



Study on the Construction Workforce Management Based on Lean Construction in the Context of COVID-19

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Abstract

Purpose – The construction industry is facing challenges not only for workers’ mobility during the pandemic situation but also for Lean Construction (LC) practise in responding to the high-quality development during the post-pandemic. As such, this paper presents a construction workforce management framework based on LC to manage both the emergency goal in migrant worker management and the long-term goal of labour productivity improvement in China.

Design/methodology/approach –The framework is created based on the integrated culture and technology strategies of LC. A combination of qualitative and quantitative methods is used to explore factors influencing the mobility of construction workers and to measure labour productivity improvement. The case study approach was adopted to demonstrate the framework application.

Findings – For method application, a time-and-motion study and Percent Plan Complete (PPC) indicator are proposed to offer labour productivity measurements of "resources efficiency" and "flow efficiency". Moreover, the case study provides an industry-level solution for construction workforce management and LC culture shaping, as well as witnesses the LC culture and technology strategies alignment, contribute to LC practise innovation.

Originality/value – Compared with previous studies, which emphasised solely LC techniques rather than socio-technical system thinking, the proposed integration framework and the implementation of "Worker’s Home" and "Lean Work Package" management models in the COVID-19 pandemic contribute to new extensions of both the fundamental of knowledge and practise in LC.

Keywords Lean construction, Workforce management, COVID-19

Paper type Research paper

1 Introduction

The sudden COVID-19 pandemic has brought great impact and influence on global social, economic, and environmental domains, as the construction workers come from all over the country with large mobility, the resumption of the construction industry faces great challenges. The government has issued the Measures for the Administration of the Identification System for Construction Workers (for trial implementation), which has officially come into effect in March 2019. This means that more than 50 million construction workers in more than 80,000 construction companies will be covered under the management of the identification system, which will effectively improve the efficiency of epidemic control. However, construction workers’ mobility problem is not fundamentally solved, and problems such as how to reduce ineffective worker gathering in the construction area, and how to improve labour productivity under the construction progress pressure still lack discussion.

Abundant literature has demonstrated successfully Lean Construction (LC) practise with performance improvements in the Architecture, Engineering, & Construction (AEC) industry globally. However, extensive management methods implemented in the construction industry that characterise the rapid expansion at the expense of poor productivity and low profit have restricted

the practise and promotion of LC in China.

At present, China's economy has shifted from a high-speed growth stage to that of high-quality development, LC practises can provide sustainable solutions (Salem et al., 2014) for the high-quality development of the construction industry. However, construction labour workers composed of much low education level and relocated migrant workers have the greatest impact on construction quality and safety issues as well as low labour productivity to construction products and processes. The outbreak of COVID-19 makes these problems even more exposed, providing rethinking for the development model transformation of the industry. There are still knowledge gaps in construction labour workers' management and LC practise in China.

Therefore, this research addresses two research questions:

Firstly, how to minimise the mobility of construction workers under a pandemic situation to meet the restrictions of strict health, prevention, and control with the COVID-19?

Secondly, how can LC implementation strategies be utilised to reduce ineffective worker gathering and improve the construction labour productivity of the industry in the post-pandemic stage?

These two research questions derive both the emergency and long-term goals of construction workforce management in this research. A case study is conducted to show how the two goals are combined into a construction workforce management framework in the context of the pandemic. It explores construction workforce management practise based on the integration of "Worker's Home" and "Lean Work Package" management models. Among them, the "Worker's Home" can not only meet the demands of prevention and control of the COVID-19 pandemic but also provide an innovative solution for managing the migrant workers in the construction industry by providing workers with steady residence, humanised facilities, and services, creating a hygienic and safe living and onsite environment. Workers are intrinsically motivated by the "Worker's Home" guided by LC's culture strategy to increase labour productivity. Additionally, a conceptual and measurement distinction must be made between "resource efficiency" and "flow efficiency". The "Lean Work Package" management model is developed by identifying the "making-do" waste and conducting Work Structuring (WS) system design, supplemented by the Last Planner® System (LPS), Just-in-time (JIT) and other LC techniques to "maximise value and minimise waste" and to improve productivity.

China contains the largest construction market in the world (Ghisellini et al., 2018; Wu et al., 2017). However, the development and practical application of LC theory are lagging (Shuquan Li et al., 2020). Accordingly, more case studies and good practices should be explored and introduced to enable industry key players to accept the lean idea and implement it effectively. The pandemic circumstances provide opportunities and innovative ideas for LC implementation and promotion in China. The theoretical value of this research is to build a framework from the socio-technical paradigm of LC for construction worker management, and the practical significance is to provide operational strategies, models, and tools to implement LC in construction workers' mobility management and labour productivity improvements.

2 Literature review

2.1 The culture and technical views of Lean Construction

Lean Construction, which was advocated as a "new production philosophy" and its application to the construction industry (Koskela, 1992) has been widely studied and applied throughout the world.

Egan (1998), in his Rethinking Construction report, provided a catalyst for the industry to improve productivity through lean implementation. At the early stage, lean tools, and methods such as 5S's methodology, Just in Time (JIT), Value Stream Mapping (VSM), and Visualisation have been introduced by scholars from manufacturing to construction to achieve higher productivity. Afterwards, Koskela (2000) explored lean theory through the integration of Transformation, Flow and Value (TFV), Lean Last Planner® and other strategic tools developed specifically for construction practises (Ballard & Howell, 1995; Ballard & Howell, 1999, 2000). Work Structuring (WS) has also been proposed to serve as an integrated product-process design framework, being a supplement to the traditional Work Breakdown Structure (WBS) tool (Howell and Ballard 1999, 2000; Ballard, Koskela, and Howell, 2001). Takt planning is a method for work structuring, through which Takt time is designed to allow field managers to structure on-site flows related to labour, equipment, workspace, and precedence flow types (Frandsen et al. 2013; Frandsen and Tommelein 2014; Tommelein 2017).

Furthermore, a cultural response within organisations aligned to lean innovation has been discussed (Green and May, 2005; Davey et al.'s, 2000). Green (1998) noted that an associated cultural change should go ahead with every improvement initiative directed at the construction sector and lean implementation. The cultural change to unleash the power of the workforce is argued to be a requirement of successful lean practise (Ted Angelo 2010; Jorge Izquierdo 2010; Keiser J.A. 2012). Therefore, in the pursuit of lean implementation awareness, two paths were followed either a suite of tools to improve strategic operations (Koskela, 1992; Ballard & Howell, 1998; Howell & Ballard, 2000; Tommelein, 2003; Hasle et al. 2012) or a strategic tool to control culture (Garrahan & Stewart 1992, Williams et al., 1992; Green, 1998; Green and May 2003, 2005).

Nevertheless, a 'socio-technical paradigm' of LC has become increasingly widely accepted and has been proposed to develop lean frameworks by considering both the cultural and technical views (Green and May, 2005; Christine Pasquire, 2013, 2018).

2.2 Productivity and its improvement in construction

Productivity in the construction industry has long been a focus for governments, industry, and academia, early in the 1990s, many productivity reports (Gyles, 1992; Latham, 1994; Egan, 1998; Bourne, 2000) were initiated by the government, and strategies such as procurement, Building Information Modelling (BIM) and supply chain management were advocated to drive productivity improvement. Some factors influencing construction productivity have also been investigated by many researchers to forecast and improve productivity (Thomas et al., 1991; Lim et al., 1995; Lema, 1995; Choy and Ruwanpura 2006; Hasan et al. 2018; Huang et al. 2009; Dolage and Chan 2013). However, over the past 20 years, construction productivity has lagged behind other industries (McKinsey consultants, 2017). According to the McGraw Hill Smart Market report, the decrease in construction productivity within the last 40 years has mainly been caused by the lack of communication and collaboration through information sharing (Young et al. 2007), and their reports showed that companies experienced a positive return from using BIM. Besides technological factors, being a labour-intensive industry, other factors such as administrative factors, labour characteristic factors, project work conditions factors and non-productive activities are also identified.

