International Journal of Construction Management

ISSN: 1562-3599 (Print) 2331-2327 (Online) Journal homepage: https://www.tandfonline.com/loi/tjcm20

Leagile Strategies for Optimizing the Delivery of Prefabricated House Building Projects

Sherif Mostafa, Vivian W. Tam, Jantanee Dumrak & Sherif Mohamed

To cite this article: Sherif Mostafa, Vivian W. Tam, Jantanee Dumrak & Sherif Mohamed (2020) Leagile Strategies for Optimizing the Delivery of Prefabricated House Building Projects, International Journal of Construction Management, 20:8, 867-881, DOI: 10.1080/15623599.2018.1494674

To link to this article: https://doi.org/10.1080/15623599.2018.1494674

Published online: 01 Oct 2018.

INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT
2020, VOL. 20, NO. 8, 867–881
https://doi.org/10.1080/15623599.2018.1494674

Taylor & Francis
Taylor & Francis Group

Leagile strategies for optimizing the delivery of prefabricated house building projects

Sherif Mostafa[a], Vivian W. Tam[b,c], Jantanee Dumrak[d] and Sherif Mohamed[a]

[a]Griffith School of Engineering and Built Environment, Griffith University, Queensland, Australia; [b]School of Computing, Engineering and Mathematics, Western Sydney University, Sydney, North South Wales, Australia; [c]College of Civil Engineering, Shenzhen University, Guandong Sheng, China; [d]Global Project Management, Torrens University Australia, Adelaide, South Australia, Australia

ABSTRACT

Australian housing supply has not been responded at a rate commensurate with its growing demand. Residential housing sector is facing this serious shortage issue by actively developing and effectively using new construction material, processes and practices for sustaining its competitive advantage over other construction sectors in the Australian context. The *Construction 2020* report confirmed prefabrication/off-site manufacturing (OSM) as a critical vision for the Australian construction industry's future, as OSM provides opportunities for not only increased productivity and safety, but also decreased cost. It also has the capability of meeting the growing housing demand within the extant level of skilled labour. By combining lean and agile concepts, OSM's supply responsiveness and efficiency can be intensified. The current research studies the association between demand–supply housing imbalance factors using mixed methods from literature and interviews. Literature has documented four main factors that drive this imbalance: (1) housing completion time; (2) cost of a finished house; (3) customer preferences and (4) level of skilled labour. Interviews with 13 industry professionals identified the four main leagile strategies used to deliver prefabricated building projects. Literature and interview findings supported the development and validation of multicriteria decision-making (MCDM) model comprising and incorporating these factors (and subfactors) and the four leagile strategies. The choice of the appropriate strategy to address the studied factors within the Australian context was optimized using analytic hierarchy process (AHP). The results from the AHP model show the suitability of applying each strategy at different degrees as influenced by the tested factors.

KEYWORDS
Australian housing; prefabrication/off-site manufacturing; leagile strategies; customer order decoupling point; analytic hierarchy process

Introduction

Construction industry is a key economic component of Australia, with the industry's productivity continuously expanding. In the financial year of 2010–2011, it was accounted for 7.7% of the country's gross domestic product with gross value added reaching AUD 102 billion (Elmualim et al. 2018). The Australian construction industry includes private and public sectors that are engaged in three broad activities: residential building, nonresidential building and engineering construction. In Australia, the residential building sector significantly contributed to the national economy with the overall production value reported at AUD 47 billion in the financial year of 2010–2011. The Australian residential building sector involves many independent building organizations in the construction of separate houses and other residential buildings including semidetached houses, town houses, flats, units and apartments. However, the value of work commenced in residential buildings is likely to be less responsive to the growth of other construction activities. Housing supply and demand factors may influence this situation. Council of Australian Governments (COAG 2012) and the National Housing Supply Council (NHSC 2013) have both reported that housing supply is not keeping pace with its demand.

Previous studies have examined housing supply shortage (Gharaie et al. 2012; HIA 2013) but have mainly focused on housing demand side rather than housing supply challenges (Liu and London 2011). This paper, therefore, addresses the undersupply of Australian housing from both housing supply and demand perspectives. The term 'housing supply' should be considered as a chain that contains all building stakeholders. Lack of coordination between stakeholders and lack of management of this chain

CONTACT Sherif Mostafa sherif.mostafa@Griffith.edu.au; sherif.mostafa@hotmail.com.au Griffith School of Engineering, Griffith University, Gold Coast Campus, Southport, Queensland 4222, Australia

may lead to a housing shortage (London and Siva 2011). That study identifies four main factors as contributing to the Australian housing supply–demand imbalance, namely, house price, housing completion time and house customization. Off-site manufacturing (OSM) is a modern construction method which involves two working sites: the off-site factory and on-site construction. Elnaas et al. (2014) highlighted the key themes of OSM decision factors with time, quality and cost being the highly important themes driving the adoption of OSM in the United Kingdom (UK). Some studies in Australia have focused on OSM uptake in building and in developing new housing technologies for buildings (Blismas and Wakefield 2009; Mostafa et al. 2014a; Arashpour et al. 2015; Mostafa and Chileshe 2017). OSM opportunities in Australia are centred on detached housing, high-density multiresidential complexes and public facilities such as hospitals, schools and prisons (Blismas and Wakefield 2009; Mostafa et al. 2016).

Suggestions have been made that manufacturing concepts, such as lean and agile, can and should be transferred to building production (PATH 2002; Naim and Barlow 2003; Mostafa et al. 2016). The selection of an appropriate strategy to achieve specific housing supply and meet demand requires a systematic process. This study associates four leagile strategies for optimizing the efficiency and integration of the two working locations in the OSM supply chain. The suggested strategies are: built to stock (BTS), assemble to order (ATO), design to order (DTO) and the self-building house (SBH). These strategies aim to improve the overall performance and competitiveness of the Australian residential housing sector.

This study aims to optimize the selection of the leagaile strategy that fit with the combination of main factors contributing to the imbalance of housing supply and demand. Analytic hierarchy process (AHP) has been employed and performed the analysis with the purpose of delivering the most suitable strategy from the obtained data. The AHP method served as a framework for prioritizing the four leagile building strategies with respect to the studied factors. This paper is structured as six consecutive sections. After the introduction, the second section reviews the literature related to Australian housing supply and demand; lean, agile and leagile concepts; and the OSM building supply chain. The third section summarizes the research methodology, while the fourth section discusses the research findings. The fifth section explains the research implications and, in the final section, the research conclusion is given with recommendations for further research.

Research background

Factors contributing to the Australian housing supply–demand imbalance

Australian housing supply does not adequately respond to the growing demand especially in capital cities (COAG 2012; Mostafa et al. 2014b). This situation has been confirmed by housing industry alliances, such as the National Housing Supply Council (NHSC), Housing Industry Association (HIA) and Master Builders Australia (Dalton et al. 2013). A report on housing supply and affordability produced by the NHSC (2013) clearly indicated the gaps between the underlying assumptions of housing demand and supply for the years 2011–2031 ranging across low, medium and high growth scenarios, as presented in Figure 1.

The gaps between demand and supply are clearly evident in all growth rate scenarios. As shown in Figure 1, it was forecast that, in 2016, the difference between demand and supply would reach 106,000, 99,000 and 85,000 dwellings at low, medium and high growth rates, respectively. By the year 2020, the expected shortage of dwellings would be 189,000, 177,000 and 158,000, respectively. The difference between supply and demand would continue to significantly increase by the year 2031 to 271,000, 259,000 and 233,000 at low, medium and high growth rates, respectively. According to a report by NHSC (2013), the public sector's delivery capacity in housing supply will sharply decline as recent housing outputs evidently decrease from the units produced in the last decades. Both housing supply and demand factors influence the Australian housing undersupply. The four main factors that contribute to the housing supply and demand imbalance are discussed in the following subsections.

