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Critical review of the research on the management of prefabricated construction

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ABSTRACT

As a sustainable construction method, prefabricated construction is increasingly being adopted worldwide to enhance productivity and to alleviate the adverse environmental and social effects as a result of conventional construction activities. In addressing management issues of prefabricated construction, an impressive number of studies have been published by internationally renowned journals related to construction management over the past decades. However, it seems that a systematic summary on the research development in the management of prefabricated construction (MPC) discipline is lacking. Therefore, this paper examines the latest research trend in this discipline by analyzing published construction management research in 10 leading journals during the period from 2000 to 2013 (as of end of June) in terms of the annual number of MPC papers, contributions of institutions, adopted data collection and processing methods, and research interest. The analysis reveals that prefabrication is becoming increasingly important to the entire construction industry. Researchers from developed countries, including the US, the UK, Hong Kong, Sweden, and Australia, have made significant contributions to the development of the prefabrication domain, while those from developing countries, including China, Turkey, and Israel where construction remains as their main economic activity, have shown increasing interest in promoting prefabrication-related research. Major research topics in MPC include "industry prospect", "development and application", "performance evaluation", "environment for technology application", and "design, production, transportation and assembly strategies". Moreover, some innovative technologies, such as Global Position System (GPS), and Radio Frequency Identification (RFID), have been effectively applied in this field and are considered as strong vehicles in improving the performance of future prefabricated construction practices. This study is of value in helping scholars gain an in-depth understanding of the state-of-the-art of MPC research and allows them to continue from the findings of previous studies.

Introduction

The increasing recognition of the importance of prefabrication technology for productivity improvement and environmental conservation has resulted in an impressive number of studies on management of prefabricated construction (MPC) in academic journals worldwide. Based on the literature review, the academic interests toward this domain are increasing, but the content analysis of existing literature appears insufficient, preventing researchers from capturing an overall picture of the research evolution of the field. A systematic classification and integration of previous publications on prefabricated construction can significantly contribute to a comprehensive understanding on the topic and inspired the examination of MPC by subsequent researchers (Tang, Shen, & Cheng, 2010; Yang, Shen, & Ho, 2009).

The research community, particularly new researchers, widely regards literature review as a key methodology in examining the development of research on a specific discipline. For example, Xue, Shen, and Ren (2010) carried out a content analysis of publications in selected journals collaborating with construction projects and found the lack of systematic theoretical framework in measuring the performance of these collaborations. Ortiz, Castells, and Sonnemann (2009) examined sustainability development in the construction industry by compiling and studying the key

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milestones in life cycle assessment and stated that further research should focus on the development of sustainability indicators in design, construction, operations, and dismantling to target global environmental and energy concerns. Hong, Chan, Chan, and Yeung (2011) conducted a critical analysis on the collaborative research trend in construction journals and suggested the expansion of the analysis to cover the entire construction supply chain as a key research interest. Tsai and Lydia Wen (2005) and Flanagan, Lu, Shen, and Jewell (2007) stated that these systematic research reviews do not only assist researchers in gaining in-depth insights on the-advancement of a chosen research field, averting the duplication of research efforts, but also help them explore new and valuable research topics for further research.

Despite the significance of a research review, no such work has been undertaken in the field of MPC. Therefore, this paper conducts a series of content analysis of academic articles published from 2000 to 2013 (as of end of June), including examination on the current status and prediction on future research trends. The objectives of this study are: (1) to determine the coverage of MPC-related academic articles published in 10 top-tier journals; (2) to identify which countries and institutions were the primary contributors to MPC research; (3) to examine the primary methods for data collection and processing employed in MPC research; and (4) to analyze the evolution of research theme evolve and explore the future research direction of this topic.

Background of MPC

Prefabrication is a manufacturing process that takes place in a specialized facility where various materials are joined together to form a component of the final installation procedure (Sparksman, Groak, Gibb, & Neale, 1999). In the construction field, prefabrication is regarded as the first level of industrialization, which is followed by mechanization, automation, robotics, and reproduction (Richard, 2005). Previous studies had used various terms and acronyms that are associated with prefabricated construction, including off-site prefabrication, precast concrete building (Kale & Arditi, 2006), off-site construction (Pan, Gibb, & Dainty, 2008), industrialized building (Jonsson & Rudberg, 2013; Meiling, Sandberg, & Johnsson, 2013), and modern methods of construction (Goodier & Gibb, 2007), to name a few. Prefabricated construction can generally be categorized into the following four levels based on the degree of prefabrication implemented on the product: (1) component manufacturing and sub-assembly that are always done in a factory and not considered for on-site production, (2) non-volumetric pre-assembly that refers to pre-assembled units not enclosing usable space such as timber roof trusses, (3) volumetric pre-assembly that refers to pre-assembled units enclosing usable space and usually being manufactured inside factories but do not form a part of the building's structure such as the toilet and bathroom, and (4) whole buildings that refer to pre-assembled volumetric units forming the actual structure and fabric of the building such as motel rooms (Gibb, 1999; Goodier & Gibb, 2007). Prefabricated construction, as a modern construction technology replacing conventional cast-in-situ concrete construction, has attracted immense attention from many countries over the past two decades. This widespread interest can be largely explained by the inherent superiority of the technology, including, but not limited to, construction waste reduction (Baldwin, Poon, Shen, Austin, & Wong, 2009; Tam, Tam, Chan, & Ng, 2006; Tam, Tam, Zeng, & Ng, 2007), improved quality control (Jaillon & Poon, 2008), noise and dust reduction (Pons & Wadel, 2011), higher standards for health and safety (Lopez-Mesa, Pitarch, Tomas, & Gallego, 2009; Pons & Wadel, 2011), time and cost savings (Chiang, Hon-Wan Chan, & Ka-Leung Lok, 2006; Gibb & Isack, 2003), reduced labor demand (Nadim & Goulding, 2010), and low resource depletion (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012; Won, Na, Kim, & Kim, 2013).

