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Integrating Building Information Modeling and Prefabrication Housing Production

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ABSTRACT

The decision-making system in Prefabrication Housing Production (PHP) lacks efficiency and collaboration because relevant information is stored and managed in heterogeneous systems of various stakeholders, who are commonly geographically isolated. Building Information Modeling (BIM) has advantages of combining its object-oriented attributes and the production-oriented characteristics of PHP to support decision-making and collaborative working for raising working efficiency. Given the emerging recognition of BIM and PHP, an integrated conceptual framework based on existing studies is needed in order to facilitate their recognition and guide future research. Based on a critical review of 65 papers published in the peer-reviewed journals from 2005 to 2017, a conceptual framework is proposed for the integration of BIM and PHP. The framework involves three pillars, including smart BIM platform (SBP), smart work packages (SWPs), and smart PHP objects (SPOs). A gateway with interoperability function is created between the three pillars to facilitate the communication and interaction with the central database. The results can help develop the system architecture of BIM and PHP, which can then be used to benefit various stakeholders to facilitate the integration.

1. Introduction

The construction industry faces challenges such as low productivity, high construction safety risk, and poor environmental performance [1]. As reported by Bock and Linner [2], these problems are associated with the relatively slow adoption and integration of advanced information technologies and industrialization principles such as mechanization, automation, robotics, standardization, modularization, and information-driven construction. Prefabrication Housing Production (PHP), as an innovative solution in the construction industry, uses the principles of industrialization in the lifecycle of construction projects, including design, manufacturing, transportation, on-site assembly, maintenance, and deconstruction stages [3]. The benefits of PHP have been addressed in many studies. For example, PHP can provide an agile production with reduced cost when compared to the conventional site-built construction [4]. It can also provide a safer and more sustainable construction environment through strategies such as improving the quality through the trial and testing of products in controlled factories using consistent standards [5]. Furthermore, widespread adoption of PHP in densely populated regions, such as Hong Kong, can efficiently help mitigate the unbalanced housing supply and demand. According to the Housing Authority of Hong Kong [6], the average waiting time of public housing for general applicants was 5.3 years in Hong Kong. PHP has, therefore, become a popular solution for construction projects such as high-rise public housing in Hong Kong [7].

However, it should be noted that many PHP projects involve various stakeholders who store, retrieve and manage information on their own isolated systems [8]. As such, information fragmentation is considered as a critical issue that may impede a higher level of collaboration and more efficient decision-making in PHP projects [3]. In Hong Kong, the issue of information fragmentation is amplified when the manufacturing work of PHP has been completely shifted offshore, e.g., to the Great Bay Area (GBA) of Mainland China. Recently, there have been many studies on how to improve collaboration and efficiency in PHP by providing the right formatted information at the right time to the right location, through the integration of Building Information Modeling (BIM) and sensing and tracking technologies [9–11]. The U.S. National BIM Standard [12] defined BIM as a term with three linked functions,

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including Building Information Modeling, Building Information Model, and Building Information Management. Building Information Modeling refers to the business process of generating and using building data in the lifecycle of buildings. Building Information Model refers to the digital representation of the physical and functional characteristics of a facility and Building Information Management is the process of utilizing digital building information for effective sharing. Previous studies related to the use of BIM in PHP include modeling the information of prefabricated components for efficient data exchange management [13], modular and parametric design optimization for reusable modules [14], information retrieval and matching for automated quality assessment of prefabricated products in manufacturing [15], information sharing and communication for supply chain planning and control of prefabricated products with real-time visibility and traceability [16], documenting the progress of the as-built status for the accurate site assembly [17], and the management of prefabricated products related resources and constraints for a reliable workflow [18].

It should be noted that with the rapid development on practical implementations of BIM and PHP, the theoretical perspectives of their integration (hereinafter referred to as BIM-PHP), which aims to bridge the object-oriented BIM models with the production-oriented PHP for improving working efficiency from multi-dimension (stakeholder-crew-product) planning and control, should not be overlooked. The objectives of this study are to (1) review the current body of knowledge relevant to BIM-PHP; (2) investigate the concept, structure, and attributes of BIM-PHP; and (3) develop a conceptual framework for the successful integration of BIM and PHP to raise working efficiency.

This study is presented by the following structure. Section 2 demonstrates the results of the literature review. The integrated conceptual framework for BIM-PHP is then established and presented in Section 3. Section 4 provides a discussion of the results and Section 5 concludes the study.

2. Literature review

In order to develop the integrated BIM-PHP framework, a comprehensive literature review of all studies which are related to BIM and PHP is conducted. Content analysis, as a structured literature review technique for making replicable and valid inferences from large bodies of literature, is adopted [19]. The method has been widely used to help researchers extract textual information from the literature [20,21]. A five-step procedure is adopted and shown in Fig. 1 [19]:

- Step 1: Setting up the objective. This objective is to critically analyze all articles that are related to the development and implementation of BIM-PHP.
- Step 2: Determining the analysis boundary. The analysis boundary of this study is related to the development of BIM and its relevant implementations in PHP, including its interchangeable representations in the housing field, such as prefabricated construction, prefabrication, modular construction, off-site construction, precast construction, manufactured construction, industrialized building system, and pre-assembly construction.
- Step 3: Identifying sample articles. A three-stage sampling process, which is previously adopted by Mok et al. [21], and Li et al. [22], is also adopted to identify articles from two databases, including Scopus and ISI Web of Science. The three-stage process includes: (1) a scope definition stage which restricts the sample articles within academic journals (articles and reviews), because of their relatively high research impact. Book reviews, editorials, and papers in conference proceedings are not included. (2) A searching stage which identifies articles that contain the keywords in the Title/Abstract/Keywords. A total of 96 publications are identified. (3) A relevance checking stage which excludes irrelevant papers through a brief and manual examination of the content of all articles. A total of 65 publications are selected for further analysis.
- Step 4: Coding and analyzing selected articles. The selected articles are coded and analyzed through quantitative variables and qualitative variables (which are shown in Table 1). These variables are adapted from Mok et al. [21]. In these codes, the production structure refers to a hierarchical structure of prefabrication products from low to high, including material, component, module and unit [3]. According to Li et al. [3], components (e.g., floor slabs) are produced from materials and assembled into modules (e.g., prefabricated bathrooms), which will then be integrated into a unit (e.g., prefabricated rooms). This taxonomy classifies PHP from the point of the physical product, which can be planned and controlled (manufactured, transported, assembled) to evaluate the working efficiency. There are also other taxonomies. For example, the subsystems of a building include structure, envelope, partitions, equipment, and services, which can be used to classify PHP from the perspective of functions. The Hong Kong government manufactures

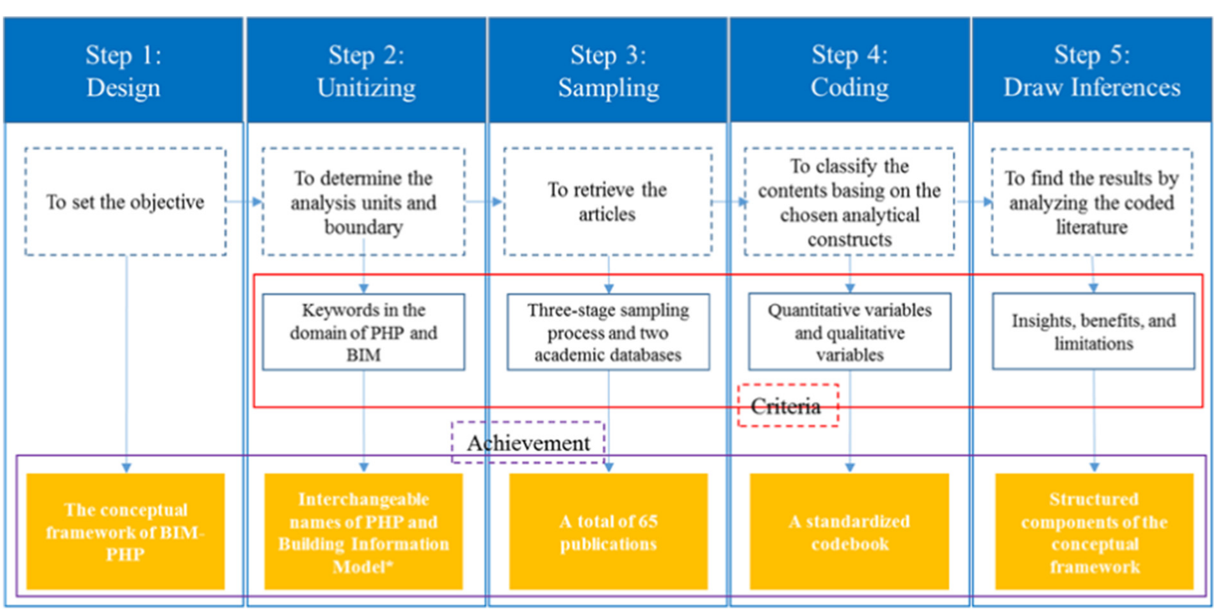

Fig. 1. Process to develop the BIM-PHP conceptual framework.