Construction cost

House price refers to residential construction costs, taxes on new housing and land release (Liu and London 2011; NHSC 2013). House price is a critical element determining new housing construction. In Australia, house prices have increased in all locations at a similar rate of growth (Fox and Finlay 2013; The Urban Developer 2018). According to the Australian Future Tax System (AFTS) report in 2010, median house prices have risen from three times the average

Figure 1. Estimated difference between demand and supply for Australian residential dwellings (in '000 units) (Adapted from NHSC, 2013, p. 10, 19).

household income in 1990 to around five times in 2010 (AFTS 2010). As mentioned above, house price includes land price and construction costs (material and labour costs) (Liu and London 2011). The Housing Supply and Affordability Reform (HSAR) Working Party report stated that the growth of house prices is driven by the increase in prices of established houses. However, the AFTS (2010) report viewed construction costs as being responsible for a higher proportion of the increase in house prices in some regions. The study by Liu and London (2011) explored the relationship between new housing supply and construction costs in Australia. Their study concluded that construction costs are a key component of the poor performance of new housing supply in Australia.

Customer preferences

Customer preferences reflect the customization of the house design to suit customer needs. The preferences may vary from person to person based on residential desirability and acceptability. Customer preferences include the design and location of a house (NHSC 2013). The house design includes the internal (floor) and external (façade width) areas of the house. The size of the average floor area of new detached houses in Australia has been increased from 162.4 square metres to 248.0 square metres between 1984 and 2009, whereas the average floor area of other types of new residential dwellings increased from 99.2 square metres to 140.8 square metres (ABS 2010). It is evident from an examination of volume builders that double-storey houses and complex street-facing façades have been significantly increased (HIA 2017).

Housing completion time

Housing completion time is a key factor indicating the quality of housing delivery to customers. 'Housing completion time' is defined as the period between the first and last physical building activities to produce a house and make it ready for occupation (Dalton et al. 2011). The average Australian housing completion time has been increased from 1.8 quarters to 2.4 quarters from 2000 to 2008 (ABS 2010), while the production rate has been relatively stable (Gharaie 2011). Dalton et al. (2011) identified the three factors that might explain the lengthening of housing completion time. The first factor is the construction method used to manage all activities within building processes. This also includes coordination and scheduling among stakeholders as building is delivered through a chain of stakeholders; therefore, building a house needs a successful construction method for achieving the schedule planned delivery. The second factor is the level of skilled labour which affects the quality of a finished house. Although additional house builders employ quality assurance systems, nevertheless, they have a poor quality record. Construction managers and supervisors must arrange with contractors and subcontractors for defects to be remediated, with remediation extending the planned construction time for the house. The third factor is the number of houses under construction. The study by Gharaie et al. (2010) showed a positive correlation between the number of houses under construction and completion time.

Construction skilled labour

Building is a labour-intensive industry with its main product being new or renovated dwellings. The supply of labour is an important element of housing supply. According to the Department of Education, Employment and Workplace Relations (DEEWR 2012), from 2008 to 2012, shortages were reported in the following construction trades: roof tilers, glaziers, plumbers and cabinetmakers. House builders work in a competitive environment in which skilled labour is required. The challenges in building include new working relationships, such as partnering and virtual enterprises, as well as changing construction technologies and adopting modern methods of construction (Daly 2009). It can be concluded that skilled labour is an essential component of the building industry if it is to successfully overcome all the above-mentioned challenges. Moreover, skills shortages contribute to the undersupply of housing (NHSC 2013).

OSM/prefabrication

OSM is a modern method of construction which has been adopted to improve the performance of the residential building industry (Tam and Hao 2014). The term 'OSM' refers to the production of house components in an off-site factory as well as the subsequent on-site construction activities (Russell et al. 2012). OSM provides several benefits to all stakeholders involved in the building process. It improves on-site safety by providing a cleaner and tidier environment at the construction site as well as enhancing the quality of house components made through factory production processes. Moreover, OSM reduces environmental effects by reducing waste generation, shortening lead time and increasing efficiency and productivity (Pan and Goodier 2011; Zhai et al. 2014a, 2014b). OSM categories are based on the degree of off-site works including component manufacture and subassembly; nonvolumetric pre-assembly (e.g. cladding wall panels); volumetric pre-assembly (e.g. toilet pods, shower rooms); and modular building (e.g. motel blocks).

In Australia, OSM has been positively addressed in some studies. For instance, the *Construction 2020* report suggested OSM as a key vision for improving the construction industry (Hampson and Brandon 2004). Two research projects carried out by Blismas (2007) and Manley et al. (2009) revealed the future of OSM in the Australian built environment. The findings of these two projects confirmed that OSM could produce high-volume, high-quality houses based on the efficiencies of manufacturing principles. Despite the benefits of OSM, physical factory production has several forms of non-value-added activities or waste. The seven forms of waste commonly found in physical factory production are: over-production, waiting time, transportation, over-processing, excessive inventories, defective products and unnecessary movement (Mostafa et al. 2016). Moreover, the customization of prefabricated house makes design specifications more complex. Three emerging challenges for a construction organization are derived from the concurrent management of two working locations (off-site fabrication facility and on-site construction). The first challenge is streamlining between off-site and on-site activities. The second is jumbled on-site processes due to the flow difference between the off-site facility and the construction site. The third challenge is ambiguous demands from unclear customers (Chang and Lee 2004; Daneshgari 2010).

Some attempts have been made to address the shortcomings of OSM building by adopting successful concepts from the manufacturing industry (PATH 2003), particularly the lean and agile concepts (Höök and Stehn 2008). Lean and agile concepts can be used to manage the OSM supply chain as they are in manufacturing (Vidalakis et al. 2013). The current research proposes that four lean and agile strategies are used to optimize the off-site construction supply chain.

Lean and agile practice within OSM

The practice of the lean concept in building requires the use of factory-based production. However, construction has unique characteristics (i.e. features of output, nature of processes, customer involvement and supply chain). Therefore, lean construction, as extended by Koskela (1992), addresses these specific characteristics. The main challenge of lean construction is related to the interfaces between off-site factory and the construction site. The production flow at the off-site factory is continuous and is different from that of the construction site which is turbulent. This is due to uncertainties at the construction site, such as changes in customer demand or site conditions which can lead to unpredictable delays in achieving the customer's order. Agile construction was proposed as a way to proactively respond to any on-site uncertainties (Daneshgari, 2009, 2010). Lean construction focuses on creating an efficient physical manufacturing process (Pasquire, 2012). Agile construction, conversely, emphasizes a high level of service through flexibility and customization (Naim and Barlow 2003). Lean and agile factors are essential for OSM which implies standardization of products and processes and emphasizes flexibility in house design. The existing literature identified some concerns in applying lean or agile as a stand-alone concept when uncertainties in construction are present (Christopher and Towill 2000). Many studies suggested a combination of lean and agile concepts in OSM (Blismas and Wakefield 2009; Mostafa et al. 2014a, 2014b). However, these studies were conducted in a different context to the Australian building environment. Literature further revealed that no specific lean and agile integration strategy for OSM in Australia has been formulated. Combining lean and agile within the whole supply chain could be accomplished using decoupling point strategy known as 'leagile' (Purvis et al. 2014). In general, the decoupling point separates the supply chain into lean at the factory site and agile at construction site.