Despite the inherent superiority of prefabrication, the implementation of MPC has produced many problems, from the precast design and component production to product stockyard layout, transportation, and assembly. Jaillon and Poon (2010) revealed that only a few studies had been conducted on the design concept to promote the reuse of prefabricated buildings at the end of their life cycle. Marasini, Dawood, and Hobbs (2001) stated that due to insufficient stockyard space management by stockyard managers and ineffective technologies in selecting suitable locations for product stocks and in tracing them for dispatch, prefabricated elements are often exposed on the yard. Li et al. (2011) indicated that safety should be emphasized during the assembly of prefabricated elements because many of these elements are bulky and heavy and can potentially harm the assembly. The defects and obstacles in applying the prefabricated construction method have also been sufficiently addressed in previous research. Vertical transportation has been identified as an issue because the prefabricated modules are generally heavy and bulky. Tam (2003) interpreted in his study that the concreting of floors will likely extend from four days to six days if the prefabricated elements are used because the vertical transportation of prefabricated components from one floor to another is more time-consuming than that in conventional construction. Labor retraining is also identified as another issue because the in-situ and cast concrete construction are by nature different from prefabrication, which requires machine-oriented skills both on-site and in the manufacturing process (Chiang et al., 2006). Other studies identified the relatively high construction cost of precast technologies as a main hindrance to the promotion of prefabricated construction (Blismas & Wakefield, 2007; Pan, Gibb, & Sellars, 2008; Pan & Sidwell, 2011).

Problems have emerged from prefabrication application, necessitating a systematical review analysis of existing literature within the research scope. This review can largely help researchers by providing details on the current problem and by identifying future research directions for this discipline.

Research methodology

Selecting target academic journals

The review methods of previous research (Ke, Wang, Chan, & Cheung, 2009; Tang et al., 2010; Xue et al., 2010) offer valuable guidance in the selection of target academic journals in the MPC research domain. Ke et al. (2009) stated that a research team might contribute their research achievements to a renowned journal from their specific field or that which has a similar research topic. Accordingly, the authors of this study used the Scopus search engine to identify the journals that have published the most research on MPC from 2000 to 2013. The most-searched keywords in this search engine included prefabrication, prefabricated construction/building, precast concrete, off-site construction, modular construction/building and industrialized building/housing. Articles containing these terms in the title/abstract/keywords were considered for review in this research. The search is further narrowed based on the subject fields of engineering, decision sciences, social sciences, management, and environment, and based on the document type of the article or review. However, a certain number of unwanted articles still show in the search results despite the rigorous search criteria. The authors of this research subsequently scanned each article from the search results to filter and retrieve MPC-related papers.

It is found that nine journals, namely, Construction Management and Economics (CME), Automation in Construction (AIC), Journal of Construction Engineering and Management (JCEM), Journal of Architectural Engineering (JAE), Construction Innovation (CI), Building Research and Information (BRI), Habitat International (HI), Energy and Building (EB), and Building and Environment (BE) have published at least four MPC-related articles from 2000 to 2013. Besides, Engineering, Construction, and Architectural Management (ECAM), one of top 10 journals ranked by Chau (1997), was considered after consulting peer reviewers in the research community. Therefore, a total of 10 academic journals were used in the review analysis of MPC literature. The selection of journals was based on two criteria, namely, (1) the journals should be mainstream journals (with a certain number of publications according to the Scopus database search results) in the area of prefabrication and (2) the journals should either be ranked by Chau (1997) as one of the top 10 journals in the construction management field or acknowledged as a first-tier journal by peer reviewers who specialize in prefabrication.

Assessing the contribution

To gain an in-depth understanding of the main research stream in this domain, the contribution of each researcher, country, or institution is quantitatively assessed and analyzed by adopting the approach of Al-Sharif and Kaka (2004), in which the published articles of each researcher during a specific period and within a specific research field are counted. This method identifies the top contributors to a particular research field, which enables researchers to trace the achievements of previous contributors and assists them in advancing the study from its findings.

The quantitative evaluation of an author's contribution in a multi-authored article is a conventional research topic that has attracted a large amount of interest from various research domains. At the beginning of a collaborative research, the contributions of each author are assumed to be even, which means that each author is regarded as an owner of a research regardless of how many authors have collaborated in a multi-authored article. This method has been improved by Howard et al., who suggested the discriminative assessment of an author's contribution by assuming that the former author has made a bigger contribution than succeeding authors (Howard, Cole, & Maxwell, 1987). This assumption has been accepted in many studies that examine the research productivity of authors. Howard et al. (1987) also presented the following formula to explain their method in detail:

$$\text{Score} = \frac{1.5^{n-i}}{\sum_{i=1}^{n} 1.5^{n-i}}$$

where n is the total number of authors of the article and i is the ordinal position of the author of the article. Each paper is assumed to have a score of one point. A detailed score matrix that is obtained based on the formula is displayed in Table 1. Based on the matrix, in a paper with two authors, the first author is given a score of 0.60, while the second author is given 0.40. However, the ordinal position of the author may not invariably reflect the actual contribution difference because in exceptional circumstances, the chief author leaves the first ordinal position to the other authors. Therefore, to ensure the reliability of the evaluation, this research adopted another method that calculated the total number of citations in a particular article. This method is based on the assumption that the more citations a paper receives from other researchers, the higher contribution the authors provide to the research community. The results of both methods are discussed in the succeeding chapter.

