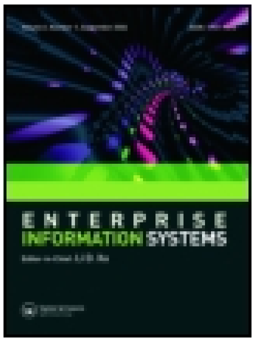

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ARTICLE

Cloud-based fleet management for prefabrication transportation

Gangyan Xu[a,b], Ming Li[c], Lizi Luo[d], Chun-Hsien Chen[b] and George Q. Huang[c]

[a]School of Architecture, Harbin Institute of Technology, Shenzhen, P. R. China; [b]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore; [c]HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, Faculty of Engineering, The University of Hong Kong, Hong Kong SAR, P. R. China; [d]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong SAR, P. R. China

ABSTRACT

Prefabricated construction heavily relies on the effective transportation of precast components, and efficient prefabrication transportation can benefit the whole construction process from many aspects, such as saving cost, time, and spaces. However, current practices of prefabrication transportation are inefficient due to various involved stakeholders, outdated decision support tools, scarce real-time data, and ineffective information sharing mechanisms. To tackle these problems, and facilitate the management and operations of prefabrication transportation, this paper proposes a cloud-based fleet management platform through integrating the advantages of Internet of Things (iot) and cloud technology. A Transportation Management Service Sharing (TMSS) mechanism is proposed, which enables the platform to be easily and economically used by various transportation service providers, and could benefit all the other stakeholders involved. Besides, relation-based data extraction approach is proposed to extract sufficient transportation data during the whole process, and the transportation data synchronization mechanism is also worked out to ensure the data consistency. Finally, based on a real-life prefabricated construction project for public housing production in Hong Kong, a case study is conducted to verify the effectiveness of the proposed platform.

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1. Introduction

Prefabrication transportation refers to the transportation process of precast components from prefab manufacturers to construction sites. Its efficiency and quality directly determine the success of prefabricated construction as all the precast components should be well delivered to the construction sites punctually and safely for final assembly (Zhong et al. 2017). The entire construction project will benefit a lot from effective prefabrication transportation in terms of cost, time, and space savings (Li et al. 2017a; Polat 2008), while the late delivery of precast components has already become a major casual factor for project delay and cost overruns (Mok, Shen, and Yang 2015). The importance of prefabrication transportation has been widely recognized and many efforts have been made in practices to improve its efficiency and quality, such as establishing professional transportation companies with special made vehicles, adopting advanced information technologies, and optimizing its management and operation processes. However, due to the complexity, fragmentation, and uncertainty of transportation in construction industry (Aloini et al. 2012), the current situation of prefabrication transportation is still far from satisfaction.

CONTACT George Q. Huang gqhuang@hku.hk HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, University of Hong Kong, Hong Kong SAR, P.R. China

This research is motivated by a real-life prefabricated construction project for public housing in Hong Kong, which is located at Tuen Mun area and led by Hong Kong Housing Authority (HKHA). Due to the limited land supply and extremely high labor cost in Hong Kong, all its precast components are manufactured in Pearl River Delta (PRD) region of mainland China, and then be delivered by 3rd party transportation companies to the construction site in Hong Kong. This process is also called Cross-Border Prefabrication Transportation (CBPT) as all the precast components should pass the customs from Shenzhen to enter Hong Kong. This feature greatly increases the complexity and cost of prefabrication transportation. According to our pilot studies, the CBPT cost could take up 15–20% of the total production cost for these precast components, and several major problems still exist in practices: 1) There is no effective tracking and tracing mechanism for precast components during the transportation processes. Phone call is still the dominant method for checking the real-time transportation status. 2) It lacks an effective information sharing mechanism among transportation companies with the other stakeholders. Much time is spent on negotiating, discussing, and decision-making. 3) The information asymmetry and low efficiency of customs control force these transportation companies investing extra storage space near customs to deal with the uncertainties and ensure Just-In-Time (JIT) delivery of precast components.