As productivity is a complex concept that could be interpreted in various contexts, Davis (2007) provides a three-level productivity measuring framework in which on-site productivity, firm productivity and industry productivity are distinguished. Furthermore, the construction labour productivity (CLP) framework is developed (Wen Yi et al., 2013, Li, Y et al., 2019), with project and

activity levels being recognised as a more sensitive subdivision. Sufficient evidence suggests that on-site productivity measurements should be the basis for making productivity improvement decisions (Oglesby et al., 1989, McCullouch, 2007, Carlos and Paul, 2010). Moreover, a system approach and lean construction as the best-known intervention methodology for construction sector productivity are argued by Koskela (2000) and Kenley, R. (2014).

2.3 Productivity improvement in Lean Construction

In lean thinking, variability in the flow of work increases the amount of waste and impedes system performance, as a consequence, it is possible to eliminate waste and reduce losses in connection with the management of flows (Koskela, 1992; Rafael Sacks, 2016). Based on a list of seven wastes presented by Ohno (Ohno 1988) in the Toyota Production System (TPS), "making-do", which refers to starting a task before all prerequisites is ready, was proposed as the eight categories of waste and even the "core and lead waste" in construction (Koskela 2004).

Regarding the central to all LC research is the application of lean principles to eliminate waste and improve productivity (Koskela & Vrijhoef, 1999; Koskela, 2001), Hines et al. (2004) further suggested encompassing not only a strategic level of understanding but also the operational tools used to eliminate waste. Therefore, LPS was developed to shield downstream operations from upstream variability (Ballard and Howell 1994), and the Last Planner tool is advised to be compared to and complemented by, to a certain degree, measuring productivity (Choy and Ruwanpura 2006; Pérez et al. 2019). Furthermore, some researchers proposed that project performance improvement should be redirected to adaptable workforce management capabilities to reduce variability in labour productivity (H. Randolph Thomas et al., 2002).

As the construction industry has been affected by the COVID-19 pandemic in many ways, such as significant delays in projects, and reduction in productivity rates, many research efforts have been conducted to unveil adopted specific efforts to manage the challenge of the COVID-19 pandemic in construction workplaces (Alsharef, A. et al. 2021). Workforce-related issues and project and workplace considerations are identified to be the main research aspects and guidelines are offered for responding to the COVID-19 pandemic in the construction sector (Assaad, R. et al. 2021).

Therefore, this paper is trying to add to the body of knowledge by taking LC strategies as a solution for the COVID-19 impacts. LC implementation is eager to follow a path of combining culture and technology strategies to bridge the gap between theory and practise, as well as detailed operational strategies and tools should be developed to guide industry participants' practise. Furthermore, the intensive, mobility and low-educational workforce characteristics of the industry should never be ignored, especially during post-pandemic.

3 Methodology

3.1 Research design

The whole research framework comprises three parts and is illustrated in Figure 1. Firstly, research goals present the combination of the emergency goals of pandemic prevention needs with the long-term goals of construction workers' professional cultivation and labour productivity improvement. Secondly, to develop a construction workforce management framework from mobility management, and labour skill development to productivity improvement based on the integration of LC culture and technology strategies. The lean culture strategy consists of essential principles that are people-centred, human development, and human motivation, while the lean technology strategy provides a series of tools and methods for adoption, such as WS system design, flow management and LPS

technique. Thirdly, a case study approach is employed to demonstrate the innovative practise in the context of the pandemic, exploring the integration of a "Worker's Home" management model and the "Lean Work Package" management model to realise the research goals.

According to Yin (2009), cases are usually selected because they are unusually revelatory, represent extreme exemplars, or provide opportunities for unusual research access, and the single case study design allows for a rich description of the phenomenon (Siggelkow, 2007). As previous LC research in China was more on the theoretical level than the practical level, and several barriers need to be overcome when implementing LC in the Chinese construction industry (Li et al., 2017), the single case study method is appropriate not only for practise exploring and innovation but also can provide theoretical implications and operational guidance.

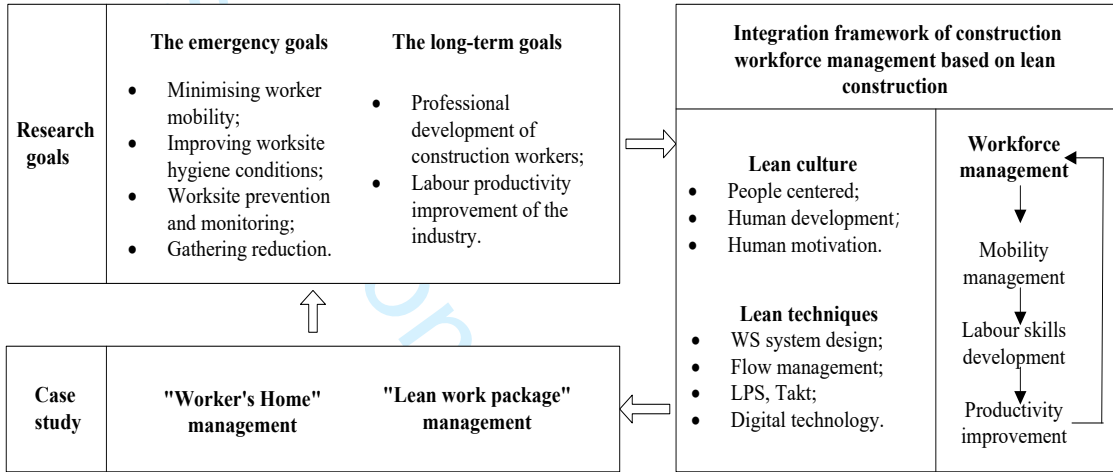


Figure 1. The research framework

Furthermore, the creation of the framework from the socio-technical paradigm of LC is interpreted in detail, see Figure 2. Influencing factors of construction workforce management are identified, and then, the relationship between influencing factors and the management objectives is established.

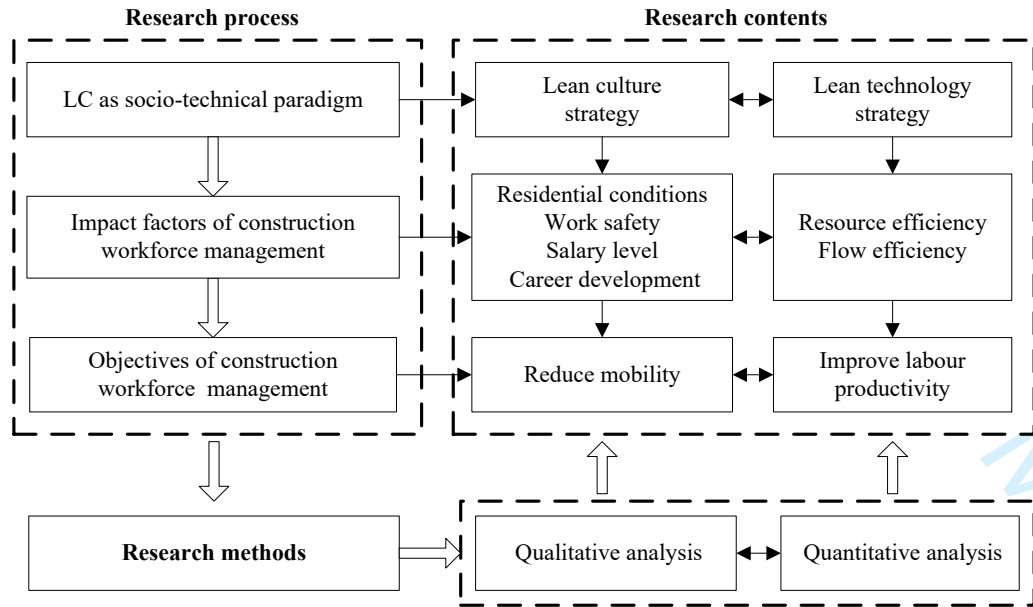


Figure 2. Outline of the integration construction workforce management framework

Correspondingly, the research takes the combination of a qualitative and quantitative method, in which, qualitative analysis is designed to explore and verify factors influencing the mobility of construction workers; while quantitative analysis is used for analysis, measurement and improvement of labour productivity. Factors affecting the management of construction workers not only contribute to reducing mobility but also play a role in improving "resource efficiency" and "flow efficiency", which contribute to the long-term goal of labour productivity improvements.