Matching leagile strategies with housing supply–demand imbalance factors

It is contended that the abovementioned housing supply and demand factors influence the shortage of Australian housing supply. Moreover, these factors impact on the selection of building supply chain strategies. To identify solutions that could improve the housing shortage situation, AHP was considered for the current study. Where the goal and set of potential criteria and alternatives are made available, AHP is a suitable application (Darko et al. 2018). Developed by Saaty (1990), AHP is a multicriteria decision-making (MCDM) model which takes into account both qualitative and quantitative judgements. In the current study, AHP was used to evaluate and rank the leagile strategies of the OSM supply chain in relation to the identified factors. Many multicriteria situations across a wide range of areas have utilized AHP including: operations management decisions based on customer requirements; construction contractor selection; supplier selection process; improving construction productivity; identifying design development factors in Australian public–private partnership (PPP) projects; new product development; and infrastructure projects with social impact. The decision-making process is facilitated by AHP which constructs a hierarchical model that presents the integrated levels of the problem from the goal through to the alternatives. Two basic components comprise the AHP method: the first component contains pairwise comparisons among all elements (e.g. criteria, subcriteria and alternatives) at all levels of the model to decide on various alternatives; while the second component involves a synthesis and ranking of the model elements to identify the key elements of the decision-making problem.

Furthermore, AHP has been used in the construction and building industry. For instance, Wang and Pan (2012) employed AHP to weight the decision criteria for selecting the best value contractors for two construction projects in Taiwan. Doloi (2008) used AHP to examine the causes of construction workers' poor productivity on building construction projects in Melbourne. This model comprised four factors: government, enterprise, custom and market. However, the model did not include any strategy for overcoming the impacts caused by these factors. In the current study, AHP is employed to match the four leagile strategies to the four main factors contributing to the Australian housing supply–demand imbalance. The goal (selecting an appropriate building strategy) is stated, and the set of criteria (housing supply and demand imbalance factors) and alternatives (four leagile strategies) are determined. The study's focus is on building activities from a house's commencement through to completion and being ready for occupation for the reason that, in the Australian housing context, the number of dwellings completed is less than the number of dwellings commenced. This study, therefore, identifies the main factors influencing the Australian housing supply–demand imbalance and associated these factors with the four suggested leagile strategies.

Research methods

The current study applied mixed methods to study the association between the four factors and the leagile strategies. Literature review was conducted to document the related literature's findings on the strategies of integrating lean and agile concepts within the supply chain. Data and information were collected from various sources related to Australian housing including peer-reviewed journals, reference books and websites as well as Australian housing and governmental authorities including the National Housing Supply Council (NHSC), Housing Industry Association (HIA), Australian Bureau of Statistics (ABS), Australian Housing and Urban Research Institute (AHURI) and the Council of Australian

Governments (COAG). The collected materials were carefully examined and allocated reference numbers. The possible factors (criteria and subcriteria) affecting the imbalance between housing supply and demand in Australia were then determined.

The research findings in the literature were complemented and extended by interviewing 13 industry professionals on the strategies used to accommodate the needs of prefabricated building customers in Australia. The researchers focused on recruiting participants with years of experince and extensive knowlleged in the prefarbciation business in Australia. The orgnizations in which particpants worked are certificed members of PrefaabAUS and MBIAA. The interview partcipants experince ranged from none to over 30 years with an average of 19 years experince in prefabricated building projcets. The participants were working as managing dricetors, consulatncy directors, markting and sales manager, project manager and production manager. The use of AHP in this study was to design the model combining the four suggested leagile building strategies and the four factors identified as contributing to the housing undersupply in Australia. This included selecting and scrutinizing possible criteria. The intervieews validated the model in relation to the identified factors and subfactors, and the suggested strategies. After the AHP model validations, pairwise comparisons were used to rate the strategies and factors according to a nine-point scale. The validity of the pairwise comparison process was determined using the consistency test. This process was carried out through determining the inconsistency index score of the pairwise comparisons. In general, a consistency ratio (CR) < 0.1 indicates a satisfactory degree of consistency (Saaty 1990). AHP priorities were then generated from the goal and synthesized while the overall priorities were calculated. The relative weights were used to identify the key factors (criteria and subcriteria). Moreover, the overall rating of the four building leagile strategies was determined. By performing a series of sensitivity analyses, an investigation was conducted to investigate the impact of changing the importance of the criteria on the overall rating of the four strategies.

Research findings

Leagile strategies for OSM supply chain

Three approaches to operating a supply chain are lean, agile and leagile. The lean approach was first developed in the Toyota Production System (TPS). The lean approach is an integrated socio-technical system comprising management practices that can be applied to eliminate waste (Mostafa et al. 2013). In 1992, Koskela introduced and discussed the lean concept in the construction environment. A transformation-flow-value (TFV) production concept was developed as a new perspective for improving construction performance. According to the TFV concept, construction production consists of three equivalent processes: transformation of material into standing structures; flow of material and information through various production processes; and value creation for customers through the elimination of value loss (Mostafa et al. 2016).

The agile concept, conversely, became popular in 1991. Sharifi and Zhang (1999) later stated that a new competitive environment is a key driver for changes in the manufacturing industry. The identified competition qualities are continuous improvement, rapid response and quality improvement. The initiative of agile construction was established in direct response to the *Latham Report* published in 1994 (Lee 2003). This report highlighted the requirement for the UK construction industry to reduce construction cost by 30% by the year 2000. To achieve this target, the whole industry needed to change, with benchmarking a method used to stimulate the required change in construction practices. As suggested by Naim et al. (1999), the employment of agile principles in construction supply chains can achieve profitable opportunities in dynamic markets. Agile construction exemplifies the characteristics of visibility, responsiveness, productivity and profitability (Daneshgari 2010).

The integration of lean and agile concepts is considered the best solution to answering all the production issues in the world-class market competition (Agarwal et al. 2007). Combining lean and agile approaches within the entire supply chain can be accomplished using decoupling point (DP), with this process known as 'leagility'. The term 'leagility' was first introduced by Naim et al. (1999). In general, the DP separates the leagile supply chain into lean in the upstream and agile in the downstream (i.e., lean before the DP and agile after the DP). In situations of market competition, Christopher and Towill (2000) emphasize that supply chains must be responsive to market demand changes by attending to three critical dimensions: variety, variability (or predictability) and volume. The lean concept is the best alternative where there is an environment of high volume, low variety and low likelihood of predictable change. In contrast, the agile concept is the best option where there is an environment of high variety, low volume and highly predictable change. The visibility of actual demand is limited in most supply chains.

In leagile supply chains, two DPs are found (Mostafa et al. 2016). The first DP is the material DP which should ideally lie as far downstream as possible to be close to the final marketplace. The second DP is the information DP which should lie as far upstream as possible in the supply chain. Agility after the DP is explained by the principle of postponement (i.e. using a generic or modular inventory to postpone the final commitment) while the final assembly or customization depends on real demand. The leagile supply chain has capabilities to achieve value for the house customer through different strategies involving the DP positions. The leagile building supply chain mainly focuses on waste removal and responsive mechanisms, applying excellence through the use of lean and agile practices. The studies of Childerhouse et al. (2000) and Naim and Barlow (2003) focused on using the material DP in the UK building supply chain. In these papers, the leagile building supply chain employed the customer order decoupling point (CODP) (or the order penetration point) which encompasses both information and material. The materials DP is the point where stocking (stocking point) of finished house modules or components occurs. The information DP is the point where customer demand enters the value chain. The following four strategies are proposed for the Australian building supply chain and represent four alternative positions for customer order decoupling point (CODP).