The rapid development of Internet of Things (IoT) provides opportunities to solve these problems, and has been proved to be effective in many other areas, such as industrial park (Qiu et al. 2015), urban flood control (Xu et al. 2017), supply chain management (Li et al. 2017b), and manufacturing systems (Cheng et al. 2016). Meanwhile, the emerging of cloud technology also makes it possible for industries to share their information and services (Curry et al. 2013), and integrate diverse applications (Li et al. 2013).

However, the attempts on prefabrication transportation are still limited. It is challenging to directly adopt these advanced technologies in prefabrication transportation due to its specific and complex environments. Firstly, most of the involved transportation companies are Small and Medium Enterprises (SMEs) with relatively small fleet size. Therefore, considering the developing time and cost of IoT system, it is not affordable for them to make individual investment. Meanwhile, prefabrication transportation is only one part of their services that lasts one or two years based on the project time. It is unworthy for them to implement corresponding systems to satisfy the specific requirements of prefabrication transportation. Secondly, for one construction project, it may involve several transportation companies with different information systems. Besides, for each transportation company, it may also work on several projects paralleled, which usually have different requirements on data sharing. The complex many-to-many relationship makes it a great challenge for effectively sharing the real-time transportation information among stakeholders. Thirdly, data inconsistence always exists. On one hand, it is because the transportation data are collected independently and stored separately by each company. On the other hand, the poor network connections during the prefabrication transportation, especially during CBPT where a switch of network providers takes place near the border area, will further impede the synchronization of data among different companies.

To well address the above issues, this paper proposed a cloud-based fleet management platform for prefabrication transportation through integrating IoT and cloud technology. By visualizing all the transportation resources into the cloud, this solution enables the pay-per-use mode that transportation companies could dynamically access and configure the services to satisfy their own management activities and fulfill the diverse project requirements. Meanwhile, to further lower the implementation cost on data collection while ensuring sufficient real-time information during the transportation processes, relation-based data extraction method is proposed. Furthermore, a data synchronization mechanism is worked out to guarantee the data consistency among stakeholders under different network connection environments.

The rest of this paper is organized as follows. The related works are reviewed in Section 2. Section 3 presents the framework of the cloud-based fleet management platform, including its business mode and information infrastructure. Section 4 describes the relation-based data extraction method and Section 5 discusses the transportation data synchronization mechanism. After that, a case study is given in Section 6. Finally, Section 7 concludes the whole paper and points out the future works.

2. Literature review

The relevant literatures can be categorized into two streams: prefabrication transportation and fleet management system.

2.1. *Prefabrication transportation*

Prefabricated construction is an innovative construction paradigm that has been accepted worldwide as it could save time and cost, improve project quality, and ensure much higher safety standards and resource levelling (Hsieh 1997). It mainly consists of three phases, from prefabrication production, transportation, to final assembly at construction sites. Transportation plays a vital role leading to the success of prefabricated construction and inefficient transportation will easily make the benefits of prefabricated construction wither away. The late delivery of precast components will cause heavy penalty on the working hour losses of cranes and workers (Pheng and Jayawickrama 2012), while earlier delivery would congest the construction site and take up its limited onsite storage spaces (Polat 2008). Besides, the cost of prefabrication transportation is usually very high, especially in CBPT or the cases involving multimodal transportation (Wong, Hao, and Ho 2003).

Some efforts have also been made to improve the efficiency of prefabrication transportation and ensure its service level. For example, Li et al. (2011) pointed out the importance of DFL (Design for Logistics) in prefabrication transportation, and adopted the technology of virtual prototyping to ensure the feasibility of transportation processes. Pheng and Chuan (2001) studied the benefits of JIT philosophy in prefabrication transportation, and proposed the cost sharing mechanism to incent stakeholder to commit to JIT deliveries. And Demiralp, Guven, and Ergen (2012) studied the cost sharing problem in prefabrication transportation for the deployment of automated data collection technologies. To simplify the complexity in tracking precast components during the transportation processes, Ergen and Akinci (2008) formalized the flow of component-related information based on the observations in United States.

However, efforts on prefabrication transportation are still scarce, leaving most of the practices at the preliminary stage. Information systems and automation tools are still luxuries for a large portion of involved companies, which makes the transportation process inefficient and costly. Besides, the coordination and information sharing among stakeholders is ineffective and most decisions are made based on limited data separately, relying heavily on the subjective experiences of logistics managers.