3.2 Qualitative analysis: reducing mobility

Construction projects have the one-off, inflexibility and temporary characteristics traditionally, and with the low threshold and low-cost development mode of the construction industry, the migrant workers' problem is severe in China (WANG Xin-Cheng et al., 2020). The outbreak of COVID-19 has put forward new requirements for the migrant workers' management of construction. While reducing the workers' mobility and strengthening prevention and control in responding to the emergency needs of the pandemic, it triggers our deep thinking on the living state of construction workers.

According to Maslow's hierarchy of needs (1943), physiology, safety & security, are the most basic needs of human beings. While in construction sites, even the basic needs of workers' accommodation and safety still cannot be met. Therefore, the site environment should be improved so that workers can have a home to live in and a safe working environment to improve health and well-being satisfaction. However, Herzberg (1959) argued that individuals are not satisfied with meeting the lower order needs at work; rather, they look for the gratification of higher-level psychological needs having to do with achievement, recognition, responsibility, advancement, and the work itself. Administrators are suggested to recognise and attend to both sets of characteristics to improve workers' job attitudes and productivity. Therefore, the long-term solution of the construction workers' mobility can be enlightened to be linked with the career development of workers, which is also a key reform direction for the high-quality development of the construction industry in China.

3.3 Quantitative analysis: productivity measurement and improvement

This research will focus on on-site productivity improvement in response to the workforce management topic. As quantifying labour productivity is an important step in managing labour productivity, following the general definition, the hourly output is designed simple enough to measure productivity (Yi and Chan, 2014, Kisi et al., 2017). The exploration research of Kisi et al. (2017) identified system and operational inefficiencies to estimate optimal labour productivity. Modig and Åhlström (2015) proposed "flow efficiency" to reflect the relationship between time spent creating value and the total time taken, and "resource efficiency" to focus on maximising the utilisation of machines and individual workers.

Therefore, "flow efficiency" and "resource efficiency" are adopted in this paper to distinguish two different labour productivity origins. Furthermore, the optimal labour productivity perspective (Kisi et al. 2017, 2018) and flow management of LC are integrated to identify the inefficiency being combined with "making-do" waste. A time-and-motion study and PPC indicator are employed to measure "resource efficiency" and "flow efficiency".

To validate the theoretical framework, a case study approach was conducted to contribute to new and valuable insights.

4 Data collection

Data acquisition includes four parts: firstly, the data of workers' daily management are obtained from the smart construction site system, which manages people, materials, machines, and whole affairs of project management on the construction site, and an intelligent management system with computer-based cloud technology is utilised to manage workers' daily living lives. Secondly, CL Construction Technology Co. Ltd., a consultant who participated in the project, is responsible for time-action research data provision. Thirdly, PPC data are collected from the on-site project statistics. Finally, widely sources of evidence on the LC implementation effect are attentively caught up in project meetings, site visits, interviews, site conversations and other forms of communication.

4.1 Worker's daily management

Workers' daily management system should not only meet the special demand for the pandemic prevention and control stages but also be the trend of construction workers' management in the post-pandemic era. Through the identification labour service system (face recognition system) and the real-time management system, it can realise real-time tracking of workers' living, working and other tracks to achieve efficient management. The employment standardisation and mobility problems have been improved greatly.

4.2 Time-and-motion studies

The discussion presented in this paper has specified labour productivity as being composed of two parts, one is as "resource efficiency", mainly affected by construction conditions, working methods, worker's proficiency and so on, and the other is as "flow efficiency", which results from good flow management, excellent planning, controlling, and implementation capability.

The "resource efficiency" is measured by a time-and-motion study that determines the required time to perform a specific task by a skilled, well-trained operator working at a normal pace (Taylor,1911). Time records will be developed for the various tasks of a process. Due to the complexity of construction, the case project is broken into activities, tasks, and actions through an appropriate and detailed WBS. Time-and-motion study is conducted at the work tasks and action level, with all conditions such as materials, equipment, workers, and weather are available, the research team of the consultant company has videoed most of the operational tasks repeatedly on the worksite to quantify the time each worker spent on each contributory action. The time of each action completed by every single-trade worker was then recorded in a spreadsheet and analysed. To facilitate the labour resource allocation, the measurement time is converted into the output of unit time, i.e., output quotas.

4.3 PPC Indicators

At the activity level, labour productivity is affected mostly by "flow efficiency", e.g., labour productivity loss resulting from interruption or stop in the production process is common. Koskela (1992) argued that one of the primary reasons for the reduction in productivity in construction projects is due to the presence of "waste". Previous studies have analysed and confirmed the causal link between workflow variability reductions and project performance improvements (Howell, Ballard et al.2004; Choy and Ruwanpura 2006; Pérez et al. 2019). Especially, production control depending on LPS is to support the elimination of "making-do", and the PPC measurements to show changes in planning reliability.

Based on the seven prerequisites for a sound process identified by Koskela (2000), the consultant company has developed a model of "Lean Work Package" management to support LPS implementation and PPC is worked as a "flow efficiency" indicator to offer improvement and comparative analysis.

4.4 Evidence of implementation effects

The case project was explored as a demonstration project in the local province. Verification and evaluation of LC benefits such as timetable acceleration, cost savings, workers', administrators', and subcontractors' satisfaction-increasing are tracked by the research group. During the period of project implementation, many seminars and site visits were held to acknowledge the progress and discuss all kinds of problems with lean implementation. In the middle stage, the pandemic being relatively stable, an observation meeting was organised and open to 13 cities in the province to provide experience exchange and discussion for the construction industry counterparts.

5 Case study

5.1 Project description

5.1.1 project overview

The case project is a multi-function project supported by the local government in Changzhou, Jiangsu Province, China. The total construction area of the project is 605200 m² with a budget of approximately 390 million USD (RMB 2.71 billion yuan). It includes resettlement housing (divided between North and South areas), schools, roads, green landscape and other supporting projects, the planned construction period is three years from the start of construction in November 2019 and finishes in November 2022.

The Public-Private Partnership (PPP) model is adopted for construction and operation, and a private construction group company undertakes the project as the general contractor. Being a grown and innovative enterprise, the general contractor decided to embed lean ideas and advanced digital information technology to improve the project performance under the pandemic circumstance, meanwhile and to enhance the enterprise's competitiveness in the post-pandemic era. Being the pioneer of LC in China, CL construction technology Co. Ltd. was invited to take part in this project as a consultant. The general contractor and the consultant cooperatively design the LC implementing strategies and execution plans. The main points are as follows:

(1) Considering the special pandemic circumstances and the post-pandemic sustainable development needs, the pilot LC implementation focuses on the safety and pandemic prevention demands for migrant workers and long-term standardising workforce management, career development and labour productivity improvement of lean implementation.

(2) The LC cultural model and "Lean Work Package" management model, which are developed by the consulting company, will be applied to the project to further test the effectiveness and offer improvements. Moreover, the LC cultural model coincides with the "Worker's Home" management model proposed innovatively by the general contractor. The challenge is to integrate the LC practises from both culture and technology strategies into a framework and serve for construction workforce management.

(3) Only the No.3 residential building in the South area is selected as the pilot considering the large scale of the whole project and the general contractor's first journey to explore LC. The building is a frame shear wall structured housing comprising 18-story above ground and one below ground, with a total area of 14758.63 m². The subcontractors, material suppliers, equipment suppliers, workers, and managers who serve in the pilot project should accept relevant LC training and be responsible for LC techniques implementation. The rest of the other 25 residential buildings served as a comparison group for performance evaluation.

5.1.2 "Worker's Home" management

The "Worker's Home" management model is suggested by the general contractor to try a reformed

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and advanced management style for construction workers. The four main parts of the model are closely connected with the lean culture strategy to aim at realising the emergency and long-term workforce management goals, see Figure 3.