Built-to-stock (BTS) strategy

In the built-to-stock (BTS) strategy (also known as the predesigned strategy), the CODP is located after the on-site construction activities and the finish of the building. In this strategy, the builder predesigns, manufactures and assembles the components/modules for reducing design time and enhancing productivity. The houses are designed and built 'speculatively' based on the builder's catalogue (Dalton et al. 2011). Customers choose from a selection of the available houses based on the location, cost, size and design. As found by Barlow and Ozaki (2005), 25% of new houses in Japan are speculative houses. The house customers have limited or no choice over the house specifications and design. The market winner in this strategy is the finished house with the lowest selling price. The panelized building designed by Monarch Building Systems, as presented by Blismas (2007), is another example of the BTS strategy. House panels are produced and utilized as standard panels in this company's building projects. With the BTS strategy, the company can ensure its capacity to construct large accommodation projects within the contracted time frame. Therefore, the activities before selling should be lean to fit the costs. The agile approach is located after the CODP to diminish delivery time, and to meet the requirements for customer satisfaction and the speed of return on investment (ROI) (Childerhouse et al. 2000; Mostafa et al. 2014a, 2014b).

Assemble-to-order strategy

In the assemble-to-order (ATO) strategy, the CODP is positioned at the off-site fabrication facility. The customer approaches an architect to develop the design that fits their needs. They then come to the builder with the plans. The builder reworks and redesigns the plans working with the architect, the customer and consultants to come up with a workable solution. The customer can add extra features to their kitchen, bathroom and external living area, as well as upgrading standard items such as windows and doors. Builder then performs the construction activities on site and assembles the selected modules to complete the house. Two examples from Swedish construction companies of the application of the ATO strategy are demonstrated in a study by Höök and Stehn (2008). In the first example, the strategy was employed in the construction of official and commercial buildings. The second example targets the development of standard modules for multifamily dwellings and students' lodgings. Both companies have an emphasis on encouraging their customers to select building designs within their existing catalogues. Another example of the ATO strategy from UK builders is provided by Pan and Goodier (2012). The claim is made that classic private builders offer their customers alterations to the house configuration based on the site and geographical area. The market winners in this strategy are house pricing, designs of house modules and completion time. It is suggested in the ATO strategy that the lean approach is employed within off-site factories, while the agile approach is employed at the shipment and on-site construction stages to ensure more responsiveness in delivering completed houses.

Design-to-order strategy

In the design-to-order (DTO) strategy, the customer's order enters the value stream at the design stage. As a result, the customer contributes to the architectural and structural design of their building components in consultation with the design team for ensuring customer's expectations are met. The customer can specify design of their house modules, with flexibility to change predesigned modules to fit their needs. In Japan, about 75% of new detached houses are built on existing land owned by house owners. These new houses are designed based on the standard floor plan, but the house owner is provided with sufficient flexibility to achieve any degree of customization. An example of the Australian experience of applying the DTO strategy is provided by Blismas (2007). A construction procedure assimilated to the DTO strategy was chosen to build prep classrooms in Queensland. The design team was obliged to incorporate specific features in the modules. Thus, a mock-up and two prototypes were prepared before module production. The modules were then produced according to the approved design. The market winner in this strategy is high customization. Therefore, the building stages require a combination of the lean and agile approaches. The lean approach is suitable for supplying the materials and running the off-site factories while other related activities are in need of the agile approach.

SBH strategy

The SBH is the final strategy. According to the Victorian Building Authority (VBA), this strategy is called 'owner-builder' as the owner of the land takes responsibility for building works carried out on their land and is legally responsible for the project from start to finish (Victorian Building Authority 2017). This strategy is suitable for self-building a house where a homeowner is intimately involved in every aspect of the building. This strategy is developed based on a concept that is similar to both building and personal computer assembly (Naim and Barlow 2003). In Australia, houses are built by organizations that range in size from small to large. In 2009, the largest 100 builders commenced approximately 37% of all residential dwellings (Dalton et al. 2011). Of all residential dwellings, 63% were constructed either by small builders or in the form of SBHs. The State Government of Victoria (2013) introduced a *group self-building initiative* to support individuals to build their own houses. The group usually consists of 12 homes within an area or nearby. Each group of participants receives a bridging loan from the Director of Housing to purchase land and build their houses. The individual participants are responsible for hiring an architect for house design and builders to assist them with some on-site construction activities. Likewise, the SBHs model has been adopted in the UK housing sector where ∼20% of total housing supply is delivered by house owners with or without an outsourcing design-and-build (D&B) contract (Marshall et al. 2013). In the SBH strategy, the key role of building organizations is to supply house modules and components to the suppliers. Building organizations, therefore, should aim to produce housing assembly as simple as possible. These organizations should provide variable designs to meet different types of house need. The lean approach is suitable for running house modules factory while the agile approach is the best option for quick responses to the demands of SBH suppliers.

AHP model

In the current study, AHP approach began by constructing the model of the decision problem. The first level was set as the goal of the model. The second level consisted of the four selected criteria: (1) housing completion time; (2) house price; (3) house customization and (4) level of skilled labour. Each criterion was further subdivided into nine subcriteria. Two subcriteria under housing completion time were the number of houses under construction and the construction method, whereas the two subcriteria under house price were construction material and labour costs. Three subcriteria came under house customization, namely, house floor area, house location and façade width. The criterion, level of skilled labour, comprised two subcriteria: contractors and trades. The four leagile strategies were placed at the bottom level of the hierarchy as decision alternatives. After setting up all elements of the AHP model, as shown in Figure 2, the model was developed using Expert Choice© software.

Four leagile strategies

The imbalance between housing supply and demand is occurring in all Australian states and territories (COAG 2012; NHSC 2013). The *Housing 100 Report* for 2016–2017 presented Australia's 100 most active builders (HIA 2017). Their main housing activities contributed around 75% of housing supply for detached houses and multiunit apartments. The current study analysed the five top potential builders for supplying houses in five Australian states: Western Australia (WA), South Australia (SA), New South Wales (NSW), Victoria (VIC) and Queensland (QLD), as shown in Table 1.

These five selected potential builders were found to be capable of adopting the four leagile strategies. Their adopting capacity was enhanced by their