Table 1
Score matrix for multi-author papers.

Number of authors	Order of specific author				
	1	2	3	4	5
1	1.00				
2	0.60	0.40			
3	0.47	0.32	0.21		
4	0.42	0.28	0.18	0.12	
5	0.38	0.26	0.17	0.11	0.08

Result analyses and discussions

Number of MPC-related papers

Table 2 presents the number of MPC-related articles that were published from 2000 to 2013. A total number of 12,653 articles were published in 10 selected journals within the specified period, among which 100 were found to address MPC-related issues. Although the MPC-related articles only comprised 0.79% of the total published articles, they demonstrated an increasing trend, from 1 to a maximum of 13 in 2012. This trend indicated the increasing amount of attention that the MPC discipline receives from researchers.

Table 2 shows that AC, CME, JCEM, and JAE journals published the highest number of MPC-related articles during the study period. AC published 21 MPC-related articles, followed by CME (19 articles), ACEM (14 articles), and JAE (12 articles). AC and CME have a higher ratio of published MPC articles than that of the other journals, indicating that these two journals have the most significant contribution to the MPC discipline. Moreover, the statistical data reveal that the average ratio of MPC-related publications is 0.79%, while their percentage in EB, BRI, and BE journals are 0.23%, 0.2%, and 0.1%, respectively, which are lower than the average level. This numerical difference may reflect, to some extent, the current research trend in which relatively fewer efforts are being exerted in exploring the roles of energy and environment in prefabrication, as EB, BRI, and BE journals mainly published articles on construction management issues from energy and environment perspectives.

Contribution of institutions and regions to the MPC publications

Table 3 shows an increasing trend in the number of authors from different regions, who exhibited interest in MPC research. The statistical data show that a total of 12 researchers had contributed at least three MPC-related articles, and 10 research centers were involved in the publication of more than three articles from 2000 to 2013. The Loughborough University in the UK contributed the most number of MPC-related publications (14 papers), followed by the Hong Kong Polytechnic University (11 papers), the Georgia Institute of Technology (7 papers), and the Luleå University of Technology (6 papers).

The research origins of the MPC publications, as presented in Table 4, are further examined along with the number of institutions, researchers, involved articles, and contribution scores for each country. Table 4 shows that the US is the biggest contributor to MPC research, involving up to 28 institutions and 43 researchers and achieving a total contribution score of 18.9 for the publication of 26 articles during the studied period. This finding is logical because the US is one of the first countries to suggest the development and implementation of industrialized construction. Five developed countries or regions, namely, the US, the UK, Hong Kong, Sweden, and Australia are responsible for 78% of the total selected publications. These nations are evidently the biggest contributors

Table 2
MPC related articles published during the period from 2000 to 2013 (as of end of June).

		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Target journals	Total	397	483	565	625	681	746	887	1075	964	977	1117	1297	1515	1324	12,653
	MPC	1	2	3	4	4	4	8	10	11	9	10	13	13	8	100
	Ratio (%)	0.25	0.41	0.53	0.64	0.59	0.54	0.90	0.93	1.14	0.92	0.90	1.00	0.86	0.60	0.79
AIC	Total	51	45	50	60	55	62	64	85	90	91	92	113	155	171	1184
	MPC	0	0	1	1	2	1	1	2	2	3	4	1	3	0	21
	Ratio (%)	0.00	0.00	2.00	1.67	3.64	1.61	1.56	2.35	2.22	3.30	4.35	0.88	1.94	0.00	1.77
CME	Total	38	48	61	73	92	99	122	118	105	100	103	96	85	28	1168
	MPC	0	1	0	0	0	2	1	2	4	1	2	2	0	4	19
	Ratio (%)	0.00	2.08	0.00	0.00	0.00	2.02	0.82	1.69	3.81	1.00	1.94	2.08	0.00	14.29	1.63
JCEM	Total	58	62	69	93	111	158	158	118	110	146	143	116	163	170	1675
	MPC	0	1	1	0	1	1	0	2	4	0	0	2	2	0	14
	Ratio (%)	0.00	1.61	1.45	0.00	0.90	0.63	0.00	1.69	3.64	0.00	0.00	1.72	1.23	0.00	0.84
JAE	Total	15	19	17	26	37	28	31	42	48	54	59	117	139	70	702
	MPC	1	0	1	0	1	0	0	0	0	0	1	4	3	1	12
	Ratio (%)	6.67	0.00	5.88	0.00	2.70	0.00	0.00	0.00	0.00	0.00	1.69	3.42	2.16	1.43	1.71
ECAM	Total	37	37	38	36	39	35	36	37	34	36	36	36	36	31	504
	MPC	0	0	0	2	0	0	0	0	1	0	2	1	1	0	7
	Ratio (%)	0.00	0.00	0.00	5.56	0.00	0.00	0.00	0.00	2.94	0.00	5.56	2.78	2.78	0.00	1.39
CI	Total	0	17	16	16	16	16	16	21	18	28	25	27	27	17	260
	MPC	0	0	0	0	0	0	1	1	0	3	1	1	3	0	10
	Ratio (%)	0.00	0.00	0.00	0.00	0.00	0.00	6.25	4.76	0.00	10.71	4.00	3.70	11.11	0.00	3.85
HI	Total	32	31	34	34	34	37	68	31	39	58	55	66	56	112	687
	MPC	0	0	0	0	0	0	3	1	0	1	0	1	0	0	6
	Ratio (%)	0.00	0.00	0.00	0.00	0.00	0.00	4.41	3.23	0.00	1.72	0.00	1.52	0.00	0.00	0.87
EB	Total	73	81	105	110	129	130	158	134	249	159	280	419	503	453	2983
	MPC	0	0	0	0	0	0	2	0	0	0	0	1	1	3	7
	Ratio (%)	0.00	0.00	0.00	0.00	0.00	0.00	1.27	0.00	0.00	0.00	0.00	0.24	0.20	0.66	0.23
BRI	Total	31	39	31	35	22	14	31	49	52	41	42	44	41	25	497
	MPC	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
	Ratio (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04	0.00	0.00	0.00	0.00	0.00	0.00	0.20
BE	Total	62	104	144	142	146	167	203	440	219	264	282	263	310	247	2993
	MPC	0	0	0	1	0	0	0	1	0	1	0	0	0	0	3
	Ratio (%)	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.23	0.00	0.38	0.00	0.00	0.00	0.00	0.10