Figure 3. "Worker's Home" management model, lean culture strategy and workforce management goals

There have built 18 2 story container type housings with 675 units (including 135 units of 270 family rooms), each dormitory is equipped with cooling and heating air conditioning units and can accommodate 2,160 people together. The "Worker's Home" also offers a canteen for 2000 people, a police station office, a mediation room, convenient stores, a clinic, hot water rooms, buffet kitchens, 24-hour hot water bathrooms and toilets, laundries, barber rooms, virtual reality (VR) safety training classroom, publicity columns, basketball and badminton courts, table tennis and pool rooms, fitness centres, as well as express Wi-Fi "cloud cabinet", clothes drying shed and battery car centralised charging facilities.

The idea of "Worker's Home" is fully fitted with the LC cultural model that focuses on people-centered, human development, and human motivation. An affordable, well-equipped living environment enhances workers' dignity and sense of belonging and offers the possibility of phased resettlement. The real-time management technology brings great convenience for tracking and data collection during a pandemic. In addition to online school learning, labour skill competitions are regularly organised to promote workers' professional skills.

Therefore, workers are not only getting incentives in living conditions, a safe workplace, salary increase and other material aspects but also in vocational skills improvement, participation in management and decision-making. The delivery of healthy, energetic, and skilled workers to a construction site provides the basis for "Lean work package" management and labour productivity improvements both in "resources efficiency" and "flow efficiency".

5.1.3"Lean Work Package" management

Instead of solely adopting LC techniques, "Lean Work Package" management is a comprehensive management model incorporating multiple lean techniques developed by the consulting company after ten years of practise. Compared with the traditional work package, the lean work package is based on moderately deepening WBS, employs WS system design, with the pursuit of value maximisation, waste minimising and on-time delivery objectives, contains more accurate requirements and richer information, and thus can offer high-quality task assignments and ensure efficient implementation, management, and delivery of work packages.

"Lean Work Package" management model mainly consists of lean work package components and

on-site flow lines. There are three categories of elements in the lean work package: Task descriptions, standards, and assessments, see Table I.

Table I. Components of the Lean Work Package

Task descriptions	Standards	Assessments
1. Work code	1. Performance standard	1. PPC
2. Work content, quantity, duration	2. Labour productivity standard	2. On-time start-up rate
3. Work start time	3. Material consumption standards	3. On-time completion rate
4. Work finish time	4. Quality standard	4. Labour productivity
5. Process logic	5. Safety standard	5. Material consumption rate
6. Labours	6. Management standard	6. Material wastage rate
7. Materials	7. Cost estimation standard	7. Rework rate
8. Equipment		8. Cost-savings rate
9. Location		
10. Package owner		

Flow management is conducted based on the seven prerequisites for a sound process identified by Koskela (2000), through which “making-do” waste is identified and eliminated. For example, construction drawings are refined and optimised by a cross-functional group to address conflicts and contradictions among different disciplines and are visualised easily and detailed enough to be understood by operational workers. JIT technology is utilised to guarantee that materials are transported to and tidily piled at the right site at the specified time and in the specified amount. Professional workers can begin their work on time with materials prepared by the handyman. The weather forecast is also embedded in scheduling to guarantee flexible task adjustment. Takt time is designed to coordinate different trades and balance different flows to synchronise activity demands with their availability to reach an on-site flow line, see Figure 4.

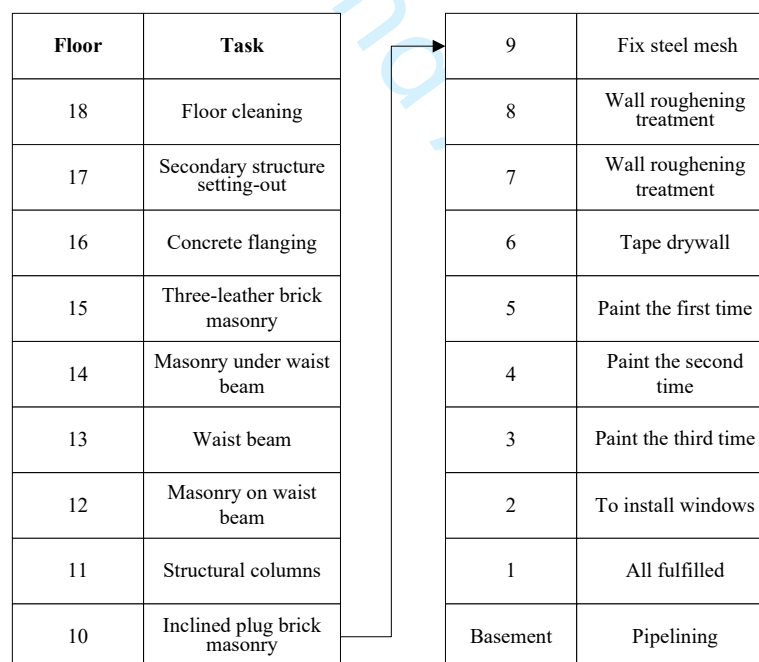


Figure 4. An on-site flow line

As poorly planned work assignments are a major cause of workflow variability and labour productivity loss in construction, "Lean Work Package" is designed and companies with the Last Planning technique to improve the reliability of task formation, assignment, and completion. Precise task assignments and workforce arrangement offer a minimum number of workers entering the construction site to reduce ineffective worker gathering to meet the prevention demands of the

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COVID-19 pandemic, the separation of preparation work from professional tasks can help promote labour skills and improve productivity. The relationship is illustrated in Figure 5.

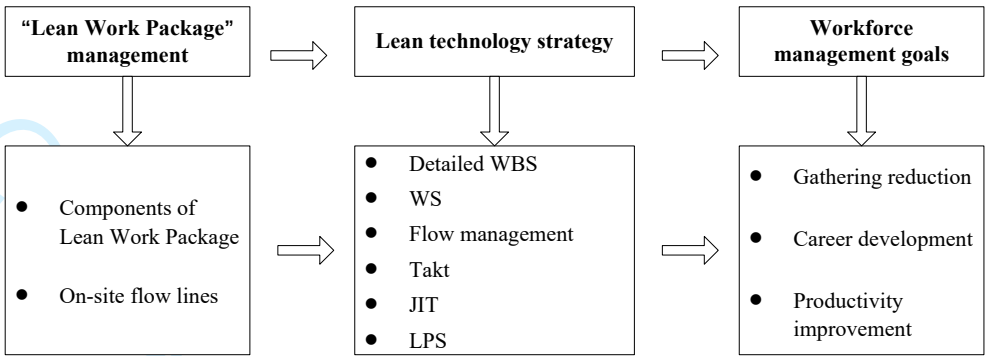


Figure 5. "Lean Work Package" management model, lean technology strategy and workforce management goals

5.1.4 Labour productivity assessment

Labour productivity assessment is a central aspect of construction workforce management and guides further productivity improvements. Since there exist different levels and implications of productivity and multi-kinds of measurement methods, it is necessary to clearly illustrate the concepts and methods adopted or expanded in this paper in Table II.

Table II. Overview of labour productivity assessments

Productivity level	Productivity origins	Measurement methods	Indicators and Equations	Reference and Extensions
Activity	Flow efficiency	Formula deduction	$T_{adu} = \sum_{i=1}^n T_{tsi} - \sum_{j=1}^m T_{tpj} + T_{tin}$ <p>T_{adu}: Activity duration times; T_{tsi}: Duration time of sequential task i; T_{tpj}: Duration time of parallel task j; T_{tin}: Interval time between sequential tasks; n: Total tasks of one activity; m: Group numbers for parallel tasks.</p>	After Krishna P. Kisi et al. (2017)
		Statistic	PPC	Howell, Ballard et al. (2004).
Task	Flow efficiency	Formula deduction	$T_{tdu} = \sum_{k=1}^l T_{task} - T_{apq}$ <p>T_{tdu}: Task duration times; T_{task}: Duration time of sequential action k; T_{apq}: Duration time of parallel action q; l: Total actions of one task.</p>	After Krishna P. Kisi et al. (2017)
		Statistic	PPC	Howell, Ballard et al. (2004).
Action	Resource efficiency	Time-and-motion research	Hourly outputs Construction labour productivity (CLP)= Hourly outputs=Output/Workhour Performance ratio (PR) $PR = \frac{\text{Actual productivity}}{\text{Expected productivity}}$ $= \frac{1}{\text{Actual labours/Excepted labours}}$ <p>Expected productivity: The optimal productivity under an ideal condition, i.e., output quotas; labour resources allocation as an alternative indicator for operational convenience.</p>	After Thomas and Yiakoumis (1987); Sonmez and Rowings (1998); Hanna et al. (2008).