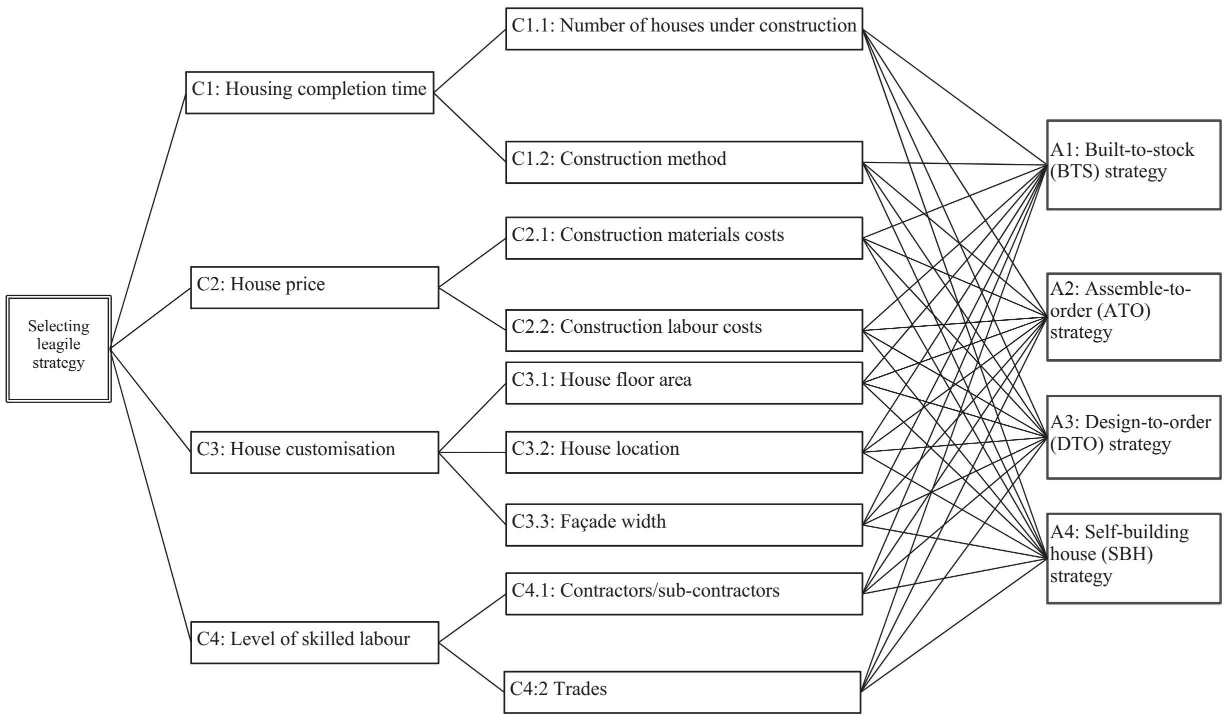

Figure 2. AHP model for selection of OSM strategies.

Table 1. Attributes of top five Australian house builders (HIA 2017).

HIA top 100: 2016–2017	Builder A 1st	Builder B 2nd	Builder C 3rd	Builder D 4th	Builder E 5th
State/s	WA	WA, VIC	SA, VIC, NSW, QLD	QLD, VIC, SA	VIC, SA, QLD
Building activity	Builder	Builder and developer	Builder	Builder and developer	Builder
House starts during 2013	3443	3199	2837	2432	1692
House market share	13%	12%	10.7%	9.2%	6.4%
Number of models	224	102	60	56	36

building work in the five states, their market share, their decision making and future trends (HIA 2011, 2017). Selecting a strategy would depend on the house market situation in Australia. House customers' demand is what shapes the housing market. Therefore, builders can respond to house market changes by adopting a suitable strategy. For example, builders might have to build houses with a small floor plan area that are less customized and with a median price affordable for Australian low-income groups (increase housing affordability). This combination could lead to the employment of one or more strategies proposed in this paper. The Australian medium-income groups might prefer to select house elements and design from the designs available in builders' catalogues. In this case, a suitable strategy would need to be carefully determined. Customers would be able to change the house design to fit their needs; therefore, they are likely to be involved in designing all house elements. The four proposed leagile strategies thus could meet different customers' demands. These strategies would allow house builders to decide to tailor their building activities. The weightings of the criteria and subcriteria for each strategy were then performed through a comparison with a builder employing each strategy. The weighting criteria and subcriteria for the four strategies are presented in Table 2.

Pairwise comparisons

Pairwise comparisons were performed to associate the relationships between all elements at all levels of the AHP model. The four criteria were compared in relation to their importance to the goal. Under each criterion, the subcriteria were compared according to their importance to the criterion. All pairwise numerical comparisons were performed using Expert Choice© software. The scale developed by Saaty (1990) allows the comparison of each two elements in the hierarchy using verbal or numerical judgements: equally (i.e. has a weight of 1); moderately (i.e. has a weight of 3); strongly (i.e. has a weight of 5); very strongly (i.e. has a weight of 7) and extremely strongly (i.e. has a weight of 9). Intermediate values

Table 2. Weighting of leagile strategies for each criterion and subcriterion.

	A1: BTS	A2: ATO	A3: DTO	A4: SBH
C1: House customization	Low	Moderate	Very high	High
C1.1: House floor area	Small floor area	Small floor area	Larger floor area	Suitable for any floor area
C1.2: House location	Fixed location	Flexible location	More flexible location	Highly flexible location
C1.3: Façade options	Limited	Medium	Large	Moderate-high
C2: House price	Low price range	Moderate price range	High price range	Low-moderate price range
C2.1: Construction materials cost	Low	Medium	High	Low
C2.2: Labour cost	Low	Medium	High	Low
C3: Housing completion time	Short	Moderate	Long	Moderate-short
C3.1: Number of houses under construction	Few	Moderate	Many	Few
C3:2: Construction method	Favourable	Favourable	Neutral	Very favourable
C4: Skilled labour	Medium	Medium-high labour intensive	Medium-high labour intensive	Low
C4.1: Contractors/subcontractors	Medium contractor intensive	Medium-high contractor intensive	Medium-high contractors	Requires less contractor workforce
C4.2: Trades	Medium labour intensive	Medium-high trades	Medium-high trades	Requires less labour force

Note: ATO: assemble to order; BTS: built to stock; DTO: design to order; SBH: self-building house.

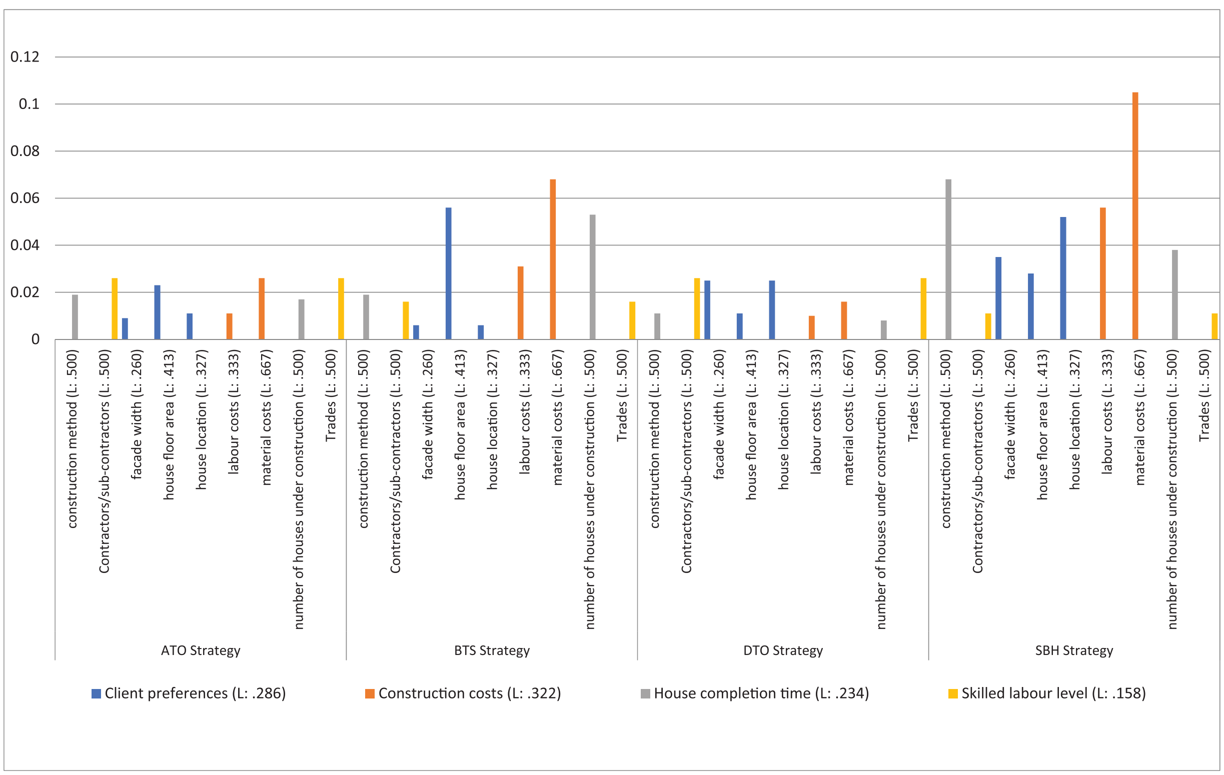

Figure 3. Weighting of the criteria, subcriteria and alternatives.

are used where appropriate ranging from equally to moderately (i.e. has a weight of 2); moderately to strongly (i.e. has a weight of 4); strongly to very strongly (i.e. has a weight of 6) and very strongly to extremely strongly (i.e. has a weight of 8) (Armacost et al. 1994; Darko et al. 2018). After completing the pairwise comparisons, all the priorities of the model were calculated, as shown in Figure 3.