Table 1
Codebook for content analysis of this study.

Code	Definitions of code
Quantitative variables coded	
Year	The publication year, from 2005 to 2017
Author	List of authors
Article title	Title of the article
Journal	The journals where the article is published
Institution	The institution of the first author
Country/region	Country/region where the study is conducted
Production structure	From high-level to low-level, including units, modules, components and materials
Information requirement	Information requirements for information modeling and exchange
BIM-PHP stages	Specific BIM applications in the lifecycle of a project
BIM-PHP areas	Specific research and application areas in BIM-PHP
Supporting technologies	Supporting technologies adopted in BIM-PHP to facilitate implementation
Methodology	Qualitative, quantitative, or mixed methods
Data collection methods	The survey, interview, case study, experiment or others
Qualitative variables coded	
Research questions	Research issues and gaps explicitly stated in the article
Contribution	Contribution to the body of knowledge
Major findings	Key findings explicitly stated in the article
Future needs	Future studies or limitations explicitly stated in the article

3D prefabricated units (precast concrete or prefabricated steel), which can act as sole vertical load-bearing structure and may integrate necessary functions, such as the envelope/partitions/space as well as relevant services. Based on the requirement of the unit, necessary materials, components, and modules of the unit can then be manufactured efficiently by specialized manufacturers and then assembled at the main factory. The product-based classification of PHP is adopted to track the physical flow of PHP.

- Step 5: Summarizing the insights, benefits, and limitations. The above codes of BIM-PHP are critically analyzed and re-structured as the basis of the conceptual framework. A case is used to demonstrate the use of the framework and the feedback is used to strengthen the conceptual framework.

2.1. Descriptive results

Table 2 demonstrates the distribution of the 65 articles by years of publication and publication venues. The results indicate an apparent increase of research on BIM-PHP since 2005, which can be partly explained by the globally rising recognition of the need to integrate the advantages of BIM and PHP to maximize their benefits to the construction industry. The first study, i.e., Sacks et al. [23], aims to establish a benchmark for measuring the benefits of integrating BIM and precast construction. It raises the need for data exchange and software integration to connect the 3D data models with the physically prefabricated components and processes for better decision making in the design and construction stages.

Fig. 2 presents the distribution of the 65 publications by the country/region and the prefabrication production structures of these publications. United States, Hong Kong, United Kingdom, and Israel are the top four countries or regions, in terms of publications on BIM-PHP. 63% of all studies related to BIM-PHP are conducted in these four countries or regions. In the United States, there is a lack of appropriate integrated frameworks, tools, and technologies for facilitating the transformation of the conventional design/construction approach to one that is based on manufacturing to improve the productivity [24]. In addition, information fragmentation and uncollaborative working environment have been recognized as significant barriers to achieving an efficient supply of public housing project in Hong Kong [25]. Miscommunication among different PHP stakeholders, especially the lack of agreement among different participants in terms of operations, expectations, and motivations, is considered as a negative factor affecting the adoption of PHP in the UK [26]. Fig. 2 also presents the production structures that are investigated in these studies. A total of 50 articles (77%) investigate prefabricated components (e.g., precast concrete floors, walls, mechanical, electrical, and plumbing (MEP) services) and the use of BIM to enhance the information exchange in these components. For example, Niu et al. [27] developed the smart construction objects (SCOs) for prefabricated façade by enhancing the façade with tracking, sensing, processing, storage, and communication capability in a BIM platform so that SCOs have inbuilt autonomy and awareness. Compared to the component, other production structures, such as material, module, and unit, have attracted relatively low research interest. This is partly because the component is the foundation in BIM and is comfortable to be identified and investigated in BIM.

Table 2
The distribution of publications in by years of publication and publication venues.

Journal title	2005	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017.08
Automation in Construction	–	1	–	1	3	1	–	1	3	7	5	1
Journal of Construction Engineering and Management	–	–	1	–	–	–	–	–	–	2	2	2
Journal of Computing in Civil Engineering	–	–	–	1	1	–	–	–	1	–	1	1
Journal of Information Technology in Construction	–	–	2	1	–	–	–	1	–	–	–	–
International Journal of Project Management	–	–	–	–	–	–	–	–	–	1	–	–
Computer-Aided Civil and Infrastructure Engineering	–	–	–	–	–	–	–	–	–	–	1	–
Journal of Management in Engineering	–	–	–	–	–	–	–	–	–	–	–	1
Advanced Engineering Informatics	–	–	–	–	–	–	1	–	–	–	1	–
Journal of Cleaner Production	–	–	–	–	–	–	–	–	–	–	1	2
Habitat International	–	–	–	–	–	–	–	–	–	1	1	–
Resources, Conservation and Recycling	–	–	–	–	–	–	–	–	1	2	–	–
Construction Management and Economics	–	–	–	–	–	–	–	–	2	–	1	–
Engineering, Construction and Architectural Management	–	–	–	–	–	–	–	–	–	1	–	–
Architectural Engineering and Design Management	–	–	–	–	–	1	–	–	–	–	–	–
Sustainability	–	–	–	–	–	–	–	–	–	–	–	1
Construction Innovation	–	–	–	–	–	–	2	–	–	–	–	–
PCI Journal	1	–	–	–	–	–	–	–	1	–	–	–
Journal of Intelligent and Robotic Systems	–	–	–	–	–	–	–	–	–	1	–	–
Journal of Architectural Engineering	–	–	–	–	–	–	1	–	–	–	–	–
Computers in Industry	–	–	–	–	–	–	–	–	1	–	–	–
Total	1	1	3	3	4	2	4	2	9	15	13	8

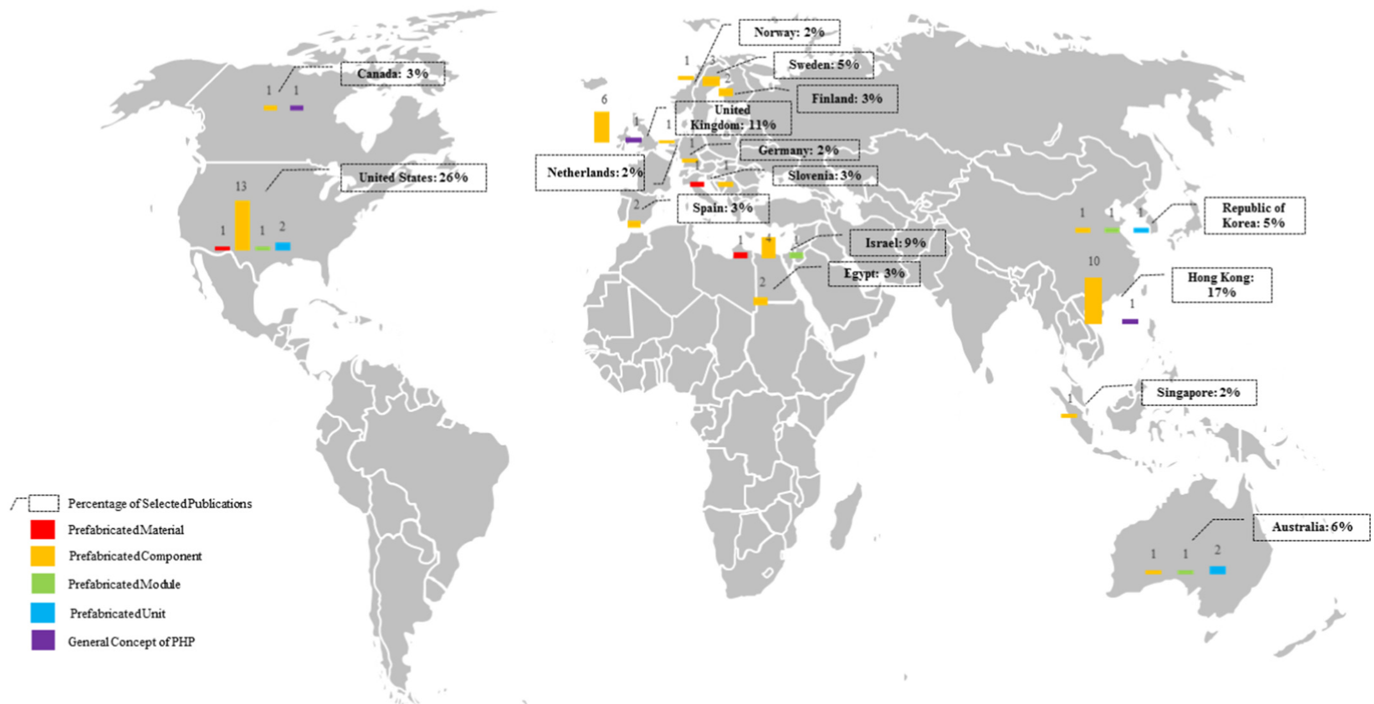

Fig. 2. The country/region distribution of selected publications with the different complexity of prefabricated structures.

2.2. Content analysis results

Content analysis can help to identify the underlying supporting elements of the BIM-PHP framework. The results are presented based on the codes which are shown in Table 1.

