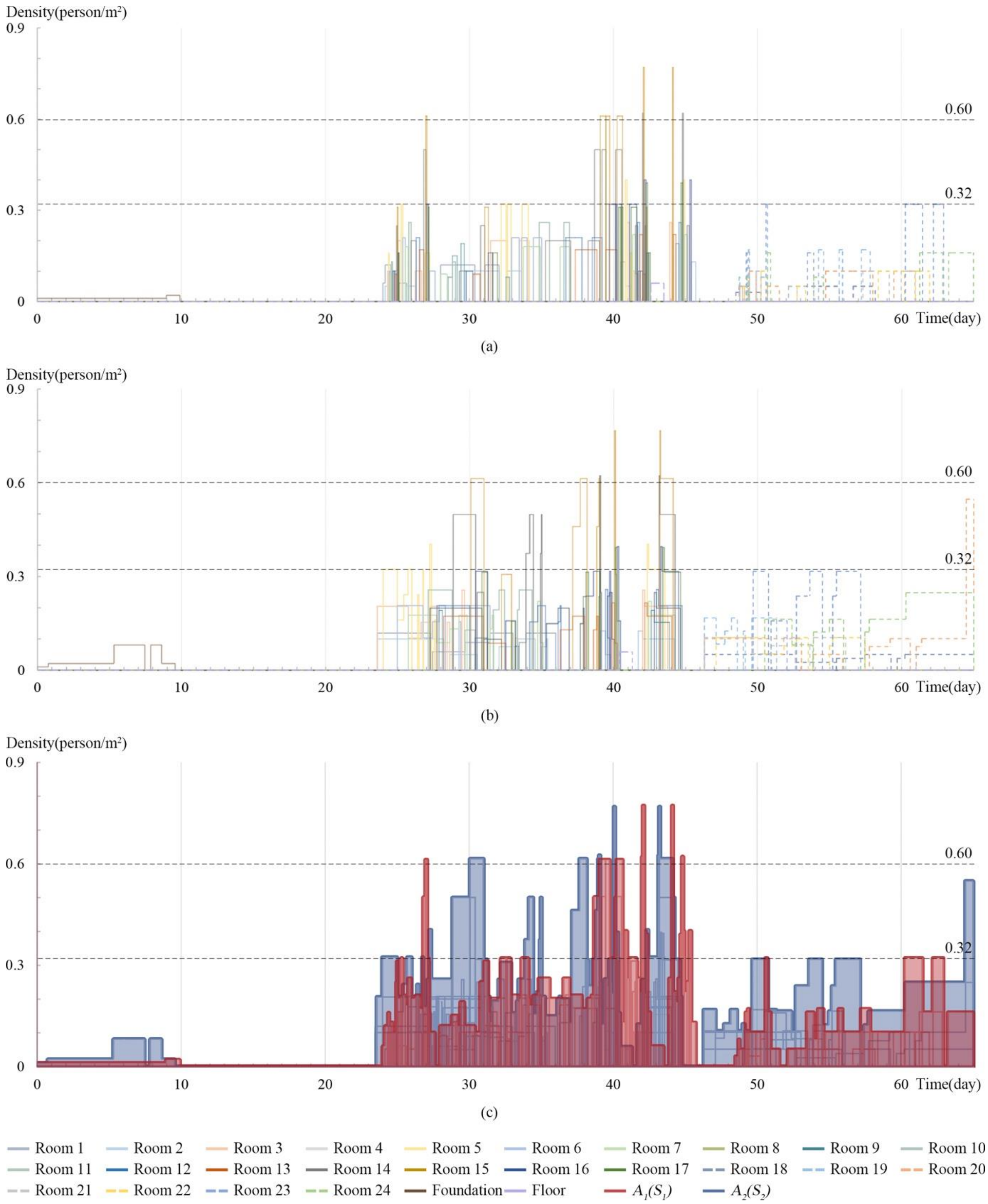

Figure 7. Variation of the $D_{i,j}$ in S_1 (a), variation of the $D_{i,j}$ in the S_2 (b), and the comparison between them (c)