As is evident from Figure 3, construction costs received the highest priority with 0.322, followed by customer preferences with 0.286, and then housing completion time with 0.234. The inconsistency index score of the judgements was found to be lower than 0.1, as required, when it was checked. Finally, the ranking of the four strategies was calculated in relation to the subcriteria under each criterion. The

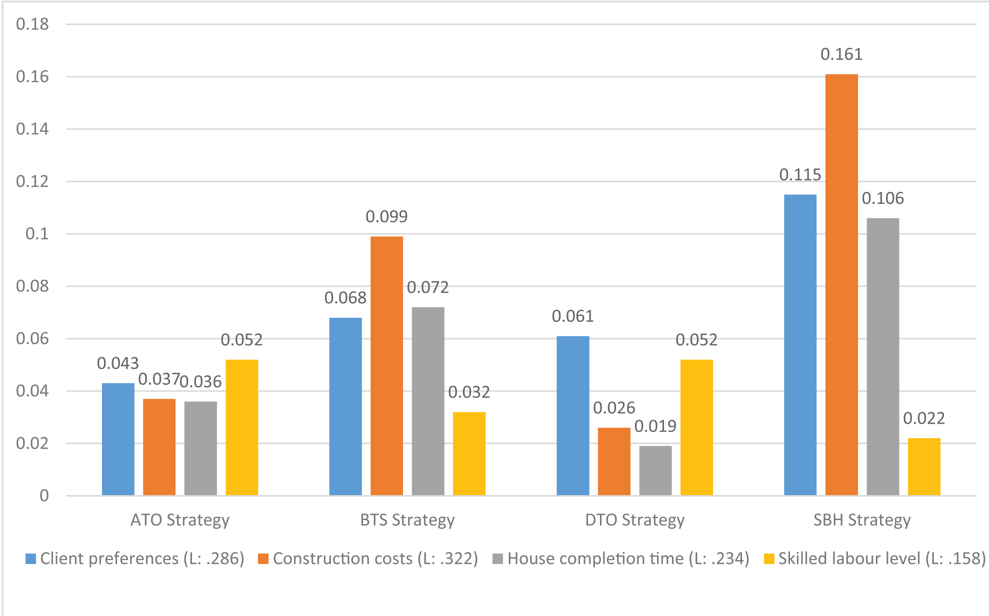

Figure 4. Overall priorities of the four leagile strategies in distributive model.

weightings of the subcriteria in each strategy were determined for each strategy adopted by the five builders (see Table 2).

Synthesis of the results

After determining the pairwise comparisons, local priorities were synthesized from the goal while overall priorities were calculated. The overall priorities of the four building strategies are displayed in Figure 4.

As shown in Figure 4, the SBH strategy was considered the best alternative, receiving the highest rating of 0.404. The second-best strategy was BTS which scored 0.271, followed by the ATO strategy with a score of 0.168, while the last strategy was DTO with a score of 0.157.

Sensitivity analyses

A series of sensitivity analyses was performed to examine the change results that occurred in the criteria priorities. A summary of the performance sensitivity of each building strategy interacting with the four factors is shown in Figure 5.

Overall, the SBH strategy was projected as the most appropriate strategy in relation to the four factors studied in this research. However, the SBH strategy did not perform as the best strategy at the individual criterion level (see Figure 5). The SBH strategy performed its best at the levels of customer preferences, housing completion time and construction cost factors while it was ranked last at the level of the construction skilled labour factor. Conversely, the DTO and ATO strategies individually performed their best at the level of contractors and trades factors.

Main criteria for strategy selection

The priorities of importance for the criteria and subcriteria under each strategy are presented in Figures 4 and 5. The construction costs were the most important criterion with a score of 0.322 (32.2%). The second most important criterion was customer preferences which consisted of the following subcriteria: façade width, house floor area and house location and obtained the highest score for importance of 0.286 (28.6%). Housing completion time was projected to be the third most important criterion with a score of 0.234 (23.4%). Thus, it can be concluded that house customization and house price were the most significant criteria for strategy selection according to data obtained in this research from five major builders in Australia. The study's results provide clear insights on the factors affecting Australian housing delivery which could have implications for decision making by house builders based on house customers' demand. Housing completion time, house customization and house price are directly affected by the builder's strategy for completing a house. The adoption of the four leagile strategies would support the uptake of OSM and enhance house delivery.