2.2.1. BIM-PHP stages

BIM has been extensively adopted in PHP in various stages of a project lifecycle, including a feasibility study, design, manufacturing, transportation, construction, and maintenance. Feasibility study and strategy development in the pre-design stage play a critical role in identifying the strengths and challenges of BIM-PHP. Some of the most notable examples in the pre-design stage are SWOT analysis of Internet of Things-enabled BIM platform for PHP [28], best practices for electrical prefabrication [29], business models in new offsite productions [26], and the impact of BIM on PHP labor productivity [30]. The design is the project lifecycle stage which receives a lot of attraction. The design stage covers interoperability, 3D parametric and geometric modeling, and visualization. In interoperability-related applications, some prominent examples are related to specifying information requirements [31], enhancing semantic representation of information [32] and information exchange [33]. In 3D parametric and geometric modeling applications, some noteworthy examples are functional information modeling from different domain knowledge [34] and physical information modeling for products modularity and flexibility [35–37]. Of all the BIM applications in the design stage, interoperability is the most important one at the technical level due to its significance in facilitating the information exchange among various BIM platforms (e.g., Revit®, Tekla, Inventor, IDAT Precast, CATIA™, Autodesk Fabrication), enterprise systems, and smart prefabricated components. The reason is that off-the-shelf software/platforms cannot well define the information for the professionals in different domain knowledge and they use different methods to model the geometric and non-geometric data. However, the standard data schema and Industry Foundation Classification (IFC) based interoperability tools can be used to improve information exchange. Such tools include Classification Manager, Model Checker, COBie Extention for Revit® to facilitate different professionals in information classification, compliance checking, and information filtering. 3D parametric and geometric modeling is also a critical one at the functional level because it is the foundation to implement the strategy of design for X (DfX) [2] that programs the details of products and models the information in order to offer an optimal level of PHP in the lifecycle of construction projects including manufacturing, transportation, assembly, maintenance, deconstruction, and recycling. The BIM applications in construction stage mainly concentrate on information sharing and communication, and visualization. In information sharing and communication applications, some notable examples are related information storage, retrieval, and documentation. For example, Niu et al. [27] investigated how the information delivered from the previous stages could be synchronized in the assembly stage, and the real-time as-built information (e.g., location and progress status) would be documented in a timely manner. As can be seen from these studies, BIM has commonly been adopted in separate lifecycle stages in PHP. For achieving integrated industrialization, there seems to be a lack of an integrated platform for setting up a continuous interaction between all the stakeholders in order to maintain an effective delivery of prefabricated products with customer-oriented performance criteria at the cradle-to-grave level [38].

2.2.2. BIM-PHP areas

Building Information Modeling is the most significant area, and it is mainly related to modeling components information and modeling process information. For example, Costa and Madrazo [39] adopted the linked data approach to connect the BIM models with a catalog of prefabricated products. The linked information obtained from multiple sources can create semantic descriptions of the prefabricated products. Similarly, Sacks et al. [33] established the information delivery manuals (IDM) which can capture the use cases and the precise information to be exchanged in the workflow. Resource management is also an important research area in BIM-PHP, partly due to the high cost of PHP components [17]. As such, enhancing the traceability and intelligence of PHP components have received much attention. Supply chain management (SCM) is always plagued with the fragmentation, discontinuity, and heterogeneity in BIM-PHP [40]. Thus, the coordination strategy and the concurrence of process and information become necessary for improving the interconnection of SCM. Production engineering management, including modularity and flexibility, and clash detection, schedule management, including schedule risk control and progress monitoring have also received much attention. Balancing the modularity and the flexibility of prefabricated products is an essential area of research in product engineering management of BIM-PHP [37]. For example, the customized and BIM supported design could be decomposed into non-repetitive assemblies of components with standardized interfaces that can be preassembled off-site [14]. This application area is necessary because it is the foundation to achieve mass customization of building products [35]. Similarly, due to the fragmentation and discontinuity of information in the lifecycle stages of construction projects, the reliability and stability of workflow should be improved through satisfying all potential constraints (e.g., rough design drawings, limited workspace, shortage of manpower and materials.) prior to execution [41]. Thus, constraints management is another vital process in BIM-PHP. As can be seen from these studies, BIM has not provided manageable and structured workflows in PHP. For achieving executable industrialization, there seems to be a lack of an advanced work breakdown approach with interfacing rules of products for simplifying the PHP process and avoiding repetitive linear sequences between all the crews in order to maintain a resilient execution for mass production [38].

2.2.3. BIM-PHP products

The building system of PHP could be a set of modular products and coordinated information where the details are resolved before actual buildings are planned. The building system of PHP usually comprises five functional sub-systems: structure, envelope, partitions, services, and equipment [42]. Each sub-system of PHP could gather a series of prefabricated products (i.e., material, components, modules, and units). An open system can swap prefabricated products to offer more options to both the customers and manufacturers in a larger market by following the principles in terms of performance criteria (PHP stakeholders), interfacing rules (PHP crews), and modular coordination (PHP products) [38]. However, the coordinated rules or information are not well organized and connected to each modular product. Thus, adopting supporting technologies with a hierarchical PHP product structure could facilitate the integration of BIM and PHP. The supporting technologies can be categorized into two groups in current BIM-PHP studies, which are sensing and tracking (e.g., RFID, GPS, 3D camera), and 3D model creation and comparison (e.g., 3D laser scanning, photogrammetry, augmented reality (AR)). These supporting technologies can directly contribute to the aforementioned BIM-PHP workflow, such as prefabricated products traceability, progress monitoring, documentation, and quality inspection. Sensing and tracking technologies are necessary for activities in manufacturing, transportation, on-site assembly, and maintenance. Some of the useful applications include identifying and searching the prefabricated products in the factory, accurately positioning the prefabricated products in the assembly process, and timely detecting defective products or systems in the maintenance stage. As one of sensing and tracking technologies, RFID is not entirely new in PHP. It is commonly used for identifying and tracking the resources (e.g., personnel, components, equipment) which can then be visualized in BIM [43]. GPS is also a powerful tool for providing the exact positions of prefabricated products in BIM through 2-way, differential GPS and kinematic GPS, which has higher accuracy [44]. As for the 3D camera, it can be integrated with mobile robotics manipulator, which is used to rapidly detect and track the prefabricated components by computer-vision-based pose estimation for assembling the components into pre-designed modular structures [45]. For 3D model creation, 3D laser scanning is particularly applicable in quality management due to its efficiency in capturing the existing condition of the prefabricated products, which has been adopted to measure the deviations between ‘as-built’ and ‘as-designed’ models for quality control [46]. Although data acquisition is relatively fast when using 3D laser scanning, post-processing tasks still take a long time to reach a high level of BIM details [15]. Thus, the photogrammetry and AR can be used as alternatives for the 3D model creation and comparison. As can be seen from these studies, these technologies have contributed to capturing, generating and analyzing the data from the physical environment. However, it is still disenabling physical objects (e.g., prefabricated products, machinery, equipment) to be smart in terms of awareness, autonomy, and communicativeness for improving the efficiency of modular coordination.

3. The conceptual framework of BIM-PHP

As can be seen from the above content analysis, most studies focus on addressing isolated implementations of BIM, such as interoperability, and information sharing and communication, to address various issues in the design and construction stages of PHP. However, the rationality of individuals in decision making, collaborative working, and modular coordination is constrained by the information, their cognitive ability, and a limited amount of time they should execute [27]. Such limitations are particularly amplified when other stages such as transportation, maintenance, deconstruction, and recycling are included. This limitation calls for the development of the smart BIM-PHP environment. In such environment, decision-making platform, collaborative working process, and modular/informational products are made smart by enhancing them be capable of tracking, sensing, networking, reacting and processing, which facilitate better decision making, collaborative working, and modular coordination. A conceptual framework of BIM-PHP, which is shown in Fig. 3, is therefore developed to facility BIM-PHP.

3.1. The architecture of the conceptual framework

The proposed conceptual framework, based on the content analysis, has three pillars, namely the smart BIM platform (SBP), the smart work packages (SWPs), and the smart PHP objects (SPOs).

3.1.1. Smart BIM platform (SBP)

Compared with the conventional BIM system, the smart BIM platform (SBP) involves not only a shared virtual 3D model developed in the design stage and updated in real-time, but also has the ability to provide service-oriented architecture (SOA) ranging from design to deconstruction and recycling.

Each service requires more value-added information (e.g., cost, progress, safety, quality, lean solutions) to extend the original 3-dimensional platform to a multi-dimensional one, which then employs a more user-friendly (e.g., interactive and immersive) interface to facilitate the decision-making among different stakeholders at various stages of PHP. The performance for building systems of PHP in each service should not be simply measured from the perspectives of project management, but also evaluated by the customers' demands [38], such as adaptability (allowing for individualization and accommodating change without demolition), flexibility (the product is capable of geometrical variations, and the work processes could generate diversified products), multi-purpose framework (the sub-systems of PHP could accommodate different options through the addition of specialized products), and combinability (mass combinations from mass production). To achieve these, SBP will highly depend on well-formatted information/data sensed, processed, computed in the central database. As data systems are commonly geographically distributed, the data brokering function, considering the willingness of stakeholders for shared data management, needs to be embedded into the central database. In addition, only authorized stakeholders can access the information, ensuring information security.