to MPC research, which, to a large extent, indicates a limitation in the MPC domain, with existing publications not having a sufficient coverage of the perspectives from developing countries. Meanwhile, developing countries, such as China, Turkey, and Israel, have a comparatively low performance in promoting MPC research in terms of their construction industry scale, each with only five MPC-related articles contributed during the given period. Thus, China, Turkey, and Israel received relatively low contribution scores of 4.67, 2.52, and 1.93, respectively. This lag in the development of MPC research may be attributed to the fact that the adoption of prefabrication is still not being prioritized in these countries because of the relatively high cost and the complexity of the application, which is not yet fully understood.

The authors are suggested to refer to their sources when the unoriginal perspective is indicated, and a reasonable reference is viewed as an evidence for supporting their findings. Therefore, the citation index analysis, as an effective method for the evaluation of the contribution of a specific paper, is conducted in this study. Tables 5 and 6 display the most frequently cited articles and journals. Given the limitations of Scopus in its coverage of MPC-related publications, Google Scholar is used to extract the citation information of selected articles to ensure consistency and reliability of

Table 3
Research centers contributing to more than four papers.

Institution/university	Country	Researchers	Papers	Score
Loughborough University	UK	9	14	8.83
Hong Kong Polytechnic University	Hong Kong	24	11	10.55
Georgia Institute of Technology	USA	5	7	4.10
Luleå University of Technology	Sweden	10	6	5.53
University of Teesside	UK	4	5	4.40
Technion-Israel Institute of Technology	Israel	2	5	2.25
University of Plymouth	UK	2	5	3.14
National University of Singapore	Singapore	5	4	2.60
Istanbul Technical University	Turkey	4	4	3.07
The Pennsylvania State University	USA	4	3	1.85

Table 4
Research origin of MPC papers published.

Country	Institute/University	Researchers	Papers	Score
USA	28	43	26	18.90
UK	11	21	24	18.76
Hong Kong	3	25	13	11.59
Sweden	3	14	8	8.00
Australia	7	14	7	5.19
Turkey	4	8	5	4.67
China	5	6	5	2.52
Israel	1	2	5	1.93
Taiwan	3	11	4	4.00
Singapore	2	6	4	3.00
Korea	3	7	4	2.94
Malaysia	2	5	3	2.40
Spain	3	6	2	2.00
Germany	2	5	2	1.58
Egypt	1	1	2	1.20
Canada	2	2	1	2.70
Brazil	2	3	1	1.00
Italy	1	4	1	1.00
Portugal	2	4	1	1.00
Sri Lanka	1	2	1	1.00
Switzerland	1	2	1	1.00
Netherlands	1	2	1	1.00
Slovenia	1	2	1	1.00
Denmark	1	1	1	0.60
Thailand	1	1	1	0.60
Norway	1	1	1	0.42

Table 5
Most frequently cited papers.

Document title	Times
Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS (Ergen et al., 2007)	111
Parametric 3D modeling in building construction with examples from precast concrete (Sacks, Eastman, & Lee, 2004b)	103
Just-in-Time management of precast concrete components (Low & Chen, 2001)	64
Perspectives of UK housebuilders on the use of offsite modern methods of construction (Pan et al., 2007)	53
Toward adoption of prefabrication in construction (Tam, Tam, Zeng, et al., 2007)	53
Future opportunities for offsite in the UK (Goodier & Gibb, 2007)	52
Process model perspectives on management and engineering procedures in the precast/prestressed concrete industry (Sacks et al., 2004a)	44
Benchmark tests for BIM data exchanges of precast concrete (Jeong, Eastman, et al., 2009)	44
Numerical and experimental analyses of MPC containing sandwich panels for prefabricated walls (Carbonari, De Grassi, Di Perna, & Principi, 2006)	44
Differentiation of rural development driven by industrialization and urbanization in eastern coastal China (Long, Zou, & Liu, 2009)	43
Developing a precast production management system using RFID technology (Yin et al., 2009)	42
Learning to see work flow: an application of lean concepts to precast concrete fabrication (Ballard et al., 2003)	39
Leading UK housebuilders' utilization of offsite construction methods (Pan, Gibb, et al., 2008)	38
Sustainable performance criteria for construction method selection in concrete buildings (Chen, Okudan, & Riley, 2010)	38
Constraint programming approach to precast production scheduling (Chan & Hu, 2002)	37