2.2. *Fleet management system*

Fleet management stays a hot topic for decades both in academy and industry. It refers to a wide range of fleet-related systems in areas of transportation, distribution, and logistics (Billhardt et al. 2014). With the development of economy, logistics and transportation companies are facing much more rigors requirements on the quality, safety, reliability, efficiency, punctuality, and flexibility of transportation services. To meet these requirements while reducing costs and empty mileage, there are increasing demands on efficient fleet management. Many efforts have been made from both theoretical and technical aspect to facilitate the management and operation of fleet management in various areas, including bus systems (Leksakul et al. 2017), emergency vehicle management (Xu et al. 2017b), delivery systems in industrial park (Qiu and Huang 2016), etc.

Many technologies have also been developed and adopted for fleet management. For example, Billhardt et al. (2014) proposed the concept of cyber vehicle to realize dynamic fleet management, and adopted it in Madrid for ambulance coordination. Focusing on the fleet of hazmat transportation, Asadi and Ghatee (2015) proposed a rule-based decision support system for searching the safest solution for routing, scheduling, and assignment of hazmat delivery. And Awasthi et al. (2011) proposed a centralized fleet management system for cybernetic transportation in dedicated environments, such as shopping centers and parks. Through using cloud computing and mobile computing techniques, Chen et al. (2016) developed a garbage truck fleet management system to forecast the arrival time of garbage trucks. Belmonte, Pérez-de-la-Cruz, and Triguero (2008) developed a multi-agent bus fleet management system, and proposed a complete ontology representation for its knowledge. Besides, Auto-ID technologies and Global Positioning System (GPS) have also been widely adopted for tracking and tracing of vehicles and the transportation processes (Oliveira et al. 2015).

However, focusing on the transportation issues in prefabricated construction, the research and practices are still limited. Moreover, since there are too many uncertainties and disturbances during the transportation processes (e.g. caused by traffic jam, custom clearance, weather conditions, and changes of project schedules), the project-based transportation modes, special trucks involved, and the heavy and bulk precast components, improvements and innovations are still needed to adopt current technologies and approaches for prefabrication transportation.

3. Cloud-based fleet management platform

The concept of cloud computing has been proposed for over ten years and its blasting development recently has greatly changed the world in nearly every aspect. With the characteristics of on-demand self-service, resource pooling, and rapid elasticity (Mell and Grance 2011), cloud computing provides opportunities for industry to do their business more efficiently, flexibly, and economically, and many cloud-based applications have been built in diverse fields, such as manufacturing (Ren et al. 2017), healthcare (Xu et al. 2017a), and land resource management (Fang et al. 2017).

Inspired by existing cloud applications and their business modes, and aiming at facilitating the management process of prefabrication transportation while minimizing the investment on relevant systems and devices for individual transportation company, a cloud-based fleet management platform is proposed. In the following of this section, its business mode will be explained first, and then the information infrastructure will be illustrated.

3.1. *Transportation management service sharing (TMSS)*

One of the most important features of cloud computing is sharing the configurable resources among many users (cloud clients) flexibly with minimal management efforts (Mell and Grance 2011), for example, virtual storage resources sharing (e.g. OneDrive, Dropbox, and Baidu Yun), website development and internet hosting services sharing (e.g. Weebly, Wix, and Google Sites), and healthcare and medical services sharing (Xu et al. 2017a). Considering the scenarios in prefabrication transportation, sharing should also be an effective approach to deal with the problems in the current practices, including unaffordable system investment for individual company, dynamic and varied system requirements, and ineffective information sharing among stakeholders. With this in mind, Transportation Management Service Sharing (TMSS) is proposed in this research which refers to sharing the management services and corresponding information infrastructure for prefabrication transportation among these 3rd party transportation companies, and applying the pay-per-use mode for them to decrease their burden on using advanced IoT system, and finally facilitating their management and operations.