Equation 2 transforms the continuous LD value into discrete numbers. This section sets f to 20,000, getting 19,969 and 20,000 numbers for S_1 and S_2, respectively. As shown in Figure 8-a, the LD of S_1 distributes wider than that of S_2. The minimum values of S_1 and S_2 are similar, but the maximum number of S_1 is greater than that of S_2. However, the mean, median, and quartile are smaller in S_1 than in S_2, which means LD distributes at a lower level in S_1. This conclusion is validated by Figure 8-b, which demonstrates the density distribution in intervals. More than half the values of S_1 are equal to or lower than 0.1. Generally, the ratio decreases with the growth of LD. The proportions equal to or smaller than 0.32 and 0.60 are 96.05% and 98.39%, respectively. These findings suggest that the AIC method controls LD at a safe level 98.39% of the time. In S_2, 45.76% of values concentrate at 0.1-0.2, followed by the intervals of 0-0.1 (29.48%) and 0.2-0.32 (19.04%). S_2 controls the value below 0.32 and 0.60 for 94.28% and 98.57% of the time, respectively.

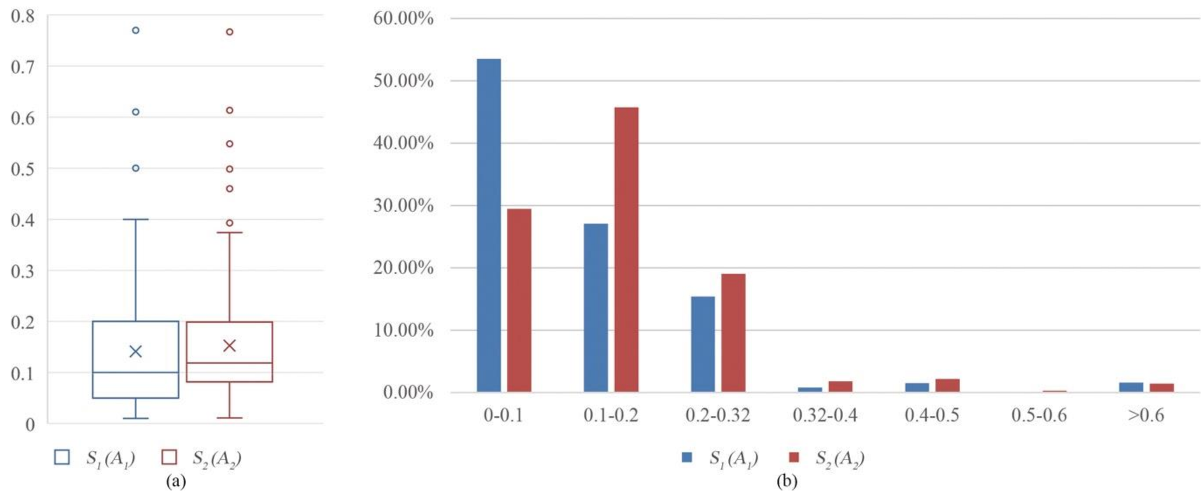

Figure 8. Distribution of the labourer density

Comparison of material consumption, equipment utilisation, and costs

Table 4 provides a comparison of A_1 and A_2. The calculation is based on the construction processes in S_1 and S_2, respectively. Generally, A_1 consumes less concrete, masonry, and mortar than A_2, but it uses more reinforcement and steel mesh. The difference in concrete consumption exists in column and foundation construction because A_1 has more structure columns and a simpler foundation structure compared to A_2, as previously mentioned. This difference causes more corresponding reinforcement consumption in A_1. Notably, A_2 uses more than two times the mortar of A_1, resulting from using the material in masonry assembly and plastering works (the AIC method only uses it to plaster the surface of the wall).

Apart from the specific utilisation of the mobile concrete pump and scarifier, the equipment utilisation is similar between A_1 and A_2 due to a similar quantity of construction. A minor increase in the value in A_2 is due to longer concrete and plastering durations than in A_1, as shown in Figure 6.