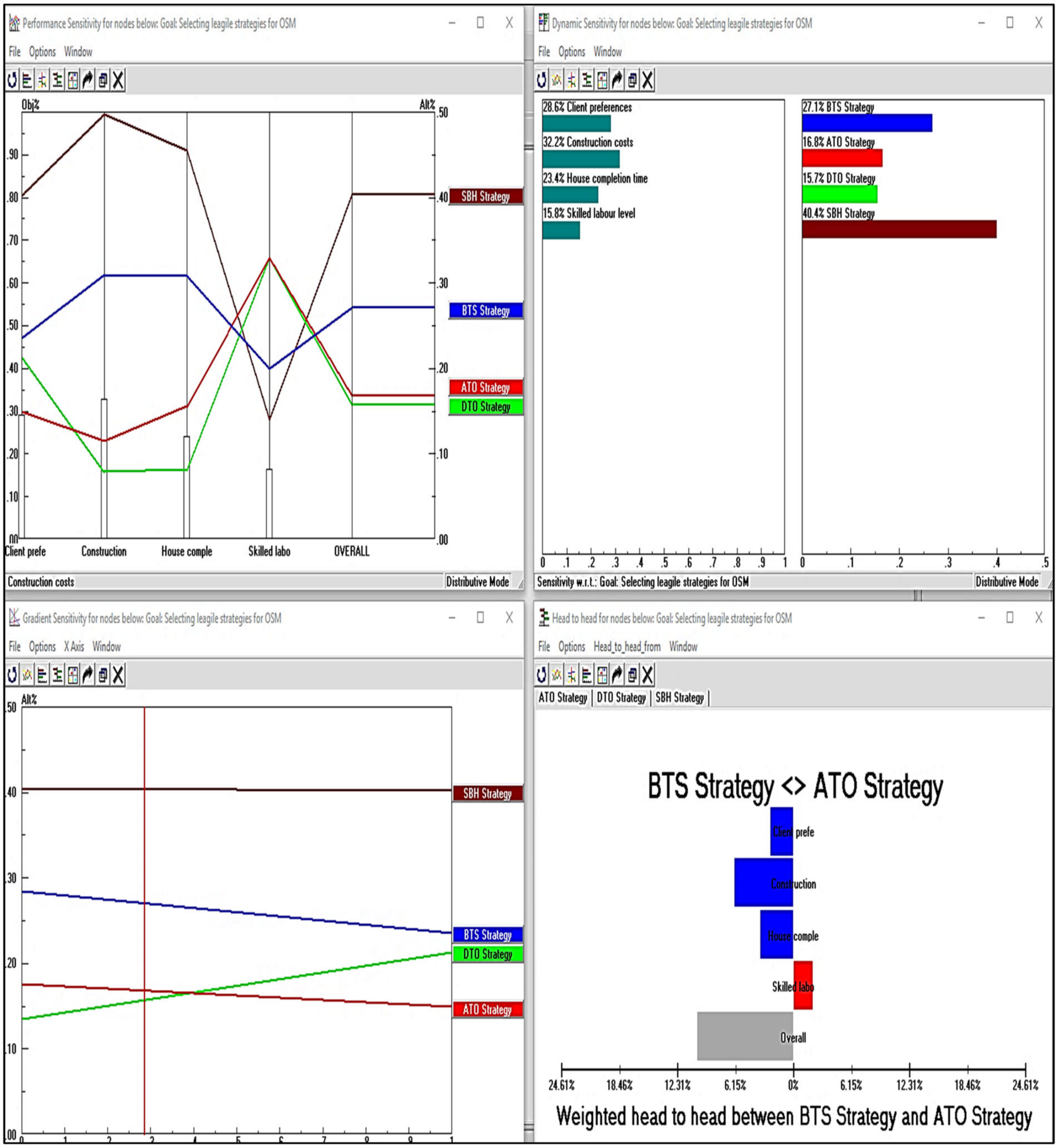

Figure 5. Sensitivity analyses of the four strategies with respect to the four criteria.

Implications of the model

The results from examining the AHP model indicated that the SBH strategy performed the most effectively in relation to the four factors. The SBH and BTS strategies could be suggested to Australian house builders and decision makers based on the current study's results with these strategies the most suitable for different combinations of the four factors. Furthermore, the results of the scenario demonstration are supported by Dalton et al. (2013) who found that 63% of Australian residential dwellings in 2009 were constructed by small builders or using the SBH (owner-builder) approach. According to the case study from the State Government of Victoria, as presented earlier in this paper, a *group self-building initiative* was introduced to support individuals building their own houses. A key role of OSM manufacturers in Australia is to supply a variety of building modules/components to suppliers so OSM can meet different types of building needs. The SBH and BTS strategies are appropriate in decreasing construction costs which enhances housing affordability for low-income and medium-income Australians. According to the current research results, the BTS strategy ranked second overall among the alternatives. This strategy could be used for volume building projects where builders have to complete the project within the contract time frame. Nevertheless, this research has shown that the BTS strategy was the last alternative for house customization. The reason for this drawback is that in the BTS strategy, builders predesign, manufacture and assemble the components/modules based on their catalogues.

Conclusions

The Australian residential building sector is experiencing continuous growth and unmet housing demand. Customer preferences, construction cost, completion time and level of skilled labour add more complexities to design specifications. Furthermore, customer demands are ambiguous and change dynamically. The four leagile strategies proposed in this paper could answer the different demand situations and balance the trade-off between builders and customers. This study developed a multicriteria decision-making (MCDM) model which incorporates both factors and strategies. The MCDM model is intended to facilitate the decision-making process for determing the appropriate strategy under different combinations of factors. The study used the AHP method to study the association between the strategies and factors using data collected from 13 interview participants. The results demonstrated that SBH (40.4%) and BTS (27.1%) are the most appropriate strategies across the four factor combinations. The results also revealed that the most influential criteria for builders' strategy selection were construction costs (32.2%) and customer preferences (28.6%). In future research, additional builders and housing undersupply factors could be added to the model developed in the current study. This may include other factors such as coordination and scheduling between stakeholders, land supply and demographic factors (e.g. economic circumstances of households, number of overseas migrants, etc.). The current study reports its findings in the Australian context; therefore, future research could employ case studies and, furthermore, could be conducted in other contexts to enhance the generalisability of the findings of the current research.

ORCID

Sherif Mostafa http://orcid.org/0000-0002-5708-3770

References

ABS (Australian Bureau of Statistics). 2010. A statistical overview of the construction industry. Australian economic indicators. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1350.0Feature+Article1Oct +2010

AFTS (Australia's Future Tax System). 2010. Australia's future tax system: Report to the Treasurer. Canberra, ACT (AU): Australian Government..

Agarwal A, Shankar R, Tiwari MK. 2007. Modeling agility of supply chain. Ind Market Manage. 36(4):443–457.

Arashpour M, Wakefield R, Blismas N, Minas J. 2015. Optimization of process integration and multi-skilled resource utilization in off-site construction. Automat Constr. 50(0):72–80.

Armacost RL, Componation PJ, Mullens MA, Swart WW. 1994. An AHP framework for prioritizing customer requirements in QFD: an industrialized housing. IIE Trans. 26(4):72–79.

Barlow J, Ozaki R. 2005. Building mass customised housing through innovation in the production system: lessons from Japan. Environ Plan A. 37(1):9–20.

Blismas N. 2007. Off-site manufacture in Australia: Current state and future directions. Brisbane (QLD): Cooperative Research Centre for Construction Innovation.

Blismas N, Wakefield R. 2009. Drivers, constraints and the future of offsite manufacture in Australia. Constr Innov: Inf, Process, Manage. 9(1):72–83.

Chang AS, Lee KP. 2004. Nature of construction technology. Paper presented at the Proceedings of the 12th Annual Conference of the International Group for Lean Construction (IGLC), Elsinore (DK).

Childerhouse P, Hong-Minh SM, Naim MM. 2000. House building supply chain strategies: selecting the right strategy to meet customer requirements. Paper presented at the Proceedings of the 8th Annual Conference of the International Group for Lean Construction (IGLC), Brighton (UK).

Christopher M, Towill DR. 2000. Supply chain migration from lean and functional to agile and customised. Supp Chain Manage. 5(4):206–213.

COAG (Council of Australian Governments). 2012. Housing Supply and Affordability Reform. Canberra, ACT (AU).

Dalton T, Hurley J, Gharaie E, Wakefield R, Horne R. 2013. Australian suburban house building: Industry organisation, practices and constraints . Melbourne, Australia: Australian Housing and Urban Research Institute [AHURI]. Final Report; No. 213.

Dalton T, Wakefield R, Horne R. 2011. Australian suburban house building: industry organisation, practices and constraints (1834-9250). Canberra, ACT (AU): Australian Housing and Urban Research Institute.

Daly G. 2009. Prefabricated housing Australia: skill deficiencies and workplace practice. Melbourne. [accessed 2018 May 20]. http://scholar.googleusercontent.com/scholar?q=cache:MglkXg-dQ9UJ:scholar.google.com/+Prefabricated+housing+in+Australia.+Skill+deficiencies+and+workplace+practice,%E2%80%9D+International+Specialised+Skills+Institute+Report,+2009&hl=en&as_sdt =0,5

Daneshgari P. 2009. Agile construction: impact of project resource management on profits. IEC Insights. 10–12.

Daneshgari P. 2010. Agile construction for the electrical contractor. Sudbury (MA): Jones and Bartlett Publishers.

Darko A, Chan APC, Ameyaw EE, Owusu EK, Pärn E, Edwards DJ. 2018. Review of application of analytic hierarchy process (AHP) in construction. Int J Constr Manage. 1–17.

DEEWR (Department of Education, Employment and Workplace Relations). 2012. Skill shortages in construction trades 2012. Canberra, ACT (AU): Department of Education.

Doloi H. 2008. Application of AHP in improving construction productivity from a management perspective. Constr Manage Econ. 26(8):841–854.