the sources (Hong et al., 2011). The article by Ergen, Akinci, and Sacks (2007) from the Istanbul Technical University was identified as the most frequently cited paper, with citations of up to 111 times, followed by Sacks, Eastman, and Lee (2004a), Low and Chen (2001), Pan, Gibb, and Dainty (2007), and Tam, Tam, Zeng, et al. (2007) of 103, 64, 53 and 53 times, respectively. AC was the most frequently referred journal, reaching a maximum of 532 times, followed by CME (255 referrals) and JCEM (238 referrals). Regarding article citations, the articles in AC were the most cited (25.33 times per article), while those in JCEM, CME, and ECAM had been cited 13.42 to 18.14 times.

State of the art and future research trend in MPC discipline

To gain a comprehensive understanding of MPC, the selected academic articles were examined and further classified by performing two steps. First, the articles were sorted based on their data collection and analysis methods. Second, the number of MPC-related papers on different topics that were published each year within the studied period was determined. The results from this classification can also determine future research directions for this discipline.

Data collection and analysis methods

The classification results demonstrated that previous MPC-related studies significantly varied in terms of their data collection methods. Researchers usually collected their data in four ways, namely, (1) literature review, which is usually conducted to extract valuable data or conclusion from previous research, (2) survey, one of the main data collection methods in construction management, which is generally carried out via face-to-face interviews involving industry practitioners with or without the use of questionnaires, (3) case study in which the researcher describes a particular case in high detail by gaining firsthand understanding of one or more building projects, and (4) experiments, which are primarily adopted to conveniently and precisely control and manipulate variables (in this case, the physical properties of a prefabricated element). Table 7 shows the number of articles based on their data collection methods. Case studies and surveys are shown to be the primary methods in gathering data (accounting for 75% of the articles) in prefabrication research. This finding can be attributed to the nature of MPC as being immediately related to the specified context of the construction industry practice, which requires researchers to conduct in-depth investigations of the industry practice before forwarding valuable measures and recommendations.

Table 6
Most frequently cited journals.

Journal	Total times	Times per paper
Automation in Construction	532	25.33
Journal of Construction Engineering and Management	238	17.00
Construction Management and Economics	255	13.42
Engineering, Construction and Architectural Management	127	18.14
Habitat International	109	18.17
Building and Environment	85	28.33
Energy and Buildings	80	11.43
Journal of Architectural Engineering	66	5.50
Building Research & Information	38	38.00
Construction Innovation: Information, Process, Management	31	3.10

After the data collection, the authors adopted three data processing methods for information analysis, namely, (1) statistical analysis, (2) descriptive analysis, and (3) simulation/modeling. Table 7 shows the classification results of the data processing methods. Half of the selected articles adopted the simulation data analysis method. Twenty-seven papers used statistical analysis, and 25 papers used descriptive analysis. It is revealed from the classification results that, at the beginning of the studied period, researchers tend to adopt relatively ordinary methods, such as statistical and scenario analyses, to process information. Complex methods, such as Georgia Tech Process (Lee, Sacks, & Eastman, 2007), Radio Frequency Identification Technology and GPS (Ergen et al., 2007; Yin, Tserng, Wang, & Tsai, 2009), Building Information Modeling (Jeong, Eastman, Sacks, & Kaner, 2009; Sacks, Kaner, Eastman, & Jeong, 2010), and Dynamic Simulation (Pan, Chiu, & Chen, 2008), are gradually having increasing important roles in data processing in the MPC domain. The employment of these innovative systematic information technologies is expected to ease the complexities and dynamics of MPC simulation to reflect actual industry practice.

Research topics and future research directions

MPC-related journals have witnessed a sustainable growth over the previous decades. The MPC research domain is characterized for its diverse themes, from industry analysis to assembly strategy research. A content analysis tool named NVivo is adopted to derive the major research topics of this domain. All collected papers, called "sources", are imported into NVivo. The sources are then analyzed

Table 7
Data collection and analysis methods in publications.

Data collection method	Number of papers	Percentage
Literature review	16	16.0%
Survey	32	32.0%
Case study	43	43.0%
Experiment	9	9.0%

Data analysis method	Number of papers	Percentage
Descriptive statistics	25	25.0%
Statistical analysis	27	27.0%
Simulation/modeling	48	48.0%

by the "Node" function in the software. The references with similar theme are categorized into the corresponding node, which is called "coding". Take a paper regarding the economic evaluation of the use of prefabrication as an example, we can generate a node structure with two levels in which the first level is "performance evaluation", and the second level is "economic performance", such that the paper can be linked to the "economic performance" node. Notice that initial codes might be iteratively revised and refined throughout the coding process. By this way, this paper identifies five categories of research interests in MPC-related articles, namely, (1) industry prospect, (2) development and application, (3) performance evaluation, (4) environment for technology application, and (5) design, production, transport, and assembly strategies. Fig. 1 presents the structure of the research topics in the MPC discipline.

As shown in Table 8, significant research efforts have been devoted to design, production, transport and assembly strategies (28%), development and application (27%), and industry prospect (26%), while relatively less attention has been paid to performance evaluation (9%) and environment for technology application (10%). In examining the five identified research topics (each category has a series of sub-topics as shown under the specific topic), future research directions can be further derived based on what has been done and what remains to be done in the MPC domain, as presented in Fig. 2.