In TMSS, a cloud-based fleet management platform, the supporting information infrastructure, will be developed and operated independently to provide rich transportation management services. The platform owner will be responsible for the implementation of these services and providing necessary technical support. It will also take charge of the maintenance and upgrading of the platform. Transportation companies could share these services by easily logging in the platform, configuring their basic information and working parameters. They do not have to know the implementation details of these services or maintain a professional technical team to use the platform, but only need to pay the platform according to their usage on these services. Besides, prefab manufacturers could also access the platform, place transportation orders to their contracted transportation companies, share their production progresses, and monitor the real-time transportation status. Meanwhile, the project contractors could track the transportation progresses of their construction projects from different transportation companies, and share the storage status at the construction sites with them. In TMSS, the prefab manufacturers and project contractors do not have to pay the platform, but use the platform freely as extra services provided by their contracted transportation companies.

TMSS could bring many benefits to all the involved stakeholders. For transportation companies, they are released from the development and management of information systems, which could greatly decrease their investment cost and make them more focused on transportation services. It would also improve their service levels and make them more competitive among other transportation service providers. For prefab manufacturers and project contractors, TMSS could provide them added value by facilitating their information sharing with transportation companies, and making real-time monitor of the transportation processes. For platform owner, by providing general transportation management services for different companies, they could receive much higher profits. Considering the whole process of prefabrication transportation, TMSS could facilitate the coordination among stakeholders, improve the transportation quality and efficiency, and finally facilitate the successful implementation of prefabricated construction.

3.2. *Information infrastructure*

The information infrastructure for TMSS, cloud-based fleet management platform, is proposed through integrating IoT and cloud technology. Especially, the concept of cloud asset (Xu, Huang, and Fang 2015) is adopted to realize automatic real-time data collection during prefabrication transportation. The framework of the platform is shown in Figure 1. Basically, it contains four layers, they are Smart Transportation Resource (STR) layer, Gateway Operating System (GOS) layer, Cloud Services layer, and Applications layer.

STR layer refers to the physical part of the platform. It consists of all the physical assets involved in the prefabrication transportation process, such as trailers, tractors, and depots. All these physical assets will be wrapped as smart assets so that they can be uniquely identified, be able to sense its real-time status, and communicate with the platform.

GOS is a light-weighted middleware system (Fang et al. 2013) that runs on fixed workstations or mobile devices. It connects and hosts a set of STRs nearby and makes onsite management of them. In this proposed platform, GOS serves as the bridge between STRs and cloud services.

Cloud Services layer provides various services for prefabrication transportation based on the mass data collected from STR layer. It has three key modules. Data/Asset Management Service module is responsible for managing all the registered cloud assets and the data collected from the physical world, and providing sufficient and consistent transportation data for the other modules. Based on these data, Decision Support Services module provides decision supports for all the management and operation activities involved in prefabrication transportation. And Platform Management Services module takes charge of the authority management for platform users and provides various platform-independent information sharing services. These cloud services can be further integrated and configured flexibly through Applications layer to meet the varied requirements in different scenarios.