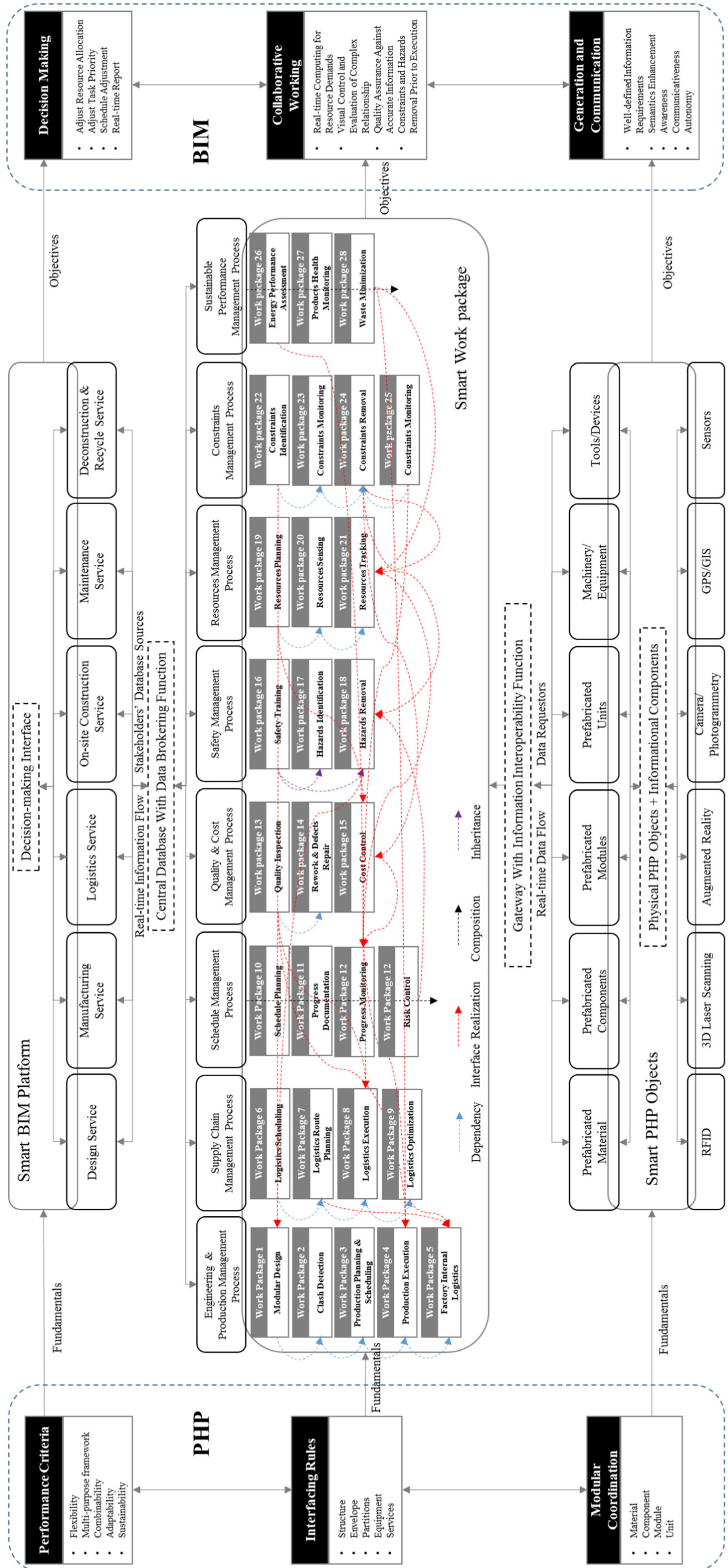

Fig. 3. The conceptual framework for integrating BIM and PHP.

Table 3
Information requirements for BIM-PHP.

Stage	Information requirements (physical & functional)	Evaluation metrics
Design	Shape & dimension	***Accessibility***: The information can be easily accessed when needed
	Products type & layout	
	Material & quantity	
	Weight & volume	***Accuracy***: The information is free of error and complete
	Structural loads	
	The specifications for coupling & decomposition	
	The relationships between products & interfaces	***Appropriateness***: There is neither too much nor too little information
	The relationships between parent & child components	
	The relationships between whole & part	
Manufacturing	Manufacturer & material supplier	***Consistency***: The information follows the same format throughout the PHP lifecycle
	Work orders & serial number	
	Date of production	
	Standardized quality control records	
	Occupancy of laydown yard	***Interpretability***: The information is defined precisely and exchanged in appropriate format
	Location of prefabricated products	
	The specifications for assembly and maintenance	
	Progress status	
	Constraints and cost	***Relevancy***: The information is applicable to the tasks
	Carbon emission	
Transportation	Transportation providers & transportation orders	***Security***: The information is protected against unauthorized access and editing
	Dispatched driver information	
	Dispatched tractor information	
	Dispatched trailer information	
	Real-time location of the vehicles	***Timeliness***: The information is real-time and up-to-date
	Progress status	
	Transportation path	
Construction	Occupancy of site, buffer, and workspace	***Traceability***: The information flow is traceable, e.g., using RFID technologies
	The position of supporting equipment	
	The position of labor position	
	Quality inspection records	
	The position of prefabricated products	***Understandability***: The information is not hard to understand and manipulate
	Erection inspection records	
	Progress status	
	Constraints and cost	
	Carbon emission	***Value-added***: The information offers benefits to downstream users
	Procedures and safety specification	
Maintenance	Warranty expiration date and contact	***Visibility***: The information could be visualized for better sharing and communication
	Energy consumption	
	Abandoned/removed/replaced products records	
	Maintenance inventory	

3.1.2. Smart work packages (SWPs)

Each service will then be decomposed into collaborative and manageable processes (represented by the application areas in Section 3.2.2), and each process includes relevant work packages. The work packaging method is to ensure activities which are highly interdependent could be decoupled into several separate packages for collaborative working [47]. Each work package delivered to each crew adopts product-oriented planning and control approach, which considers the interfacing rules of sub-systems of PHP (i.e., structure, envelope, partitions, equipment, services) to improve the reliability of workflow. The relationships among processes and work packages can be defined into four types: composition, interface realization, inheritance, and dependency.

- Composition: This relationship mostly exists between one process and its relevant work packages. For example, the schedule management process can be decomposed into several work packages, including schedule planning, progress documentation, progress monitoring, and risk control.
- Interface realization: This relationship is based on software engineering and refers to a group of work packages which support or rely on the behavior that is defined in an interface. For example, the work packages of constraints monitoring, energy performance assessment, cost control and resources tracking can be used to support the work package of progress monitoring, although these work packages have a composition relationship with constraint management process, sustainable performance management process, quality & cost management process, and resources management process respectively.
- Inheritance: This type of relationship exists between a parent work package and its succeeding work packages. Both the parent and the succeeding work packages share some common characteristics while the succeeding work packages may have their own unique characteristics. For example, the safety training work packages generally include the approaches, tools, and specifications for hazards identification and hazards removal. However, on-the-job hazards identification and removal may be different from the general safety training work packages to reflect specific site characteristics.
- Dependency: This is the most popular relationship where the downstream work package is dependent on the upstream work package. The upstream activity provides the outputs which will be the inputs of the downstream activity, and any changes in the upstream outputs may affect the downstream activity. For example, the four work packages in the constraints management process, which are constraints identification, constraints optimization, constraint removal, and constraints monitoring, have a dependent relationship.

The relationships between processes and work packages can be used to achieve the intelligence of work packages. Automatic analysis of the topological relations between smart PHP objects can be conducted with the support of the aforementioned relationships in the smart BIM platform. In addition, visual guidance and interactive representation of the work sequence can be obtained by applying lean solutions by which the smart PHP objects are assembled. The resource requirements, such as the quantity and location information, can also be evaluated in real-time. Based on the real-time information, evaluation of project success factors, such as productivity, safety, and quality can be conducted. The results can then be used to adjust work packages for further improvement.

3.1.3. Smart PHP objects (SPOs)

SPOs are PHP objects, such as prefabricated materials, components, modules, units, machinery, and devices, that are equipped with supporting technologies. For example, when PHP objects are enabled with tracking, sensing, processing, storage, and communication capability, SPOs have inbuilt autonomy and awareness [27]. SPOs generate various types of information. Table 3 represents the information requirements in BIM-PHP and their relevant evaluation metrics. Specifying the requirement for these types of information could improve the modular coordination (i.e., dimension, space) of prefabricated products (i.e., material, component, module, unit) in a smart environment. The information requirements can be categorized into two groups: physical information requirements, such as dimension, weight, quantity, and functional information requirements, such as carbon emission, quality records, cost, energy consumption and the location [32,48,49]. Correspondingly, many evaluation metrics have also been developed as benchmarks for assessing the information requirements [40,50], The most commonly adopted evaluation metrics include accessibility, accuracy, appropriateness, consistency, interpretability, relevancy, security, timeliness, traceability, understandability, value-added and visibility.