The action-level productivity, which measures the "resource efficiency" is obtained through the time-and-motion study. For example, taking the secondary-structure activity, see Table III, which

consists of 10 different tasks and 30 actions, in the level of activity and tasks, multiple workers perform sequential and parallel operations, featuring sufficient repetitions to draw statistical conclusions.

Table III. Time-and-motion study record of secondary structure-activity

Activity (duration days)	Tasks (duration days)	Actions	Construction logic	Labour resources	Output quotas (output/ person/ hour)
Secondary structure 29.5d	T1: Floor setting-out 1d	A1: Setting out the wall body line A2: Elevation measurement	Sequential	Three surveyors	22.57 m ² /p/h
	T2: Planting bar 2d	A3: Location identification A4: Drilling and hole cleaning A5: Glue injection and planting	Sequential	One steel worker	79.25 steel bars/p/h
	T3: Concrete flanging 2.5d	A6: Templates installing	Sequential	Two carpenters	2.18 m ² /p/h
		A7: Concrete placement		Three masons	0.14 m ³ /p/h
		A8: Form removable		One carpenter	8.72 m ² /p/h
	T4: Three-leather brick masonry 1.5d	A9: Brick delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A10: Mortar preparation transportation		One handyman	/
		A11: Masonry		Six masons	0.11m ³ /p/h
	T5: Masonry under waist beam 3d	A12: Aerated block delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A13: Mortar preparation transportation		One handyman	/
		A14: Masonry		Six masons	0.19m ³ /p/h
	T6: Waist beam 6d	A15: Reinforcement binding	Sequential	One steelworker	0.05t/p/h
		A16: Formwork erection		Two carpenters	2.01 m ² /p/h
		A17: Concrete placement		Three masons	0.26 m ³ /p/h
	T7: Masonry on waist beam 3d	A18: Form removable	Parallel	Two carpenters	10.07m ² /p/h
		A19: Aerated block delivery		Two handymen	5.17 m ³ /p/h
		A20: Mortar preparation transportation		One handyman	/
	T8: Structural columns 5d	A21: Masonry	Sequential	Six masons	0.17 m ³ /p/h
		A22: Reinforcement binding		Two steel workers	0.05t/p/h
		A23: Formwork erection		Two carpenters	5.88 m ² /p/h
	T9: Inclined plug brick masonry 1.5d	A24: Concrete placement	Parallel	Six masons	0.12 m ³ /p/h
		A25: Form removable		Two carpenters	6.91 m ² /p/h
		A26: Brick delivery		Two handymen	5.17 m ³ /p/h
	T10: Installing the flue 3.5d	A27: Mortar preparation transportation	Sequential	One handyman	/
		A28: Masonry		Five masons	0.09 m ³ /p/h
		A29: Installing		Two installers	2 flue pipes/p/h
		A30: Hole treatment		One general worker	6 holes/p/h

389 However, the same action, such as masonry, formwork erection, or concrete placement may have
 390 different labour productivities because of different locations or components. Professional workers
 391 and handymen are also distinguished by arranging different works, not only labour productivity
 392 difference considered but cost-saving realising. Moreover, the handyman's preparation work is
 393 helpful for the whole workflow continuity and labour productivity improvement.

394 A coordination plan should be developed among the general contractor and the labour
 395 subcontractors, and the performance ratio (PR) indicator is designed to measure the relative
 396 efficiency of actual and expected productivity. In particular, given that actual staffing ultimately
 397 determines the resource efficiency, labour resources allocation is extended as an alternative indicator
 398 for operational convenience and can be further used for productivity comparisons.

399 The minimum task duration is determined by each action duration based on output quotas and
 400 reasonable labour resource allocation. Additionally, equations are established to assess productivity
 401 at the task and activity levels based on action-level data, and PPC information from site statistics
 402 will measure the actual productivity of the "flow efficiency", see Table II.

403 5.2 Results and Discussions

404 5.2.1 "Worker's Home " as an innovative construction worker management mode

405 Responding to more attention paid to the humanistic care for migrant construction workers,
 406 "Worker's Home" as an innovative idea provides the industry with several insights. The mobility of
 407 construction workers has its profound social reasons, such as informal employment systems,
 408 workers' inability to afford living costs, worker migration between projects, etc. (WANG.et al.,2020).
 409 Improving living conditions, providing convenience, and meeting the practical needs of workers,
 410 are very conducive to solving the fundamental mobility problem. During the peak season, there are
 411 more than 2,300 people from 25 provinces, cities and autonomous regions across the country are
 412 working on the project. Efficient management during the pandemic benefits from the smart
 413 construction site system and real-time management system of "Worker's Home". The model has got
 414 great satisfaction from construction workers because of both the residential conditions improvement
 415 and the home-feeling accommodation provided. Furthermore, the learning, training and other
 416 activities also incubate innovative ideas for the construction workers' professional cultivation.
 417 Besides, it is proposed that "Worker's Home" will serve not only this project but also neighbouring
 418 projects in the corresponding area, thus forming a regional centralised management model for the
 419 development and operation of the construction workers' community.

420 5.2.2 "Worker's Home" serves as the industry-level practise of LC culture strategy

421 The culture of LC takes a long time to shape, from senior management to frontline workers and
 422 therefore becomes an obstacle to its implementation. The LC culture model of the consultant,
 423 focussing on on-site environmental improvement, workers' professional dignity, vocational ability
 424 enhancement and the transformation of craftsman's spirit have played a great role in the case project.
 425 However, it is limited to the corporate or project level and has high requirements for corporate social
 426 responsibility. Nevertheless, the joining of "Worker's Home" results in exploring a more general
 427 realised model at the industry level, which will be conducive to the wider promotion of LC
 428 implementation in China.

429 5.2.3 "Lean Work Package" Management develops as a practise model for LC technology 430 strategy

431 The "Lean Work Package" management model has been applied in residential projects in some
 432 provinces in China and has received excellent project performance. In the case project, the LC

implementation process of demonstration No.3 building, and its performance are compared with the other samples, shown in Table IV and Figure 6. According to the on-site statistic, PPC increased from 45% to 85% and the project duration was saved by 16%, which are the benefit of "Lean Work Package" management to offer a complete and detailed timetable and smooth workflow for preparing the resources on time and accordingly shortening the waiting time. The findings are following the research of Xing, et al. (2021) and offer evidence for project performance improvements by reducing workflow variability (Howell, Ballard et al.2004).

Therefore, it provides a practical model for both the LC technology strategy and operational implementation. Nevertheless, we also felt several obstacles that LPS did not fully address on the construction site, attributed to in harmonic relationships among different stakeholders (Miller et al., 2002). In the case project, material delivery delay results in most of the interruptions, work delays and PPC decreases, because of not well addressing the relationship with material suppliers.

Table IV. LC implementation process and performance of demonstration No.3 building

Lean implementation process		Lean techniques utilisation	Lean implementation effect
Training	Managers: 20, 60 hours Operators: 36, 30 hours	5S; WS (work structuring);	PPC increased from 45% to 85%; Labour productivity increased by 27%; Skilled workers reduced by 15%; Duration saved by 16% (from the foundation to the main structure capping);
WS system design	Detailed design of the construction drawings; Flow optimisation; Lean Work Package; Flowline models.	VSM (value stream mapping); LPS (last planner system);	Material consumption was 1.2% lower than expected;
Organisation and implementation	Lean leader team; LPS deployment; Lean conference system; Lean crews.	JIT (just in time); Takt; Visualisation; Digital technology.	Material loss was 0.05%-0.1% less than expected; Satisfaction of 90 points (total score of 100).