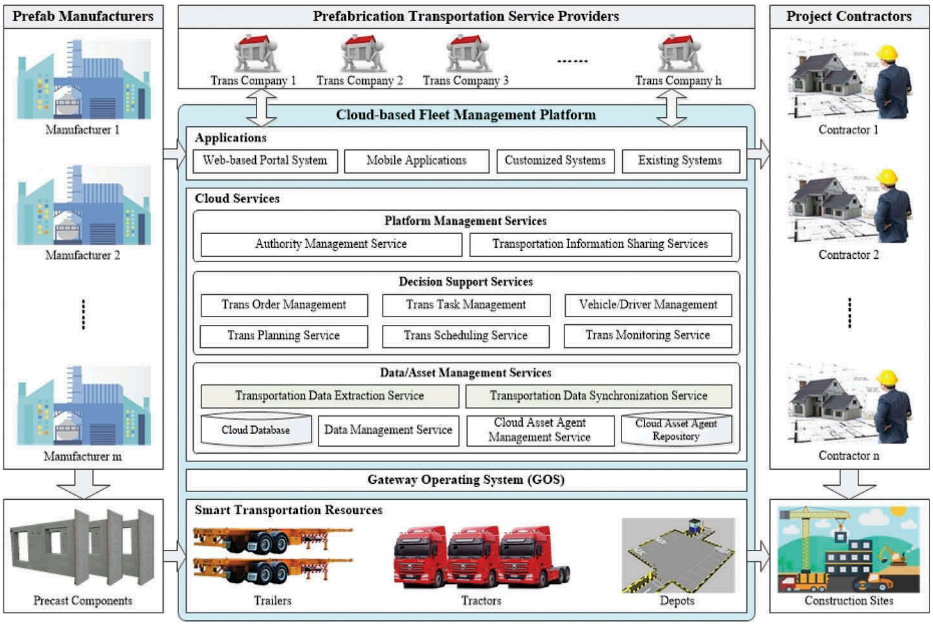

Figure 1. Framework of cloud-based fleet management platform.

Applications layer contains all the applications that are built upon these cloud services. Generally, four types of applications are provided: 1) Web-based portal system is the unique access point for different companies to use the platform. It provides general management and decision support tools for prefabrication transportation. For transportation companies, they only need to configure several basic parameters to use these tools. 2) Mobile applications serve as the Mobile GOS to make onsite management of STRs and collect real-time data from them. It also serves as cloud clients to access the cloud services, especially during the prefabrication transportation execution processes. 3) For those transportation companies with special requirements, they could build customized management applications based on cloud services. And 4) the platform is also compatible with existing systems deployed by involved stakeholders, which could access specific cloud services according to their own requirements. These four types of applications provide various means for users to access the platform, and further decrease the burden for diverse companies to use the platform.

4. Relation-based transportation data extraction

Data plays a fundamental role in the proposed cloud-based fleet management platform as they are the source to make decisions during prefabrication transportation. Despite STRs are capable to collect real-time data during the transportation process automatically, the accuracy and variety of data they collected rely heavily on the advancement and completeness of smart devices attached. It will be a great investment on smart devices to collect all the necessary transportation data from STRs, which may be unaffordable for transportation companies.

In order to decrease the investment of smart devices while ensuring sufficient transportation data collection for decision making, the relation-based data extraction approach is proposed and developed as a key data management service in the cloud-based fleet management platform. In the following, its basic design principles and working logics will be discussed in detail.

4.1. *Overview of relation-based data extraction*

Relation-based approach has been well developed and used in areas of computer science, like web search, knowledge discovery, and information retrieval (Li, Wang, and Huang 2007). Recently, it has also been widely applied in many industrial applications. For instance, Gorbenko, Popov, and Sheka (2011) adopted relation-based approach to realize self-awareness of mobile robots. Guibas (2002) used relations between sensors to improve the capabilities of sensor networks for high-level tasks. Yuan et al. (2017) used complete tolerance relation to fill the missing data in renewable energy analysis. And Bisio, Sciarrone, and Zappatore (2015) used the relations between BLE tags and assets to query and update the information associated with assets. However, it is still rarely adopted in transportation systems, and most of the current works are developed case by case. Improvements are still needed to apply relation-based approach to fit the dynamics and mobility of STRs in prefabrication transportation.

During the process of prefabrication transportation, all these involved STRs could connect with each other through physical or logical connections. For example, during the execution of a transportation task, the trailer would physically connect with a tractor that is dragging it to the construction site. Meanwhile, the trailer would also logically connect with the other trailers that are working on the same project. These ubiquitous connections form a large STR network, as shown in the upper part of Figure 2, which provide opportunities for extracting much richer real-time transportation data from STRs.

As illustrated in the lower part of Figure 2, none of STR 1, 2, and 3 have been fully equipped with smart devices to sense all their properties. Fortunately, through connecting with each other, relations among their properties are built, as shown by dashed arrows. Therefore, the value of previous unavailable properties can be extracted from corresponding properties of the other STRs without adding additional smart devices. Taking STR 2 as an example, the values of its property A and C could be extracted from STR 1 and 3 separately. Meanwhile, the values of its property B, D, and E can also be assigned to corresponding properties of STR 1 and 3. In this way, all the properties of STR 1, 2, and 3 can be collected. This method not only ensures sufficient transportation data collection, but also decreases the investment on smart devices.

Meanwhile, considering the dynamics of connections and make the approach easy to implement, the relations among their properties are designed as separate models of STRs, so that they could be dynamically established and removed along with the connection and disconnection between STRs.