In addition, it should be noted that understanding the information requirements within the specific knowledge domain has also been recognized as the fundamental needs for better information flow management [51]. In the design stage, the product related information should be well defined. For example, Ramaji et al. [24,52] integrated the PHP characteristics of both projects (e.g., site-built parts and on-site activities) and products (e.g., industrialized and object-oriented) into BIM to develop a product architecture model (PAM) which includes the information of functional elements (e.g., attributes, descriptions, specifications), physical objects (e.g., shape, dimension, weight, volume and quantity) and their interactions (e.g., relationships). In the manufacturing stage, the product performance related information should be specified, such as the date of production, quality records, cost, location, and carbon emission. In the transportation stage, traceability related information is required, such as the information of the driver, tractor, and trailer, location, progress status, and transportation path. In the construction stage, the process performance related information including cost, safety, schedule, quality, carbon emission, constraints, position, and space are necessary. In the maintenance stage, the interaction between physical prefabricated products and functional information units can help monitor and predict the required information such as energy consumption, warranty expiration date, and defects. Hence, the bottom-up information requirements from objects and work packages to the platform could facilitate the information delivery through the PHP lifecycle.

3.1.4. The interactions between SBP, SWPs, and SPOs

To support the implementation of the framework, an example service-oriented architecture (SOA) can be developed on the basis of cloud computing and Internet of Things (IoT) technologies (see Fig. 4). The SOA includes three layers: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).

The IaaS layer includes the SPOs and SWPs. A gateway of data interoperability service is created between the SWPs and SPOs. The gateway is an Internet of Things (IoT)-enabled industrial computer, which provides a communication link between the field (SPOs) and the central cloud database in PaaS. It could perform several critical functions in work packages to set up an information infrastructure, which can connect, manage and control the SPOs by defining, configuring, and executing the PHP tasks in a user-friendly manner. The data interoperability service could provide data query techniques for data requester to approach different SPOs for improving the interoperability issues in information sharing. To this end, the entitled APIs and drivers of different SPOs should be managed and referenced in a consistent manner. A consolidated query mechanism should also interpret requests to appropriate query languages that are required by SPOs. Additionally, fresh data retrieved from SPOs can be pre-processed and stored in a specific format by data process and data repository service. For example, the gateway to SWPs can help pre-process the data collected from the SPOs and decipher the control commands sent from the upstream. To this end, the complex task processing technology could be applied to reorganize the heterogeneous data into a standardized scheme, which can be understood, shared and used by various SWPs. The IoT Gateway in SWPs can help SWPs to link and handle a set of SPOs by wired or wireless communication. It can also facilitate SWPs to communicate and interact with the central cloud database by uploading their outputs and downloading their inputs in a standardized format.

The PaaS layer offers several services for facilitating the implementation of SBP including platform management service, PHP management service, visibility and traceability service, decision support services (DSSs) and collaborative working services (CWSs). Here, DSSs and CWSs refer to sets of services that help SWPs in modeling, planning, optimization and monitoring of each task in PHP. All these services are issued and distributed through the IoT service-sharing module. The central cloud database within data source management could provide a self-service portal for managing SBP infrastructure and service provision, and the services across the SBP could reinforce SWPs and host the smart PHP objects. The gateway to SWPs acts as an information bridge between the SPOs and SBP. Thus, decisions could be seamlessly synchronized into the work packages for their task executions.

The SaaS layer contains final applications for different users in different stages of PHP, which includes web-based system (e.g., for SBP which can be accessed easily through different ways), mobile applications (e.g., for SWP which can be used in mobile devices), and software development kit (which can connect with existing systems).

3.2. An example of BIM-PHP

A case study of a PHP public housing project in Hong Kong is investigated to illustrate the applicability of the conceptual framework. The primary stakeholders in this project include the Hong Kong Housing Authority (HKHA) (the designer and client), the main contractor, an offshore prefabrication plant located in the Great Bay Area (GBA) of the Mainland China, and various transportation companies. The client aims to develop a new integrated approach to address the challenges identified in previous pilot cases of RFID-enabled BIM platform (RBIMP) (see [11,16]). For example, there was a lack of agile and lean management process to connect the informational components and BIM platform. This BIM-PHP conceptual framework extends previous studies and provides theoretical support for the integration by clarifying the information requirements, potential technical solutions, and proper evaluation.

A typical scenario which can demonstrate the usefulness of the framework at the task execution level is related to managing constraints in buffer management in PHP, which is shown below.

A smart work package containing the functional and physical information of prefabricated components is generated from the smart BIM platform based on the building systems and product breakdown structure (PBS) of PHP and is assigned to a site buffer operator for managing relevant constraints so that efficient on-site assembly and just-in-time delivery can be achieved. The SWP should identify critical constraints, which may include the availability of workforce and work order in the

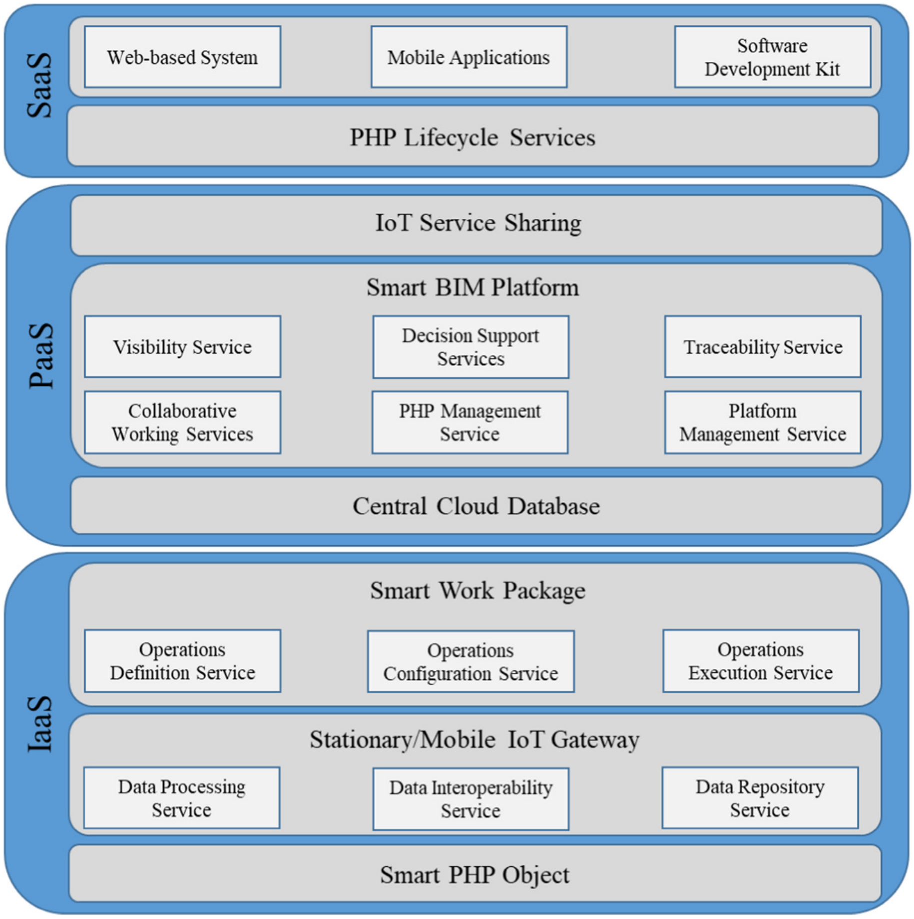

Fig. 4. Example service-oriented architecture.

assembly point, the quality of arrived prefabricated products, the availability of space and workforce. The interrelationships between the critical constraints in terms of composition, interface realization, inheritance, and dependency should also be fully mapped. The SWP will then assign tasks with optimal solutions to the buffer operator for improving the constraints. For example, if buffer shortage is identified as a critical constraint, optimal buffer utilization and hoisting sequencing (e.g., first-in-first-assembly) will be crucial for raising working efficiency through the use of advanced optimization algorithms. At the same time, constraints status will be timely collected because all SPOs have the capabilities of tracking, updating and predicting to achieve real-time decision making.

In addition to this scenario, the usefulness of this framework from the perspective of a PHP lifecycle is also demonstrated.

3.2.1. Design stage

In this PHP project, the project team does not adopt the traditional design process but using the BIM library of HKHA. In order to achieve the strategy of DfX, three principles are implemented in the design process, following the conceptual framework of BIM-PHP. A hierarchical structure of the prefabricated product, from units, modules, components, and materials, is adopted (see Fig. 5). The physical and functional information flow in this hierarchical structure has two categories: whole and part, parent and child. For example, the properties of material and components can be part of the module or unit, but not the same as the module or unit. While the module can inherit some characteristics of the unit. In addition, each prefabricated product's physical and functional information, including dimension, weight, volume, quantity, material and its relationship with other products, is well defined to facilitate the process of computer-aided-manufacturing (CAM), transportation and on-site assembly. More importantly, Level of Development (LOD) 300 is adopted to ensure sufficient information can be obtained to meet the requirements of DfX strategy [53]. Higher LOD is not necessary because LOD 300 can meet the information requirements for BIM-PHP. Each design task (e.g., modular design and clash detection) has an SWP with relevant inputs and outputs, which can be downloaded and uploaded from the central database. For example, the SWP of modular design extracts the components, modules, and units from the BIM library of HKHA to conduct permutation and combination under the basic design codes. In addition, the information required in subsequent work packages is embedded in the products.