Table 4 Materials and equipment utilisation of A_1 and A_2

		$A_1(S_1)$	$A_2(S_2)$	Unit
Material				
Concrete (total)		123.22	149.44	m^3
	Column concrete	41.42	33.05	m^3
	Floor concrete	30.51	30.51	m^3
	Beam concrete	10.75	10.75	m^3
	Foundation concrete	40.54	75.13	m^3
Masonry		167.75	176	m^3
Reinforcement (total)		9259.40	8036.77	kg
	Reinforcement bar	3904.00	8036.77	kg
	Reinforcement cage	5355.40	-	kg
Mesh		2043.05	-	m^2
Mortar		40.86	91.86	m^3
Equipment				
	12t Truck crane	17	19	num*day
	Concrete mixer	25	29	num*day
	Concrete pump truck	2	2	num*day
	Mobile Concrete pump	24	-	num*day
	Scarifier	1	-	num*day

The actual construction cost of the sample building (A_1) is approximately 1,050 CNY/m^2 (117 GBP/m^2) and could be reduced to 970 CNY/m^2 (108 GBP/m^2) by employing experienced labourers. The cost of A_2 is 1,200 CNY/m^2 (135 GBP/m^2), which is 14% more than that of A_1. Importantly, the construction costs of both A_1 and A_2 are reported by the contractor rather than calculated based on the construction quota due to the lack of a benchmark data for the AIC method. Meanwhile, the standard quota does not accurately reflect the actual rural conditions. The calculation result based on the standard quota (Jiangsu department of housing and urban rural development, 2014) (1,588 CNY/m^2 or 178 GBP/m^2) is much higher than the actual cost because the standard quota mainly represents the average situation of urban construction.

Discussion

The results of the comparative analysis suggest that although the AIC method (A_1) demands more building products and equipment than the conventional method (A_2), it shows better performance in construction efficiency, safety, and costs. Employing adaptive construction methods, equipment, and industrial building products in A_1 reduces the construction duration of earthwork, foundation, masonry, reinforcement, and concrete projects by 67%, 75%, 91%, 32%, and 15%, respectively. Although contractors could deliver the project within a similar period by employing more labourers, there would be a higher risk of gathering and COVID-19 transmission.

This research employs the LD as the primary indicator to evaluate labourer safety. As shown in Figure 7, both S_1 and S_2 have high LD values (greater than 0.6) but within a reasonable duration. These results mean that both methods can meet the demand of preventing labourer gathering most of the time. However, there are still more peaks (when the line is above 0.32) in S_2 than in S_1. Figure 8 further confirms that the LD of S_2 distributes more in the range above 0.32 than S_1. This difference indicates that applying the AIC method can keep a 2m social distancing for a longer period than employing the conventional method. Additionally, Figure 8 shows that the LD of S_1 distributes in a lower range than that of S_2, implying that labour management is more flexible in the AIC method than in the conventional method. For example, managers can accelerate construction speed (through increasing labourer numbers) to a higher level in urgent situations by employing the AIC method. The distribution of LD also suggests that the project can be completed in a shorter period using the AIC method if the labourer number is increased to the upper limit (considering pandemic prevention).

As for the material utilisation, the AIC method consumes less concrete and mortar than the conventional one due to the reduction in the foundation and masonry assembly. However, the material analysis reveals that the AIC method shows significant disadvantages of using more reinforcement and steel meshes. This finding is consistent with the result of Hong *et al.* (2016), who found that prefabrication requires additional structural/material strength during the construction and transportation to avoid potential damage. Although a greater reinforcement content in A_1 may lead to better structure performance than A_2, the reinforcement content could impede the promotion of this AIC method due to a higher material cost.

There is no significant difference in the equipment utilisation between A_1 and A_2 due to similar construction quantity. The employment of mobile concrete pumps and scarifiers may not inhibit the application of the AIC method because the equipment is commonly available in rural areas (**Error! Reference source not found.**-b).