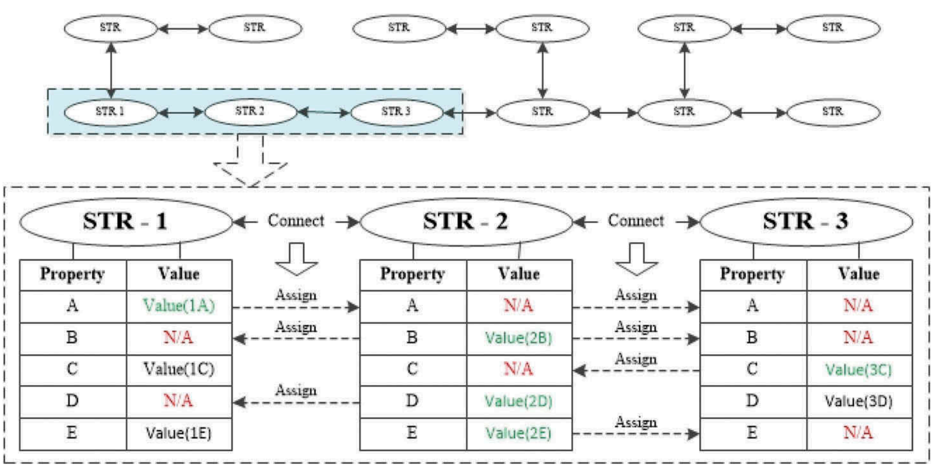

Figure 2. Relation-based transportation data extraction.

The formal description of a relation is depicted as follows:

$$R = (id, STR_1, STR_2, Property\,PairList, time, status)$$

Here, *id* is the unique identifier of the relation, which is used to build the cross-reference between STRs and relations. STR_1 and STR_2 represent the identifiers of the two connected STRs.

PropertyPairList presents the list of property matching pairs between the two connected STRs. Each property matching pair can be represented as:

$$PropertyPair = (STR_1.P_a, STR_2.P_b)$$

where $STR_1.P_a$ refers to the property *a* of STR_1 and $STR_2.P_b$ is the property *b* of STR_2. It is a directed pair that the first property is data provider while the second one is receiver. The above *PropertyPair* means the value of $STR_2.P_b$ can be obtained from the value of $STR_1.P_a$.

The last two elements are supportive parameters for the execution of the relation. *time* stores the last modification time, and *status* denotes whether the relation is active or inactive.

4.2. *Working logics*

The working logics of relation-based transportation data extraction can be divided into three stages, they are relation creation, execution, and removal, as shown in Figure 3.

4.2.1. *Relation creation*

The creation stage starts with the establishment of connection between the two STRs. After the connection is established, it will first check whether there is a relation generation rule for the current connection. Here, the generation rule provides guidelines of building the property matching pairs for the current connection type. The rule can be built manually by managers or operators based on their experiences, or extracted from knowledge base. If there is a generation rule, the relation will be generated automatically. Otherwise, it will be generated by filling all its necessary parameters manually. Meanwhile, this manual generation scheme will also be saved as a new relation generation rule. In this way, when the same connection type is established in future, relations can be automatically generated.

For every receiver (property) of an STR, it can only have one data provider (property) at a time, otherwise, collision may occur. Therefore, to avoid such collisions, the comparison of the