The usual tasks fulfilled by BIM in a combination of various hierarchical products for different typical floor layouts include: (1) selecting the appropriate family template of cores (flat unit 1–4); (2) layout reference planes to aid in drawing component/module geometry; (3) adding dimensions to specify parametric component/module geometry; (4) adding labels/attributes/materials to component/module to create type or instance parameters; (5) testing the new cores to verify correct component/module behavior; (6) integrating the cores with all other spaces, areas, structure, equipment and services in the typical floor.

3.2.2. Manufacturing stage

In this case, the SWPs of production planning and scheduling, production execution, factory internal transportation are established. The SWP of production planning and scheduling help to decide what should be produced and the sequence of production. For example, the information of the prefabricated products is extracted from the BIM platform to a CAM system for manufacturers to generate production

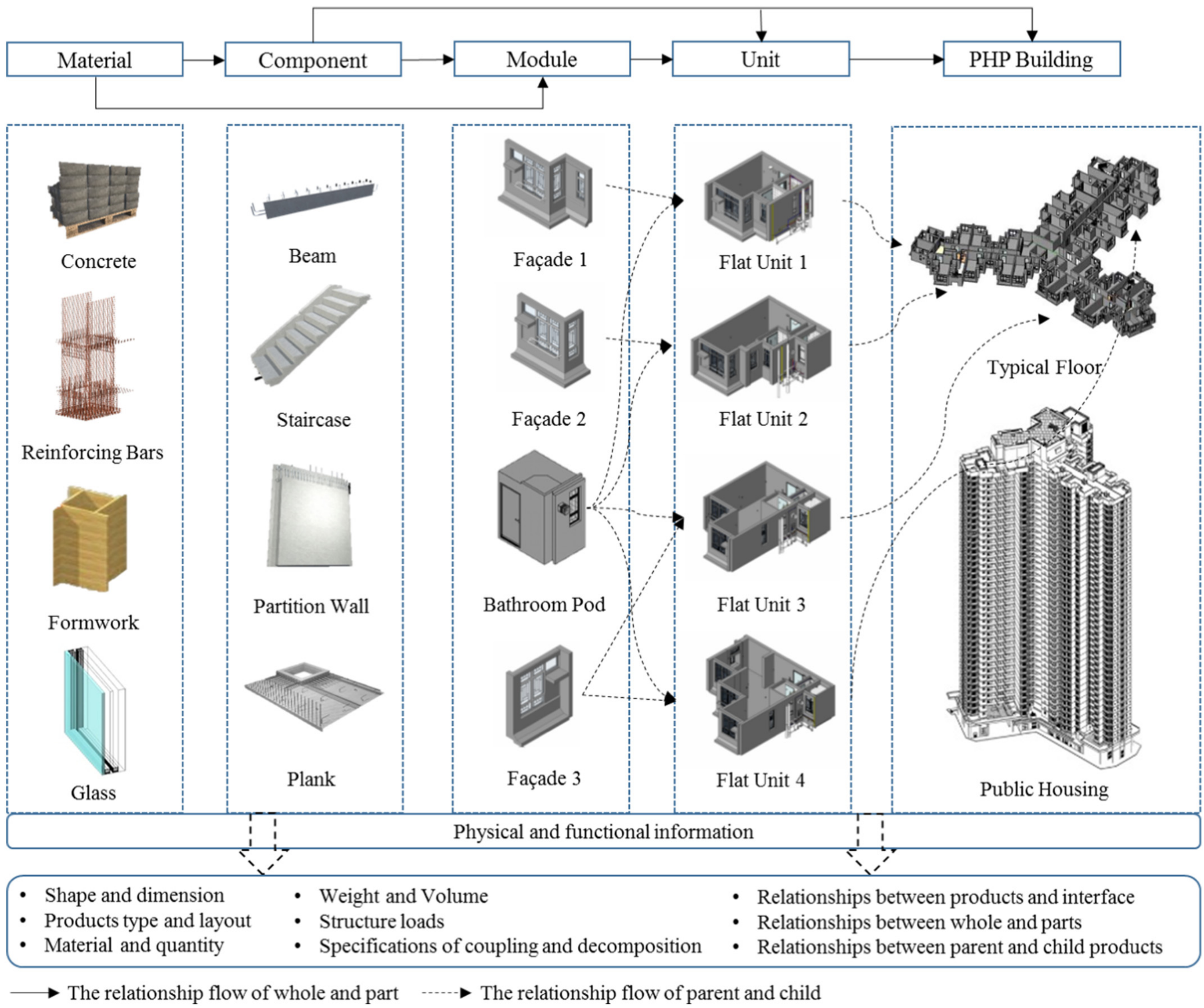

Fig. 5. The hierarchical structure of prefabrication products with physical and functional information.

orders. The priority of these orders is determined by the urgency of actual demands on construction sites by the pull method. In the production execution SWP, RFID tags are embedded into the prefabricated products, and laser scanning is adopted for documenting the dimensions of prefabricated products and storing such information into the related SPOs. These SPOs facilitate the production execution SWP to provide updated progress for stakeholders to remove constraints and make necessary changes. The factory logistic SWP clarifies where the products should be delivered and how to search for them in the inventory yard when they are required. AR-based visual guidance and barcodes mounted in the SPOs can assist in inventory management.

3.2.3. Transportation stage

The pull method is adopted to plan the transportation SWPs, which are synchronized with the BIM platform. The SWPs include transportation planning and scheduling (e.g., driver, vehicle, route), transportation execution, and transportation optimization. In the transportation scheduling and planning SWPs, the most urgent or expensive goods will be automatically assigned to the drivers with better driving track records. This process can be optimized by the dispatch algorithms in the SWPs to better schedule and plan the transportation tasks. Lim et al. [54] adopted the reroute-enabled dispatch optimization to improve the response time of urgent calls for ambulance fleet, and Truong et al. [55] designed a patent of dispatch system that can receive requests from customers to run a match operation by selecting the qualified drivers from historical performance data. These studies are useful for the optimization of arranging transportation. Whenever a new order arrives, the ranking (priority or normal) of the importance of the order will be computed based on the historical data of lead time and goods value. The order that has a higher priority will be assigned to the driver that has demonstrated superior performance. Their performance will also be updated when the products arrive on time. The drivers can confirm their tasks and obtain relevant information about their assigned tractors and trailers by scanning their RFID staff cards through their personal digital assistants (PDAs). In the transportation execution SWP, drivers need to verify the matched vehicles by using their PDAs to scan the NFC (Near Field Communication) tags which are mounted in the tractors and trailers. They are also required to scan the RFID tags of the prefabricated products to ensure the right products are loaded in the right trailers. In addition, it is critical to achieving Just-in-time (JIT) delivery in the transportation execution SWP due to the constrained site space and buffer areas in Hong Kong. In order to achieve this, the location information of vehicles is also captured by GPS in PDAs and uploaded into the BIM platform, which then provides visible and traceable routes.