- **Industry prospect**: (1) benefits and incentives of prefabrication adoption (Tam, Tam, Zeng, et al., 2007), (2) defects and barriers in the application of the precast technology (Blismas & Wakefield, 2007; Polat, 2008), and (3) future opportunities for the precast industry (Nadim & Goulding, 2010; Song, Fagerlund, Haas, Tatum, & Vanegas, 2005).

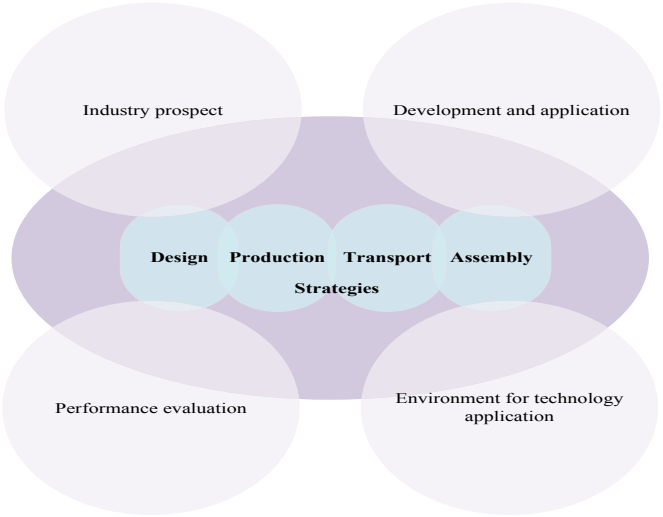

Fig. 1. The framework of research interests in the MPC discipline.

Literature on the first topic, "industry prospect", mainly focuses on factors that facilitate or inhibit the adoption of prefabrication technologies. Through an industry-wide survey, Tam, Tam, Zeng, et al. (2007) found that "better supervision", "reduced overall construction costs", and "shortened construction time" were the most essential advantages in adopting prefabrication. Through interviews and workshops, Blismas and Wakefield (2007) identified "a low level of knowledge", "negative sentiments from past failures", and "immense changes to existing processes" as major constraints to the success of an off-site manufacturing process. By analyzing the selected papers, many research efforts in MPC have been found to focus on developed economies such as the US (Ballard, Harper, & Zabelle, 2003), Australia (Blismas, Wakefield, & Hauser, 2010), Hong Kong (Poon, Ann, & Ng, 2003), and the UK (Arif & Egbu, 2010). These efforts significantly contributed to the increased performance of the entire construction industry in developed countries. In the 1950s and the 1960s, for example, after World War II, a number of prefabricated building systems, such as prefabricated beams, slabs, facade units, and vertical structural components, were extensively developed in Eastern and Western Europe to satisfy the massive demand for housing reconstruction (Warszawski, 2004). In Denmark, the highest precast level of 40% was recorded in 1996, after the implementation of the law on precast standardization, which aims to promote the adoption of prefabricated components (Jaillon & Poon, 2009). In the mid-1980s, Hong Kong began to introduce prefabrication along with standard modular designs in public housing projects (Mak, 1998). By 2002, prefabricated components accounted for approximately 17% of the volume of concrete products adopted in housing projects (Chiang et al., 2006). However, it is found that the similar SWOT (strengths, weakness, opportunities, and threats)-related analyses of the adoption of MPC lag behind those in some developing countries, such as China, India and Brazil, where there is a high demand for sustainable buildings as a result of rapid urbanization.

- **Development and application**: (1) case experiences analysis (Meiling et al., 2013; Tam, Tam, & Ng, 2007; Wang, Liu, Hsiang, & Leming, 2011) and (2) evolution of prefabricated building systems (Jaillon & Poon, 2009; Nahmens & Bindroo, 2011).

Regarding the second topic, "development and application", existing prefabricated construction practices were found to be mainly confined to the public sector, whereas private enterprises still heavily rely on cast-in-situ conventional construction methods, which involves the use of scaffolding, large amount of wet trades, timber formwork and in-situ concreting (Jaillon, Poon, & Chiang, 2009). Maas and van Eekelen (2004) differentiated a prefabricated government office building, which was constructed and transported over water, from a conventional building. By employing a dynamic simulation software program, N.-H. Pan, Chiu, et al. (2008) examined a high-speed railway project based on the overall production procedures in the planning of the precast yard, equipment capacity, production, transportation, and launching. Jaillon and Poon (2009) emphasized the limited availability of a comprehensive database on high-rise buildings, verifying the lack of data on the application of prefabrication in private enterprises. Studies by Girmscheid and Rinas (2012) were the only literature to examine the adoption of volumetric and modular prefabricated components in a conceptual residential building, which was never built. All these findings indicate a lack of research on the adoption of precast technologies in private enterprises and residential buildings. Future research should therefore be conducted to bridge

Table 8
Number of papers on different research topics.