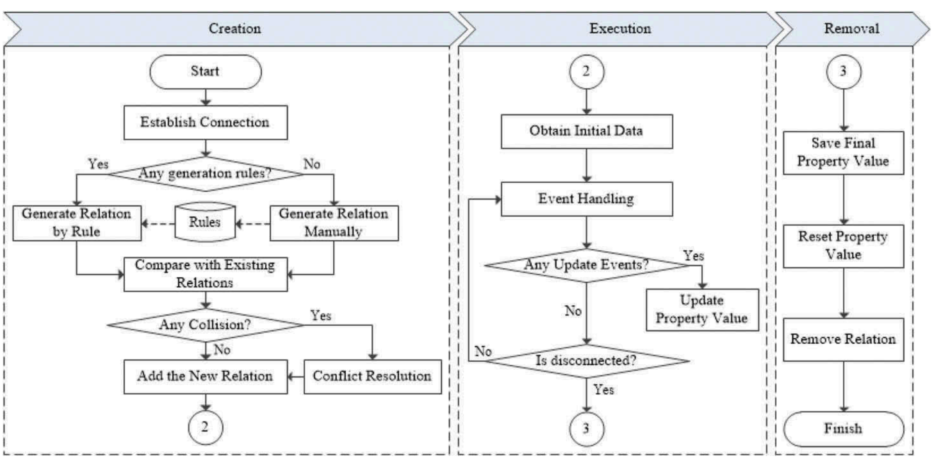

Figure 3. Working logics of relation-based transportation data extraction.

newly generated relation with existing relations should be made first before adding it into the relation list of STR.

Taken RP_{new} as receiver (property) set in the newly generated relation, and $RP_n^{STR_1}$ and $RP_m^{STR_2}$ as the receiver (property) sets in existing relations of STR_1 and STR_2 separately (n and m denote the relation numbers of STR_1 and STR_2). The comparison process can be depicted as follows:

$$C = RP_{new} \cap \left[\left(RP_1^{STR_1} \cup RP_2^{STR_1} \cup \ldots \cup RP_n^{STR_1} \right) \cup \left(RP_1^{STR_2} \cup RP_2^{STR_2} \cup \ldots \cup RP_m^{STR_2} \right) \right]$$

Only when $C = \varnothing$, which means no collision exist, the relation can be directly added into the relation lists of STR_1 and STR_2 without any modification. If $C \neq \varnothing$, collisions exist and C contains all these collide properties. Then it comes to the collision resolution step. The collision resolution can be made manually by adjusting these collide matching pairs. Besides, it could also be conducted by predefined rules automatically, such as keeping the latest matching pair through comparing the last modification time of relations. After all these collide properties are well handled, the revised relation can be added into the relation lists of the two STRs.

4.2.2. *Relation execution*

Once the relation has been added into the relation list of STR, the STR will obtain the initial data from corresponding STRs according to the property matching pairs defined in the relation. After that, the regular transportation data update cycle begins.

Considering the dynamic and varied relations among STRs, it would be difficult to implement any additional or specific data update mechanisms for each of them. Therefore, to make it easy to implement, all the receiver properties will update their data in accordance with the updating of their data providers.

Event-based method is selected to implement this idea into reality. When there is an event, the event handling process begins. If it is a data update event, the corresponding receiver (property) will update its value accordingly. Otherwise, it will check if the two STRs are disconnected. If not, the data update cycle continues. Otherwise, it enters the removal stage.

4.2.3. *Relation removal*

During the removal stage, the two STRs in the relation will first save the final value of the involved receiver properties as the last available status in a separate place/file, and then reset their current values to ‘N/A’. After that, the status of the relation will be changed into ‘inactive’, and finally be removed from the relation lists of the two STRs.

5. Transporation data synchronization

Data inconsistency is another important and frequently happened issue in prefabrication transportation as there are so many sources available that provide diverse transportation data. Besides, the network connection of STRs cannot always be guaranteed, which further increases risks of data inconsistency. To address this problem, transportation data synchronization mechanism is worked out in this section with its detailed data reconciliation method.

5.1. *Overall synchronization mechanism*

Efficient data synchronization mechanism is effective for maintaining data consistence, and many mature models are available for data synchronization (Foster et al. 2007). In IoT systems, considering the adoption of smart objects, Suzuki and Harrison (2006) defined five degrees of data synchronization, in which the highest level is allowing disconnected operations while allowing data updates in both smart object side and the platform side. To realize the highest level of synchronization, Kubler et al. (2015) introduced a data synchronization strategy in CL2M (Closed

Loop Lifecycle Management) through using 'communicating materials', and proposed several data synchronization models for CL2M (Kubler et al. 2014).

Based on these efforts of data synchronization in IoT system, and considering the scenarios of prefabrication transportation, the transportation data synchronization mechanism is proposed, as illustrated in Figure 4.