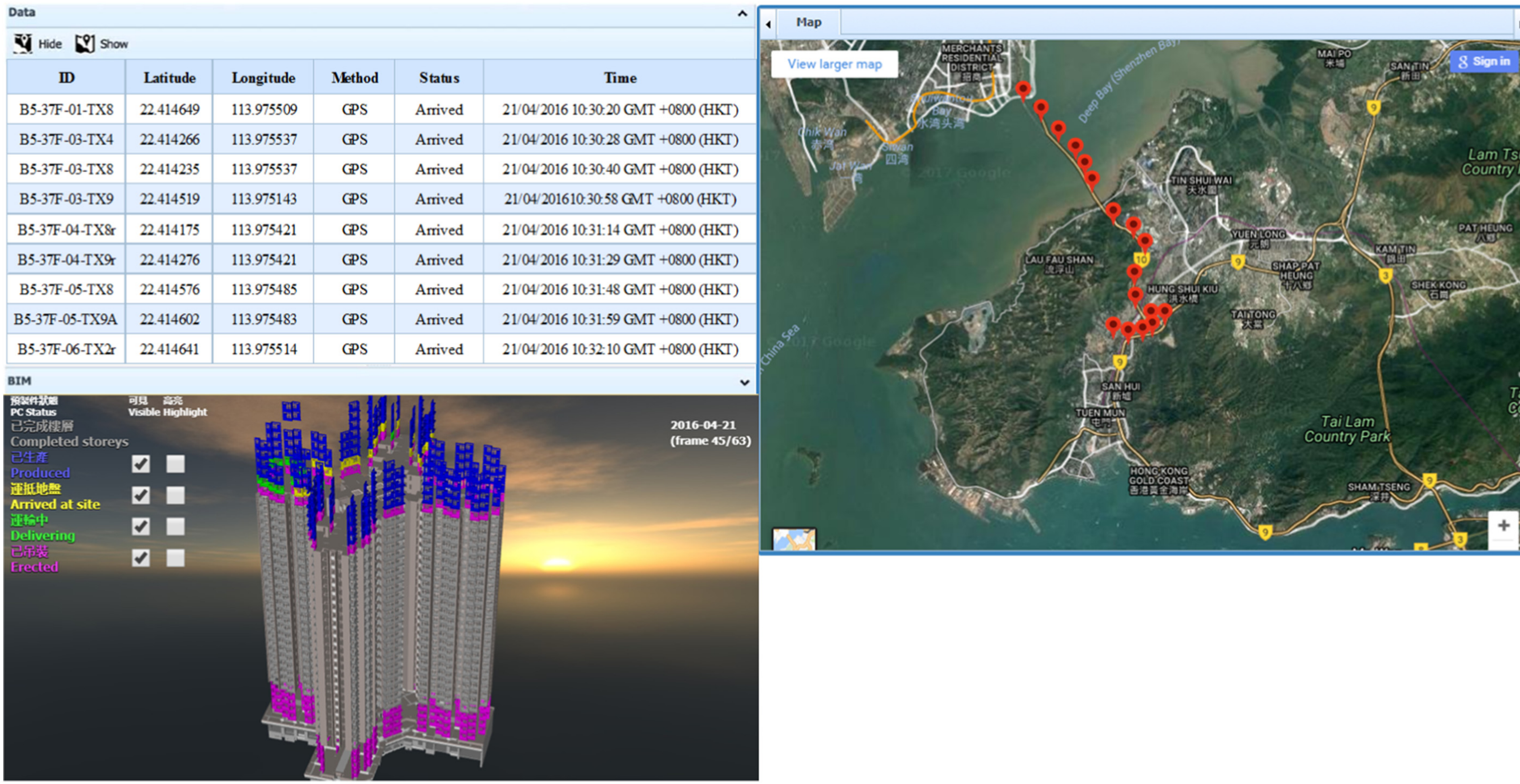

Fig. 6. The user interfaces of location information tracking in transportation execution SWP.

As shown in Fig. 6, both the status of vehicles (ID, location, tracking method, and status) and prefabricated products can be visible and traceable in one interface. Four logistic stages of the prefabricated products, including produced, arrived at the site, delivering and erected, are indicated by blue, yellow, green and purple respectively. In addition, in the transportation optimization SWP, the google map is also integrated into PDA for providing an optimized transport route (with minimum driving time) based on real-time traffic data.

3.2.4. On-site construction stage

A set of SWPs are involved in this stage such as resource management related SWPs (e.g., planning, sensing, and tracking), safety management related SWPs (e.g., training, hazards identification and hazards removal), schedule, quality and cost control related SWPs (e.g., schedule planning, progress documentation, progress monitoring, risk control, quality inspection, cost control, rework and defects repair). For example, progress monitoring SWP can provide real-time status information such as progress, on-site situation, and current assembly requirements with the support of RFID and laser scanning [11]. In hazards identification SWP, AR can provide a step-by-step assembly instruction with hazards warning information which is extracted from the BIM platform and captured by RFID and other sensors [22].

3.2.5. Maintenance stage

The case is an ongoing project which is in the construction stage. However, the case is designed to facilitate maintenance. In this PHP project, the modularity improves maintainability, because some prefabricated products with mechanical joints may allow safe, quick and easy replacement. All prefabricated products have RFID tags and other sensors for identifying, tracking and monitoring their location and status, which can then be used for health monitoring to provide early warning.

3.2.6. Summary

The conceptual framework does not require the integration of every individual PHP process such as deconstruction and recycling, given the long duration of the operational stage and the uncertainty of the deconstruction and recycling method after such a long operational stage. The deconstruction and recycling are not available for this case. For example, the prefabricated facades are bonded together at the construction site when concrete is cast over the semi-precast slab to thereby generate the equivalent of a monolithic structure modifiable only through a demolition sequence. Thus, design for deconstruction could be considered in a future project to minimize the waste and improve the sustainability performance by adopting an adaptability framework, which is based on a standard denominator called support structure and allows for variation to accommodate the individual needs through the permutation of detachable components [56,57]. Specifications related to the recycling and reuse of products can also be integrated into the SWPs to support decision making [58]. This case study, based on the current conceptual framework can offer an intuitive platform for mainstreaming the integration of BIM and PHP, which can be usefully improved with the support of other specific considerations. For example, a list of the evaluation indicators for the three stages of PHP is listed in Table 4. The list of indicators can be used to further validate the effectiveness of the proposed framework on project performance (e.g., productivity, quality, and cost).

4. Discussion

The need for a theoretical framework to re-engineer the BIM-PHP for better supporting stakeholders and workers with the capabilities of planning and control in an integrated environment has been highlighted by many studies. At the stakeholder level, Chen et al. [9] proposed a framework for bridging the BIM and building by establishing three layers including BIM, central database and physical projects to improve project management performance. However, it does not involve the PHP context and considers the data sharing willingness or incentive mechanism from stakeholder perspectives. To address these, this study proposes an integrated platform, namely SBP, which considers customer-oriented PHP performance criteria (e.g., adaptability, flexibility, multi-purpose framework, combinability) and stakeholder-oriented BIM data brokering function to set up a continual and interactive decision-making mechanism to meet requirements of both stakeholders and customers in the lifecycle of BIM-PHP. This can reduce mistrust and ineffective communication among stakeholders to enhance the efficiency of decision making with well-formatted information sharing. At the task execution level, Zhong et al. [16] developed several services (e.g., production scheduling, production execution, transport monitoring, on-site asset management) in the IoT-enabled BIM platform to achieve visibility and traceability in prefabricated construction, which various end-users can monitor a project's status, progress, and accumulative cost in a real-time manner. However, it does not propose a systematic planning and control approach at a more detailed level (e.g., look-ahead planning). This study introduces a smart workflow management approach, namely SWPs, which defines four relationship types (composition, interface realization, inheritance, and dependency) in workflows to facilitate coding the interface rules of products into SWPs. As the relationships among all tasks are well defined, it can lessen the time of task executions and improve the coordination of all crews to improve the efficiency of collaboration. At the object level, Niu et al. [27] developed smart construction objects equipped with properties of autonomy, awareness, and communicativeness. However, it does consider the information requirements for the PHP. This study introduces the smart objects concept to work as information generator with specific PHP information requirements, particularly the geometric information for modular coordination. It can reduce human interventions so as to raise the efficiency of collecting data with good quality with accessibility, accuracy, appropriateness, consistency, and traceability. In summary, the innovative contribution of this study is to integrate the object-oriented BIM and product-oriented PHP for specifying the services, processes and information under three manageable pillars, including SBP (used for decision making), SWPs (used for collaborative working) and SPOs (used for information generation and communication), in order to achieve a higher level performance in terms of decision-making and collaborative working in PHP.

The conceptual framework also echoes the concept of industry 4.0 [59,60] which is considered as an emerging trend for achieving a timely interaction between the virtual platform and the physical environment through information technologies such as cyber-physical systems (CPS), the internet of things (IoT), cloud computing and cognitive computing [61,62]. The proposed framework (SBP, SWPs, SPOs) could be the kernel of the concept of industry 4.0 and be extended by integrating more advanced technologies, sustainable material, flexible approach, and secure information. Although such systems have seldom been tested in a real-world situation in the construction industry, the future needs in the construction industry 4.0 ecosystem can be proposed using some insights from this study (see Fig. 7). For example, sustainability is an important performance criterion in the proposed BIM-PHP conceptual framework. The concept is also reflected in the design stage of construction industry 4.0 such as using renewable and energy-efficient materials or technologies [63,64]. In addition, the customized building can be automatically decomposed into modular products and work packages through BIM in construction industry 4.0 which can be used to generate the smart PHP objects and smart work packages proposed in this study with the support from IoTs. The logistics (e.g., transportation) in construction industry 4.0 has already involved georeferencing on a GIS platform to trace the materials and prefabricated products and predict the delivery time based on the spatial routing network analysis [65,66]. This is also the primary objective of smart BIM platform proposed in this study to achieve high-level decision making for integrated supply chain with coordination, traceability, and visibility. Robots and

Table 4
Evaluation indicators for the proposed framework in the stages of manufacturing, transportation, and on-site assembly.