Despite using more material and equipment, the final cost of A_1 is approximately 12.5% less than that of A_2. Apart from less construction quantity for the foundation, a fewer manual construction quantity contributes the most to the result. Labour cost is a significant expenditure in the Chinese construction industry (Liu and Diao, 2014). The average salary of construction migrant workers increased 34% to 4,699 CNY/month (528 GBP/month) from 2015 to 2020 in China (Chinese National Bureau of Statistics, 2016, 2021). Therefore, achieving a balance between industrialised technology and labour is significant for cost-efficiency (Wang *et al.*, 2020). Compared with the cost of the steel structure (1,500-1,800 CNY/m^2 in 2018) (Zhang, 2018) and other adaptive construction methods (625-830 CNY/m^2 in 2008-2012) (YUAN *et al.*, 2019), this AIC method (with the cost of 970-1,050 CNY/m^2) is applicable in Chinese rural areas.

The findings implicate the significance of AIC application in the rapid delivery of rural projects during COVID-19. The construction of the sample building lasted for 65 days. The simulated scenarios indicated that the duration could be shortened to approximately 45 days when adopting a single-floor structure, and less than 30 days with a shorter curing time. This is not as fast as the pure industrialised construction method (12 days to build the Leishenshan Hospital), but it could be a more practical and efficient solution for rapid construction in rural areas. The method is not dependent on developed technologies, equipment, and material supply, and thus it can be extended to regular project delivery and help to advance the local construction industry.

Considering the high infection rates and spread of COVID-19 in developing countries and its continuous impact, the analysis framework can be used as a reference for construction method evaluation. The framework measures the key aspects of performance in candidate methods (when applied in current rural project delivery) and represents those aspects with five quantitative indicators. Therefore, architects and contractors can conduct an objective comparison among methods, which could help determine the most suitable solution. Meanwhile, the LD monitoring method could be employed in the construction plan. The integration of DES and LD calculation allows for a continuous prediction of the labourer distribution. It reveals the period and area with high infection risk (high LD value) and the construction operations leading to that risk. Accordingly, construction managers can make effective decisions to prevent the pandemic transmission, e.g., by staggering the construction times or locations of conflicting projects.

This study has some limitations. First, the number of construction methods evaluated in this paper is limited to one AIC method and one conventional construction method. Evaluating more methods could provide a more comprehensive view in future studies. Second, the construction simulation is not entirely accurate. Construction efficiencies of non-benchmarked operations must be verified in more cases to provide more accurate data. Additionally, labourers' movements among construction areas (rooms) were not considered, which would add additional (wasted) time related to workers gathering in groups and moving between rooms. Future research should consider these aspects for a more practical simulation.

Conclusions

The COVID-19 pandemic has increased the demand for rapid project delivery in Chinese rural areas. Considering the constraints from rural conditions and pandemic prevention, the AIC method provides a potential solution to fill this demand. The comparative analysis between AIC and conventional construction methods illustrates the advantages of AIC: higher construction speed, more scattered, and hence safer, labourer distribution, and lower costs. Thus, it is more efficient and safer to deliver rural projects using the AIC method than the conventional method during the pandemic.

This research contributes to the development of more practical construction solutions that have less dependence on technology and equipment. Although the focus is on China, the research is applicable to other developing countries and rural regions. Additionally, this study contributes to the knowledge of rural construction and safer working in a pandemic. These indicators could be useful for influencing the development and implementation of construction technologies for rural regions. For example, architects and contractors could employ the evaluation method to explore other construction methods for rural areas and better optimise the construction schedule in relation to the resources available locally. The evaluation method may be particularly useful during a pandemic or local outbreak of infection diseases, helping contractors to reduce the risk of transmission within the workforce. Future studies are expected to produce additional practical analysis and methods for a more comprehensive view of AIC methods.

Geolocation information

This research conducted the case study in Peixian, Xuzhou City, Jiangsu Province, China.

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Credit authorship contribution statement

Yiming Xiang: Conceptualization, Methodology, Investigation, Programming, Validation, Data Collection, Writing - original draft. **Jiachen Bu:** Methodology, Investigation, Validation, Data Collection, Writing - original draft. **Ke Zhu:** Data Processing, Writing - original draft. **Kehan Ma:** Writing - original draft. **Alex Opoku:** Supervision, Writing - review & editing. **Laura Florez Perez:** Supervision, Writing - review & editing. **Hong Zhang:** Supervision, Funding acquisition. **Yanhua Wu:** Engineering design.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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