Topic	Sub-topic				
Topic 1: industry prospect (26%)	Benefits and incentives of prefabrication adoption	Defects and barriers in the application of the precast technology		Future opportunities for the precast industry	
26	9	10		7	
Topic 2: development and application (27%)	Case experiences analysis	Evolution of prefabricated building systems			
27	20	7			
Topic 3: performance evaluation (9%)	Environmental performance	Economic performance	Social performance		
9	4	3	2		
Topic 4: environment for technology application (10%)	Guideline and policy	Attitude of various stakeholders	Public perspectives	Stakeholder relationships	
10	3	3	3	1	
Topic 5: design, production, transport and assembly strategies (28%)	Production control	Transportation and stockyard layout planning	Architectural design measures	Precast assembly technologies	Construction information flow processing
28	13	2	5	6	2

this research gap and to understand the evolution and application of prefabrication technology in residential buildings in private enterprises.

- **Performance evaluation**: (1) environmental performance (Aye et al., 2012; Lu & Yuan, 2013; Pons & Wadel, 2011), (2) economic performance (Pan, Dainty, & Gibb, 2012; Pan, Gibb, et al., 2008), and (3) social performance (Eastman & Sacks, 2008; Johnson, 2007).

The various benefits of the use of prefabrication comparing with traditional cast in-situ construction technologies have been identified by many researchers, including: (i) shorten construction period; (ii) less labor demand; (iii) better quality supervision on the construction progress; (iv) a greater potential for automation and intelligent management systems; (vi) better safety environment for workers on site; (vii) reduce overall construction cost and the time of return on investment. As stated by Tam, Tam, Zeng, et al. (2007), the promotion of the adoption of precast technologies will be only successful when various stakeholders earn their actual benefits. Nevertheless, it would appear that recent studies on "performance evaluation" have moved from "a conventional focus on cost–benefit analysis" to "a more extensive perspective of sustainability", which not only covers economic benefit, but also

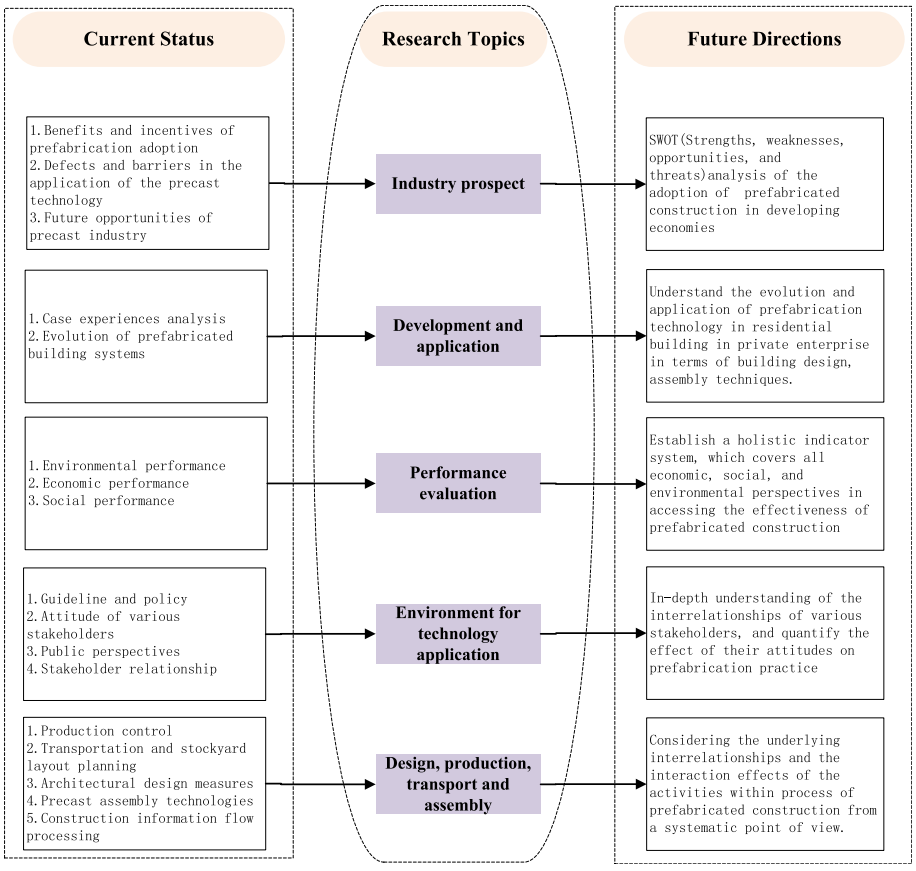

Fig. 2. Future research directions in the MPC discipline.

environmental and social effectiveness. For example, to determine the extent of quality improvement and reduction of environmental effect contributed by precast technologies, Pons and Wadel (2011) conducted a life cycle analysis to compare three main industrialized technologies that have been extensively applied in building school centers in Catalonia with a non-prefabricated one, from a technical and environmental point of view. López-Mesa et al. (2009) performed a contrastive analysis of residential buildings in Spain to verify if the environmental effect of a precast concrete floor is weaker than that of an in-situ cast floor. Aye et al. (2012) examined a multi-residential building to assess the potential environmental and social benefits of precast technologies in terms of reusability of materials, reducing the required space for landfill and the need for additional resource requirements. The review of the identified literature reveals that although the separate evaluation of the environmental and social effects of prefabrication is recently being conducted by research in this domain, existing literature should be further extended to establish a more holistic indicator system, which covers all economic, social, and environmental perspectives in assessing the effectiveness of prefabricated construction.