Stage	Evaluation indicators	
Manufacturing	1. Time to tag prefabricated products with RFID 2. Number of prefabricated products to be tagged with RFID 3. Time to locate prefabricated products in factory laydown yard for transportation 4. Est. time saved locating and updating SBP 5. Number of prefabricated products not been correctly selected	6. Level of streamlined access to engineering information from SBP or mobile device 7. Time to update inventory 8. Reduction in use of paper sheets to process inventory 9. Total Man-Hrs saved 10. Expected labor savings 11. Number of prefabricated products not been prepared for pickup
Transportation	1. Time to generate prefabricated products manifest 2. Total number of prefabricated products to be tagged with RFID 3. Time to attach GPS/NFC 4. The cost to attach GPS/NFC 5. Average time to log SPOs information into delivery manifest (time per SPO) 6. Time to track vehicle registration on/off-site 7. Est. time saved though auto vehicle registration per on/off event 8. Total number of vehicles tracked	9. Total Man-Hrs saved 10. Expected labor savings 11. The productivity of knowing exactly what has been transported/arrived on-site 12. Time to locate SPOs per crew or per shift 13. Time delays in delivery to expeditor who is waiting for the prefabricated products 14. Est. time saved locating and updating SBP 15. Efficiency to access cross-border permits documents 16. Average entries/exits per day per vehicle
On-site assembly	1. Time to update SPOs log when received on site 2. Level of risk when assessing prefabricated products quality 3. Reduction in use of paper sheets to process handover 4. Time to locate prefabricated products on the buffer for the issue to crews 5. Number of prefabricated products not been prepared for pickup 6. Time delays in delivery to workers who are waiting for installation 7. The productivity of knowing what has arrived on-site 8. Average time spent locating a prefabricated product with RFID 9. Worker crews' travel time/distance 10. Time to locate supporting equipment 11. Time to collect work-in-progress information by tracking the SPOs status	12. Est. time saved progressing construction status of a key SPO 13. Percentage of total SWPs progress that can be tracked at a detailed level 14. Reduction in use of drawings to process installation 15. Cost for misplaced prefabricated products 16. Number of misplaced prefabricated products 17. Time to identify misplaced prefabricated products 18. Time to rectify misplaced prefabricated products 19. Reduction in use of paper sheets to process installation 20. Total Man-Hrs saved 21. Expected labor savings 22. Time saved per working shift (h) 23. Est. time saved identifying SPOs in the field and locating in SBP

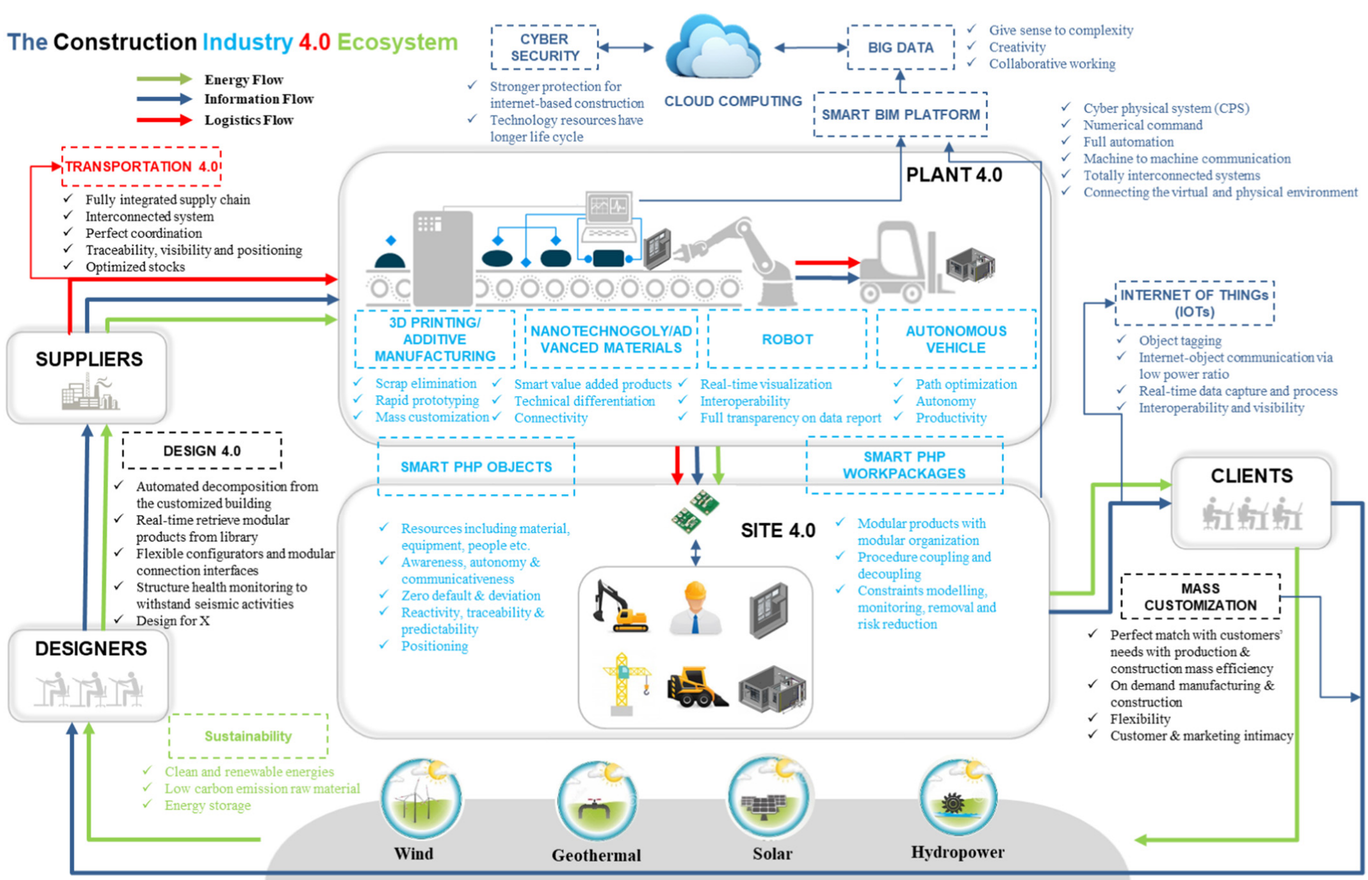

Fig. 7. Future needs in BIM-PHP for establishing the construction industry 4.0 ecosystem.

autonomous machines, the necessary elements of the construction industry 4.0, which are well connected to the new generation BIM platform, will be widely used in plants and on construction sites [67]. These are also the essential supporting technologies to achieve adaptivity, sociability, autonomy, and awareness of SPOs and SWPs in this study. In addition, mass customization which combines the flexibility, adaptivity, and personalization with low unit costs associated with mass production is one of the final objectives of construction industry 4.0. This is also a critical performance criterion in the proposed BIM-PHP conceptual framework.

5. Conclusions

The primary contributions of the proposed conceptual framework of integrating BIM and PHP to the body of knowledge are twofold. The framework enriches the planning and control approaches of project management, particularly in the PHP field, by integrating SBP, SWPs, and SPOs with guidelines of the modular open system (performance criteria, interfacing rules, modular coordination) to improve working efficiency in PHP. Traditionally, the planning and control methods such as Last Planner® System (LPS) and advanced work packaging is passive and manual to interact with individuals, which often leads to schedule delay, cost overrun and quality/safety issues, especially without considering guidelines of the modular open system for PHP. In this study, an agile planning and control approach is provided with capabilities of sensing, processing, computing, networking, and reacting. In addition, this study proposes methods and technologies for addressing the information fragmentation and discontinuity in PHP processes and synchronizing the PHP processes with BIM, using a central database with data brokering function, IoT gateway and four types of work packages, which are emerging research areas in the construction industry.

The most significant finding of this study is that this framework can provide theoretical support for the integration of BIM and PHP by clarifying the information requirements, potential technical solutions, and proper evaluation. The integration of BIM and PHP is achieved through three tiers, including the smart BIM platform (comprising a series of services ranging from design to deconstruction and recycling to facilitate decision-making), smart work packages (modular and manageable work processes), and smart PHP objects (prefabricated products and other resources with tracking, sensing, processing, storage, and communication capability). SWPs can help link and handle a set of SPOs through wired or wireless communication. They are also linked with the SBP through the central database by uploading their outputs and downloading their inputs in a standardized format. The conceptual framework can be adopted by stakeholders as a robust approach to popularizing the practice of BIM-PHP to improve working efficiency.

This study inevitably has a few limitations. In this study, the case study is an illustrative example of the implementation process of the BIM-PHP framework. The detailed evaluation of the effectiveness of the framework is not provided and will be investigated in a separate study. In addition, deconstruction is not considered in the current PHP projects in Hong Kong. As such, although deconstruction, as an integral part of a project lifecycle, is included in the BIM-PHP framework, it is not presented in the case. Researchers are also recommended to further explore the connection of the BIM-PHP conceptual framework with the construction industry 4.0 ecosystem.

Glossary

Building Information Modeling (BIM) It is to provide users with the ability to integrate, analyze, simulate and visualize the geometric or non-geometric information of a facility.

Prefabrication Housing Production (PHP) It is a practice of manufacturing or fabricating the material, components, modules, and units of high-rise housing building efficiently at different locations and then converging at the site for installation.

Smart BIM Platform (SBP) It is a digital platform to extend BIM to a multi-dimensional application with service-oriented architecture by integrating central database and data brokering function so that decisions and performance evaluation in PHP planning and control could be more feasible, accurate, and systematic.

Smart Work Package (SWP) It is an automatic planning and control approach to ensure activities which are highly interdependent could be decoupled into several separate packages for collaborative working.

Smart PHP objects (SPOs) SPOs are PHP objects, such as prefabricated materials, components, modules, units, machinery, and devices, which are equipped with supporting technologies to achieve inbuilt autonomy and awareness.

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