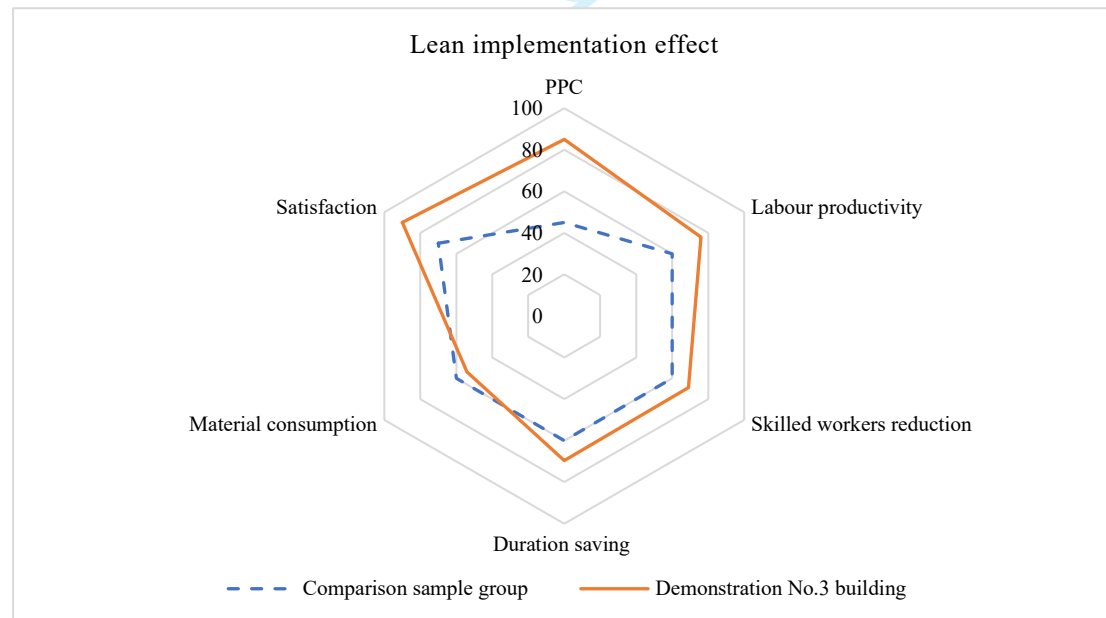


Figure 6. Radar diagram of performance comparison between the demonstration building and the sample group

5.2.4 Establish an integrated construction workforce management framework

Based on LC culture and technology strategies, an integrated framework of construction workforce management is established, which consists of three progressive levels: workforce mobility management, labour skill development and labour productivity improvement.

The "Worker's Home" practise being directed by the LC culture strategy contributes most to

construction workforce mobility management and labour skill development. Moreover, it provides intrinsic motivation for construction workers resulting in "resource efficiency". Meanwhile, "Lean Work Package" management offers practitioners processes and tools for both "resource efficiency" and "flow efficiency" improvements. As seen in Table IV, feedback to the research team (authors of this paper) from the project management staff showed satisfaction of 90 points. Through site visits and on-site chatting, most construction workers expressed their satisfaction with residential and construction site conditions improvement and noted: "as task allocation and operational standards are sufficiently clear, less rework and few repairs will happen, with income increased and paid promptly".

Although it is taking a long time for cultural transfer, researchers highlight the need to further understand the relationship between culture and lean implementation (Green, 2003; Pavez & Alarcon, 2006). The LC culture strategy adopted for workforce management in this case project won unanimous praise from workers, increased satisfaction (from on-site chat and the static data of 90 points) and offered incentives for labour productivity improvement. The results are under the importance of cultural acceptance of workers towards the lean advocated by Pavez & Alarcon (2006) and the lean implementation incentives explored by Alves (2011).

LPS and JIT are recognised as the most appropriate techniques to use and benefit from the reduction of waiting times, defects, and underutilising people, who agree with the findings of Sarhan et al. (2017) and Xing, et al. (2021). The results of the performance assessment in the pilot-building present labour productivity increased by 27%, while skilled workers were reduced by 15% and material consumption was 1.2% lower than expected. Nevertheless, the practises of WS system design and comprehensive flow management are relatively unknown and fewer utilised in LC implementation in China. Therefore, the gap between academia and industry should be bridged through the development of research projects and the promotion of events to disseminate and consolidate LC practises (Alves et al. 2010).

6 Conclusions

Facing the severe pandemic restrictions condition, the worker-management problems are exposed to the weak points in the construction field that must seek innovative solutions. This paper reports a case study of an innovatively designed integration framework and implementation of LC in a construction project in China.

The findings provide useful implications for theories and industry practises. Firstly, the paper has clarified the current knowledge in lean construction as a socio-technical paradigm system, which provides the foundation of the integration framework. Secondly, the research focuses on LC practise from a unique perspective of workforce management, countering the demands of both emergency goals under a special pandemic context and long-term sustainable development for the construction industry.

For method application, a combination of qualitative and quantitative methods is conducted, "resource efficiency" and "flow efficiency" are introduced to explore the origins of construction labour productivity, and the time-and-motion study method and Percent Plan Complete (PPC) indicator are proposed to offer measurements. Based on the series study of optimal productivity by Kisi (2017-2018), expected productivity is developed by the research team (authors of this paper), with the Performance Ratio (PR) can be counted for performance comparison and improvement, and labour resources allocation is designed as an alternative indicator for operational convenience,

all of which contribute to reducing inefficient worker gathering and productivity improvement.

Furthermore, the case study showed a comprehensive construction workforce management framework from humanistic care to labour productivity promotion. The "Worker's Home" model not only provides a solution for workers' tracking through a real-time management system in a specific pandemic but also addresses the workers' mobility by offering regional settlement choices to construction workers. The "Lean Work Package" management model presents mixed LC techniques adapted to identify and eliminate "making-do" waste and improve workflow reliability and "flow efficiency".

The findings can also guide industry practitioners' thinking and explore the mixed strategies and practises of LC. As the general contractor and the predecessor of the consulting firm are both small- and medium-sized enterprises (SMEs), the proposed framework and practise model fit for. Instead of solely LC techniques adoption, culture response cannot be ignored. Moreover, the case project provides an industry-level solution for workforce management and LC culture shaping, while also witnessing the alignment of LC culture and technology strategies, contributing to innovation in LC practises.

As single case studies cannot be generalised in a statistical sense, in future studies, the integration framework and the practise models should be further verified by more projects and continually be improved to offer evidence of effectiveness. Accurate and objective quantification is further needed to validate the presented results. Especially, some conclusions may only fit in the construction industry context in China, so further investigations should be conducted in other countries. Additionally, further research should be conducted into the links between digital technologies (such as smart construction site systems) and LC technology to achieve greater effectiveness.

In conclusion, we have seen a high level of interest in LC among construction practitioners rather than researchers, signifying a major step forward in the acceptance of innovative ideas and the implementation of LC in China. Through this study, we seek to contribute to the existing knowledge of workforce management frameworks and practices based on a mix of LC culture and technology strategies in a particular pandemic context and post-pandemic era.

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Study on the Construction Workforce Management Based on Lean Construction in the Context of COVID-19

We greatly appreciate the detailed and constructive comments/suggestions given by the editor and reviewers. Modifications have been made highlighted in blue colour in the main manuscript accordingly – all comments have been taken, as described below. Our responses text below are highlighted in blue colour.

Reviewer(s)' Comments to Author:

Reviewer 1

Comments:

1. Authors should consider presenting the results in various ways. What can be presented in a figure such as pie chart, radar, etc should be presented.

Response: In '5.2 Results and Discussions', we have added a radar diagram to present the performance comparison between the demonstration building and the sample group to make the contrast more visible (Page 14, Lines 446-448).

2. Why the last paragraph of the conclusion has different font and size. Although, authors have considered the British English for their manuscript, yet, still there are some types of American English especially in the tables.

Response: A meticulous full-text check was carried out and corrections were made especially for tables and figures.

Reviewer 2

Comments:

1. I would point out that not much has been said about pandemics or similar situations which I believe this research has set the context within. Is there any way to address this deficiency?

Response: We have reviewed some of the literature on specific efforts, main research aspects and guidelines in responding to the COVID-19 pandemic in the construction sector, and have added to this in the last two paragraphs of '2 Literature Review' to provide clarity on the context of the study (Page 4, Lines 152-163).

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2. I would ask why Table 1 is in the data collection area and not the results section perhaps? The data collection section should perhaps just be discussing the approach in my opinion. Also, are photos or pictures really required in a research paper such as this one? Note that I can't read the spreadsheet provided intext.