Elmualim A, Mostafa S, Chileshe N, Rameezdeen R, London K. 2018. Construction and the circular economy: smart and industrialized prefabrication. In: Crocker R, Saint C, Chen G, Tong Y, editors. Unmaking waste in production and consumption: towards the circular economy. UK: Emerald; p. 313–326.

Elnaas H, Gidado K, Ashton P. 2014. Factors and drivers effecting the decision of using off-site manufacturing (OSM) systems in house building industry. J Eng Project, Prod Manage. 4(1):51–58.

Fox R, Finlay R. 2013. Dwelling prices and household income. [accessed 2018 Apr 25]. http://www.rba.gov.au/publications/bulletin/2012/dec/2.html

Gharaie E. 2011. House completion time in Australia: workflow planning approach [Thesis for Doctor of Philosophy]. Melbourne (AU): RMIT University.

Gharaie E, Blismas N, Wakefield R. 2012. Little's Law for the US house building industry. Paper presented at the Proceedings for the 20th Annual Conference of the International Group for Lean Construction (IGLC). San Diego (CA).

Gharaie E, Wakefield R, Blismas N. 2010. Explaining the increase in the Australian average house completion time: activity-based versus workflow-based approach. Aust J Constr Econ Build. 10(4):34–49.

Hampson KD, Brandon P. 2004. Construction 2020 – A Vision for Australia's Property and Construction Industry. Brisbane (QLD): CRC Construction Innovation.

HIA (Housing Industry Association). 2011. Housing to 2020: The states of Australian housing to the year 2020. Avaiable from: HIA?JELD-WEN; http://economics.hia.com.au.

HIA (Housing Industry Association). 2013. Housing 100: Australia's Largest Homebuilders and Residential Developers 2012/2013. Campbell, ACT.

HIA (Housing Industry Association). 2017. Housing 100: Australia's Largest Homebuilders and Residential Developers 2016/2017. Campbell, ACT.

Höök M, Stehn L. 2008. Applicability of lean principles and practices in industrialized housing production. Constr Manage Econ. 26(10):1091–1100.

Koskela L. 1992. Application of the new production philosophy to construction. California (CA): Stanford university Stanford.

Lee S. 2003. Agile Report 'The Agile Peformance Improvement Database: A tool to improve construction performance'. [place unknown]: University of Bath. http://www.bath.ac.uk/management/larg_agile/publications/pdf/public/01.010.300.pdf

Liu J, London K. 2011. Analysing the relationship between new housing supply and residential construction costs with regional heterogeneities. Aust J Constr Econ Build. 11(3):58–67.

London K, Siva J. 2011. Housing supply chain model for innovation. Research Report. Melbourne, Victoria.

Manley K, McKell S, Rose T. 2009. Innovative practices in the Australian built environment sector: An information resource for industry. Brisbane (QLD). http://eprints.qut.edu.au/27818/

Marshall D, Worthing D, Dann N, Heath R. 2013. The construction of houses. 5th ed. Oxon: Routledge.

Mostafa S, Chileshe N. 2017. Application of discrete-event simulation to investigate effects of client order behaviour on off-site manufacturing performance in Australia. Architectural Eng Des Manage. 14:1–2, 139–157.

Mostafa S, Chileshe N, Abdelhamid T. 2016. Lean and agile integration within offsite construction using discrete event simulation. Constr Innov. 16(4):483–525.

Mostafa S, Chileshe N, Zuo J. 2014a. Enhancing Australian housing affordability: Off-site manufacturing supply chain strategies. Paper presented at the Proceedings of the 22nd Annual Conference of the International Group for Lean Construction (IGLC); Jun 25–27. Oslo (NO).

Mostafa S, Chileshe N, Zuo J. 2014b. A synergistic supply chain enhancing offsite manufacturing uptake in Australian house building. Paper presented at the Proceedings of the 30th Annual Association of Research in Construction Management (ARCOM) Conference; Sept 1–3. Portsmouth (UK).

Mostafa S, Dumrak J, Soltan H. 2013. A framework for lean manufacturing implementation. Prod Manuf Res. 1(1):44–64.

Naim M, Barlow J. 2003. An innovative supply chain strategy for customized housing. Constr Manage Econ. 21(6):593–602.

Naim M, Naylor J, Barlow J. 1999. Developing lean and agile supply chains in the UK housebuilding industry. Paper presented at the Proceedings of the 7th Annual Conference of the International Group for Lean Construction (IGLC). Berkeley (CA).

NHSC (National Housing Supply Council). 2013. Housing supply and affordability issues 2012-13. Canberra.

Pan W, Goodier C. 2011. House-building business models and off-site construction take-up. J Archit Eng. 18(2):84–93.

Pan W, Goodier C. 2012. House-building business models and off-site construction take-up. J Archit Eng. 18(2):84–93.

Pasquire C. 2012. Positioning Lean within an exploration of engineering construction. Cons Manage Econ. 30(8):673–685.

PATH (Partnership for Advancing Technology in Housing). 2002. Technology roadmap: Whole house and building process redesign. One Year Progress Report. Washington DC, USA.

PATH (Partnership for Advancing Technologies in Housing). 2003. Technology roadmapping for manufactured housing, Manufactured Housing Research Alliance (MHRA). Washington, DC, USA.

Purvis L, Gosling J, Naim MM. 2014. The development of a lean, agile and leagile supply network taxonomy based on differing types of flexibility. Int J Prod Econ. 151:100–111.

Russell K, Kanjanabootra S, Ouyang C, Wynn MT. 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. Paper presented at the 16th Pacific Association of Quantity Surveyors Congress – Innovation and Sustaining: Challenges and Opportunities, Darussalam, Brunei.

Saaty TL. 1990. How to make a decision: the analytic hierarchy process. Eur J Oper Res. 48(1):9–26.

Sharifi H, Zhang Z. 1999. A methodology for achieving agility in manufacturing organisations: An introduction. Int J Prod Econ. 62(1):7–22.

State Government of Victoria. 2013. Group Self Build, Housing and Community Building. Housing & Community Building: Finance & Business Services. [accessed 2015 Jul 4]. http://www.dhs.vic.gov.au/for-individuals/housing-and-accommodation/home-owner-support/group-self-build

Tam VWY, Hao JJL. 2014. Prefabrication as a means of minimizing construction waste on site. Int J Constr Manage. 14(2):113–121.

The Urban Developer. 2018. House Prices in Australian Cities Less Positive in 2018: SQM. [accessed 2018 May 8]. https://theurban developer.com/articles/house-prices-in-australian-cities-less-positive-in-2018-sqm-?utm_medium-=email&utm_campaign=090518%20QLD&utm_content=090518%20QLD+CID_0ce17ffa2d74b7460e8e5729123988cd&utm_source=email &utm_term=House%20Prices%20in%20Australian%20Cities%20Less%20Positive%20in%202018%20SQM

Victorian Building Authority. 2017. Owner-builder information & study guide. Victoria (AU): Victorian State Government.

Vidalakis C, Tookey JE, Sommerville J. 2013. Demand uncertainty in construction supply chains: a discrete event simulation study. J Oper Res Soc. 64(8):1194–1204.

Wang Q, Pan S. 2012. On influence factors of Wuhan Housing Industry based on the AHP. Syst Eng Proc. 3:158–165.

Zhai X, Reed R, Mills A. 2014a. Addressing sustainable challenges in China. Smart Sustain Built Environ. 3(3):261–274.

Zhai X, Reed R, Mills A. 2014b. Factors impeding the off-site production of housing construction in China: an investigation of current practice. Constr Manage Econ. 32(1–2):40–52.