- **Environment for technology application**: (1) guideline and policy (Kale & Arditi, 2006), (2) attitude of various stakeholders (Pan et al., 2007), (3) public perspectives (Engström & Hedgren, 2012), and (4) stakeholder relationships (Jeong, Hastak, & Syal, 2009)

Regarding the third topic, "environment for technology application", following the report by Egan (1998), many studies had attempted to investigate the attitudes of stakeholders toward the application of prefabricated construction. The attitudes of developers, architects, contractors/producers, maintenance and operational staff may influence the application of innovative modern construction technologies in the development process because of the significant role they play in the decision-making process (Palmer, Jones, Coffey, & Blundell, 2003; Pan et al., 2007). A study by Edge et al. (2002) revealed that, owing to the strong negative influence of the post-war "precast", house purchasers will reject any innovations in the housing industry that will likely influence the structure of a conventional house. These obstacles that directly or indirectly result in the historical failure of prefabrication practices also exist among other stakeholders (Pan, Dainty, & Gibb, 2004). A few government-backed studies have explored the drivers and the obstacles of prefabrication application from a more extensive range of stakeholders' attitudes. A Housing Forum in the UK examined the obstacles in innovative construction methods that developers, architects, contractors, consultants and clients encounter on a daily basis in their organizations (Brown, 2002). These studies provide recommendations on the culture and the regulatory environment, in design and construction and encourage actions from the entire supply chain of prefabricated construction. However, although the contributions of previous studies had been acknowledged, the interrelationships among the different attitudes of stakeholders, as well as how the attitudes of industry practitioners influence the usage of precast technologies, have been slightly explored. Therefore, future research should develop approaches that can quantify the effect of stakeholders' attitudes toward prefabrication adoption.

- **Design, production, transport and assembly strategies**: (1) production control (Pan, Gibb, & Dainty, 2012; Yin et al., 2009), (2) transportation and stockyard layout planning (Chan & Lu, 2008; Marasini et al., 2001), (3) architectural design measures (Leskovar & Premrov, 2011), (4) precast assembly technologies (Manrique, Al-Hussein, Telyas, & Funston, 2007), and (5) construction information flow processing (Ergen & Akinci, 2008)

Regarding the fifth topic, "design, production, transport and assembly strategies", the monitoring and control of prefabricated construction processes, as well as their variables, are widely considered to have a strategic importance in responding to the dynamics of the building industry. Many monitoring processes focus on controlling time and cost, and the overall performance is evaluated through a standard set of key performance indicators (Fang & Ng, 2011; Shamsai, Whitlatch, & Sezen, 2007; Vukovic & Trivunic, 1994). These passive approaches do not consider a holistic/system view. Therefore, the interrelationships among various external and internal variables that affect a construction process are ignored (Marasini & Dawood, 2006). The entire management process of prefabricated construction is highly complex, in which its interrelated activities should be systematically analyzed and organized. Without considering the underlying interrelationships of these activities, this complexity cannot be better understood (Yuan & Shen, 2011). A number of researchers who had been aware of this significant feature had conducted relevant studies from a systematic point of view. By adopting the SIMPROCESS dynamic simulation software, N.-H. Pan, Chiu, et al. (2008) investigated the overall production procedures involved in the planning of precast yard, equipment capacity, production, transportation, and launching. To create the optimal or near-optimal combination of interactional production sequences, resource utilization, and minimum makespan, Leu and Hwang (2002) employed a genetic algorithm-based searching technique, while considering the resource constraints and the systematic mixed precast production. Despite the contributions of these studies, further research on the similar path should be conducted.

Conclusion

Prefabricated construction is becoming increasingly popular in the construction industry because of its potential in sustainable building. Along with the advancement of off-site construction, researchers across the world are actively reviewing the precast construction practice and suggest various measures for improvement. To gain an in-depth understanding on the research trend in this domain, this study conducts a systematic review of MPC-related articles that were published from 2000 to 2013 in nine academic journals, namely, CME, AIC, JCEM, JAE, ECAM, CI, BRI, HI, EB, and BE.

A total of 100 MPC-related articles were analyzed in this study. The annual number of published articles reflects the increasing trend in MPC research. Developed economies, such as the US, the UK, Hong Kong, Sweden, and Australia, are found to be main contributors in MPC research, with their publication of the most number of MPC-related studies. Developing countries, such as Turkey and China, are expected to increase their efforts in promoting MPC research, given the continuing prevalence of construction practices. Regarding academic communities, the Loughborough University, the Hong Kong Polytechnic University, and the Georgia Institute of Technology were identified as the three most productive institutions in MPC research.

Case study and survey were found to be the primary methods for data collection, whereas simulation/modeling was identified as the most popular method for data processing in the MPC field. More complex techniques, such as the Georgia Tech Process, Radio Frequency Identification Technology, and Building Information Modeling, are increasingly being implemented for data collection and processing. Five categories had been identified as major research interests of MPC publications, which include (1) industry prospect, (2) development and application, (3) performance

evaluation, (4) environment for technology application, and (5) design, production, transport, and assembly strategies. “Design, production, transport and assembly strategies” and “industry prospect” have been identified as the most dominant among these topics. Future research directions are identified based on the analysis of the current research status of MPC.

This study provides a critical overview of the MPC research development, which provides a valuable reference for both scholars and industry practitioners. This study helps scholars gain an in-depth understanding of the state-of-the-art of MPC research and allows them to continue from the findings of previous studies. This study can also benefit industry practitioners by providing them with effective methods in prefabricated construction practice. Furthermore, it should be noted that although the selected articles can reflect the overall trend of the MPC discipline, not all relevant studies are considered in this study. Some issues in the prefabricated construction practice are also not discussed because the objective of this research is to offer useful information on the current status and future directions of MPC research based on the information provided in previous literature.

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