Response: The original Table I was changed to Table III, along with some of its explanations being adjusted to the '5 Case study' section, and '5.1.4 Labour productivity assessment' was added to explain the results of the time-and motion study, and the relationship between Table II and III (Page 11, Lines 377-402). Three photos and the spreadsheet have been removed, so the numbering of some figures has changed.

3.The limitation posed by only one case study was mentioned. Some future research was also included.

Response: The limitation is modified by "As single case studies cannot be generalised in a statistical sense, in future studies, the integration framework and the practise models should be further verified by more projects and continually be improved to offer evidence of effectiveness. Accurate and objective quantification is further needed to validate the presented results" (Page 16, Lines 513-516).

Other statement:

1. We updated the line number by ourselves so that the reviewer can easily find the corresponding modification position.

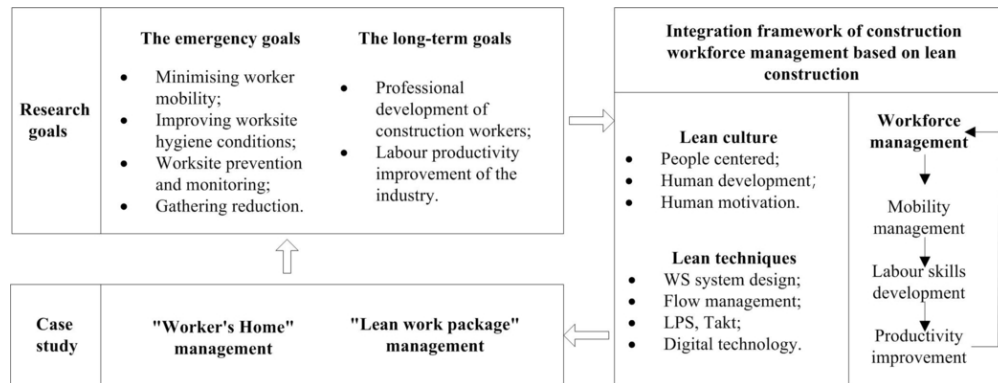


Figure 1. The research framework

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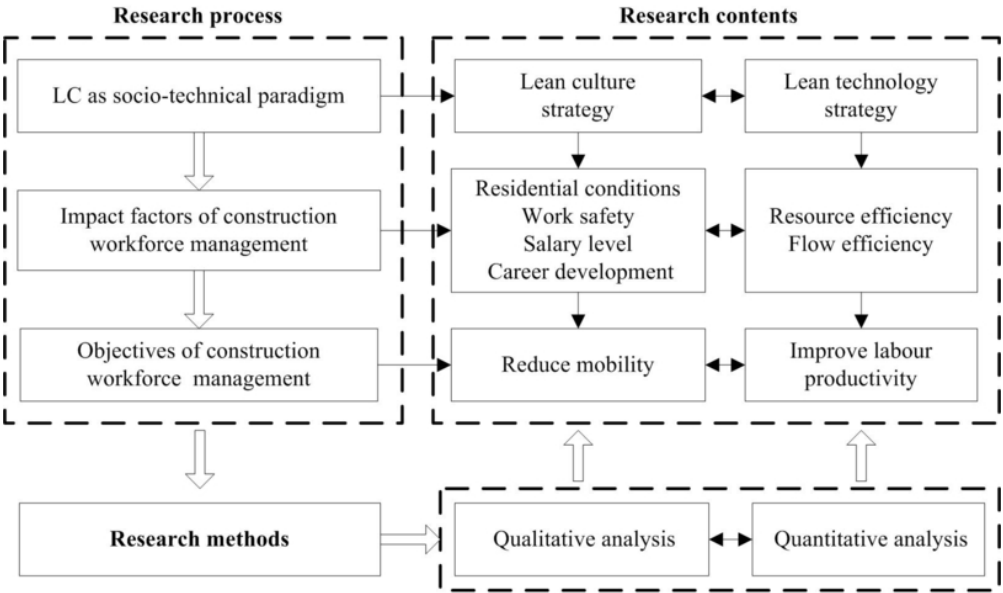


Figure 2. Outline of the integration construction workforce management framework

137x90mm (150 x 150 DPI)



Figure 3. "Worker's Home" management model, lean culture strategy and workforce management goals

139x72mm (150 x 150 DPI)

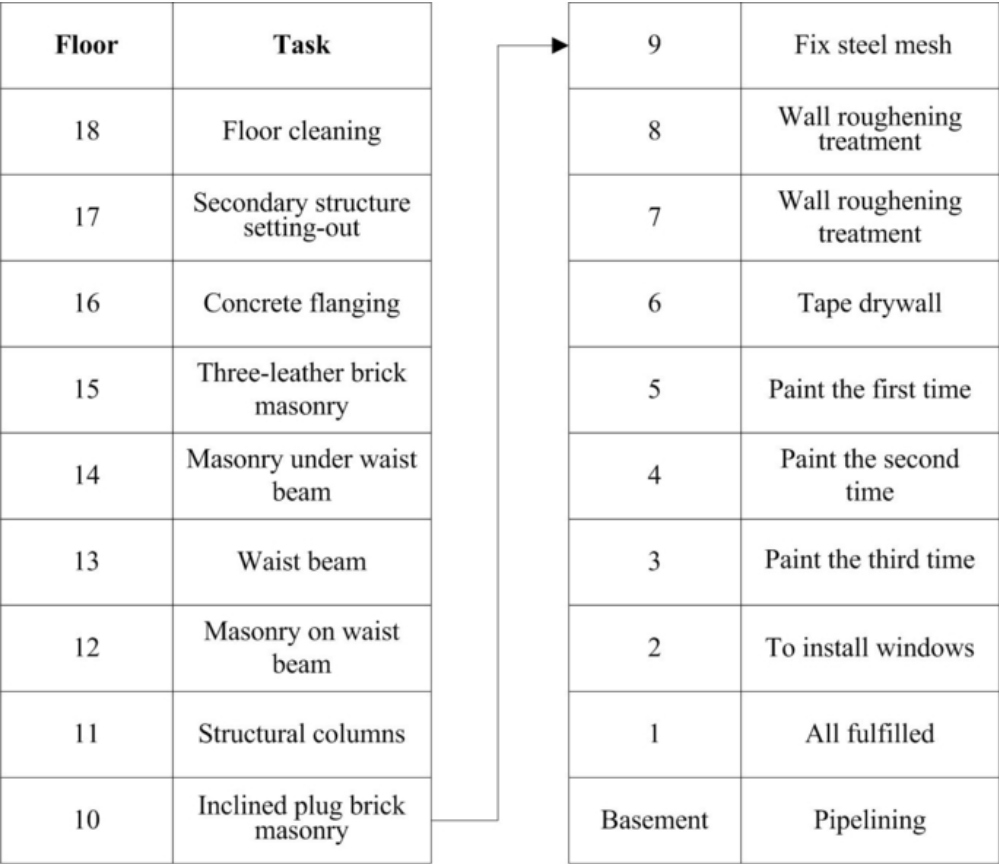


Figure 4. An on-site flow line

115x106mm (150 x 150 DPI)

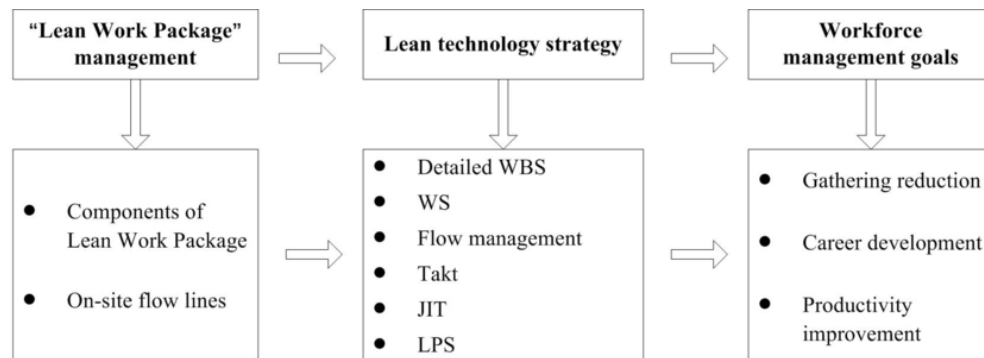


Figure 5. "Lean Work Package" management model, lean technology strategy and workforce management goals

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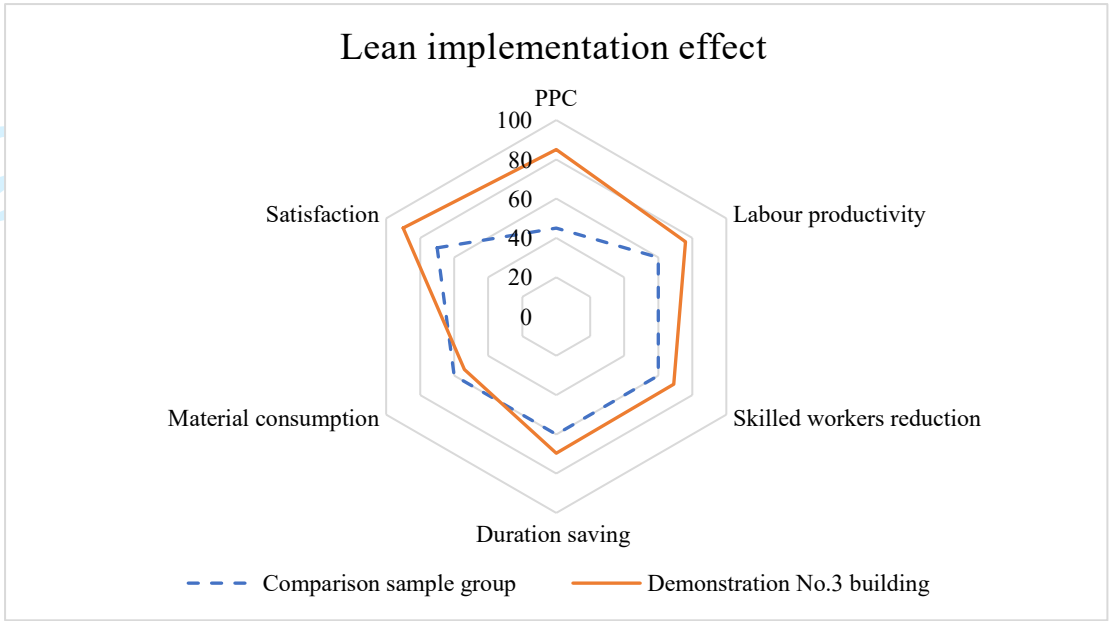


Figure 6. Radar diagram of performance comparison between the demonstration building and the sample group

Table I. Components of the Lean Work Package

Work description	Standard	Assessment
1. Work code	1. Performance standard	1. PPC
2. Work content, quantity, duration	2. Labor productivity standard	2. On-time start-up rate
3. Work start time	3. Material consumption standard	3. On-time completion rate
4. Work finish time	4. Quality standard	4. Labor productivity
5. Process logic	5. Safety standard	5. Material consumption rate
6. Labors	6. Management standard	6. Material wastage rate
7. Materials	7. Cost estimation standard	7. Rework rate
8. Equipment		8. Cost-savings rate
9. Location		
10. Package owner		

Table II. Overview of labour productivity assessments

Productivity level	Productivity origins	Measurement methods	Indicators and Equations	Reference and Extensions
Activity	Flow efficiency	Formula deduction	$T_{adu} = \sum_{i=1}^n T_{tsi} - \sum_{j=1}^m T_{tpj} + T_{tin}$ <p>T_{adu}: Activity duration times; T_{tsi}: Duration time of sequential task i; T_{tpj}: Duration time of parallel task j; T_{tin}: Interval time between sequential tasks; n: Total tasks of one activity; m: Group numbers for parallel tasks.</p>	After Krishna P. Kisi et al. (2017)
		Statistic	PPC	Howell, Ballard et al. (2004).
Task	Flow efficiency	Formula deduction	$T_{tdu} = \sum_{k=1}^l T_{ask} - T_{apq}$ <p>T_{tdu}: Task duration times; T_{ask}: Duration time of sequential action k; T_{apq}: Duration time of parallel action q; l: Total actions of one task.</p>	After Krishna P. Kisi et al. (2017)
		Statistic	PPC	Howell, Ballard et al. (2004).
Action	Resource efficiency	Time-and-motion research	Hourly outputs Construction labour productivity (CLP)= Hourly outputs=Output/Workhour Performance ratio (PR) $PR = \frac{\text{Actual productivity}}{\text{Expected productivity}}$ $= \frac{\text{Actual labours/Excepected labours}}{\text{Expected productivity}}$ <p>Expected productivity: The optimal productivity under an ideal condition, i.e., output quotas; labour resources allocation as an alternative indicator for operational convenience.</p>	After Thomas and Yiakoumis (1987); Sonmez and Rowings (1998); Hanna et al. (2008).

Table III. Time-and-motion study record of secondary structure-activity

Activity (duration days)	Tasks (duration days)	Actions	Construction logic	Labour resources	Output quotas (output/ person/ hour)
Secondary structure 29.5d	T1: Floor setting-out 1d	A1: Setting out the wall body line A2: Elevation measurement	Sequential	Three surveyors	22.57 m ² /p/h
	T2: Planting bar 2d	A3: Location identification A4: Drilling and hole cleaning A5: Glue injection and planting	Sequential	One steel worker	79.25 steel bars/p/h
	T3: Concrete flanging 2.5d	A6: Templates installing	Sequential	Two carpenters	2.18 m ² /p/h
		A7: Concrete placement		Three masons	0.14 m ³ /p/h
		A8: Form removable		One carpenter	8.72 m ² /p/h
	T4: Three-leather brick masonry 1.5d	A9: Brick delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A10: Mortar preparation transportation		One handyman	/
		A11: Masonry		Six masons	0.11m ³ /p/h
	T5: Masonry under waist beam 3d	A12: Aerated block delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A13: Mortar preparation transportation		One handyman	/
		A14: Masonry		Six masons	0.19m ³ /p/h
		A15: Reinforcement binding		One steelworker	0.05t/p/h
	T6: Waist beam 6d	A16: Formwork erection	Sequential	Two carpenters	2.01 m ² /p/h
		A17: Concrete placement		Three masons	0.26 m ³ /p/h
		A18: Form removable		Two carpenters	10.07m ² /p/h
	T7: Masonry on waist beam 3d	A19: Aerated block delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A20: Mortar preparation transportation		One handyman	/
		A21: Masonry		Six masons	0.17 m ³ /p/h
	T8: Structural columns 5d	A22: Reinforcement binding	Sequential	Two steel workers	0.05t/p/h
		A23: Formwork erection		Two carpenters	5.88 m ² /p/h
		A24: Concrete placement		Six masons	0.12 m ³ /p/h
		A25: Form removable		Two carpenters	6.91 m ² /p/h
	T9: Inclined plug brick masonry 1.5d	A26: Brick delivery	Parallel	Two handymen	5.17 m ³ /p/h
		A27: Mortar preparation transportation		One handyman	/
		A28: Masonry		Five masons	0.09 m ³ /p/h
	T10: Installing the flue 3.5d	A29: Installing	Sequential	Two installers	2 flue pipes/p/h
		A30: Hole treatment		One general worker	6 holes/p/h

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Lean implementation process		Lean techniques utilisation	Lean implementation effect
Training	Managers: 20, 60 hours Operators: 36, 30 hours	5S; WS (work structuring);	PPC increased from 45% to 85%; Labour productivity increased by 27%; Skilled workers reduced by 15%;
WS system design	Detailed design of the construction drawings; Flow optimisation; Lean Work Package; Flowline models.	VSM (value stream mapping); LPS (last planner system);	Duration saved by 16% (from the foundation to the main structure capping); Material consumption was 1.2% lower than expected;
Organisation and implementation	Lean leader team; LPS deployment; Lean conference system; Lean crews.	JIT (just in time); Takt; Visualisation; Digital technology.	Material loss was 0.05%-0.1% less than expected; Satisfaction of 90 points (total score of 100).