In cloud-based fleet management platform for prefabrication transportation, four types of entities are involved: STR, GOS, cloud services, and applications. All of them have databases except applications, and conflicts and data inconsistences may exist among these databases. Compared with the connections between STRs and GOS (see arrows a and b in Figure 4(a)), the connections between GOS and cloud services (see arrows c and d in Figure 4(a)) are much more vulnerable since they mainly rely on public communication network while the formal ones rely more on local connections. Therefore, in the following, besides the always-connected situation, the disconnected situation where GOS temporary disconnects with cloud services will also be considered to discuss the transportation data synchronization strategy.

(1) Always-Connected Situation (the left part of Figure 4(a)): In this case, every entity is networked and the STR is available in the network at any time. To realize its transportation data synchronization among all these entities, only STR is assigned as the master source, and the others only have

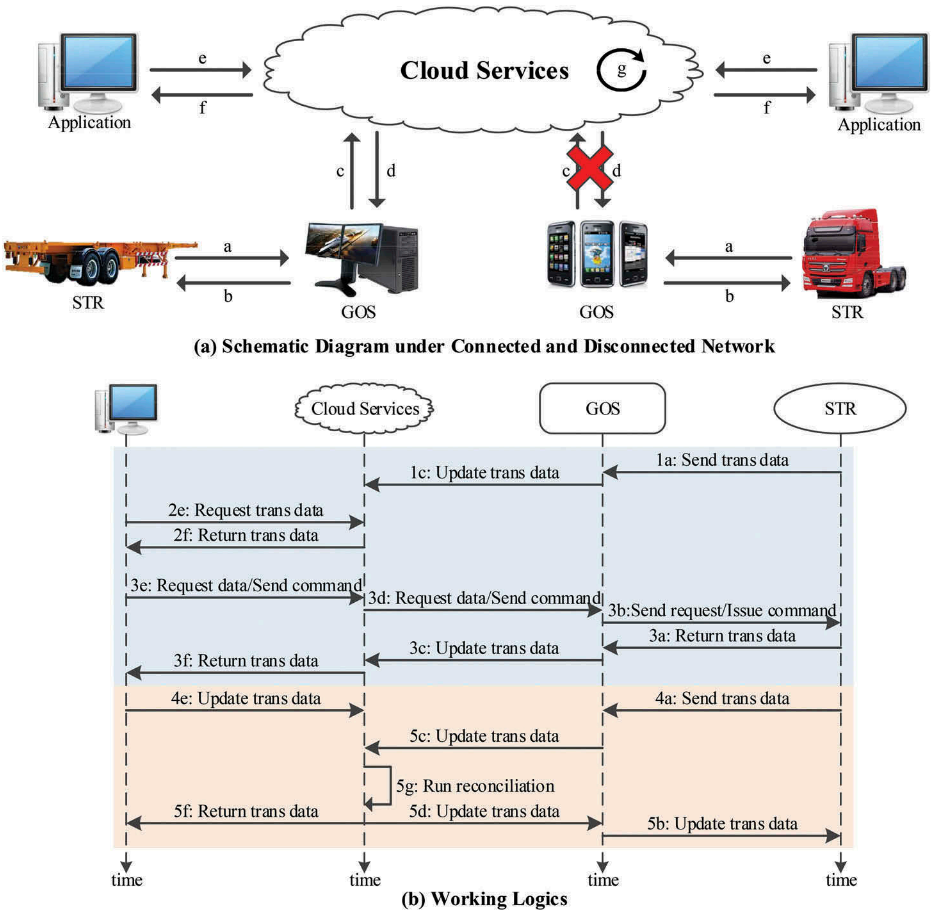

Figure 4. Transportation data synchronization mechanism.

replica versions of its data. In other words, only the STR could update its transportation data. The detailed working logics in this situation are depicted in the follows:

- Update transportation data (see arrows 1a and 1c in Figure 4(b)): based on the predefined updating strategies, STR updates its data to GOS automatically (1a). Then GOS will update the data into the cloud (1c).
- Read transportation information (see arrows 2e and 2f in Figure 4(b)): users send request to the cloud (2e), and then, the cloud will retrieve its own database for the information and return to users.
- Read information or send command (see arrows 3e, 3d, 3b, 3a, 3c, and 3f in Figure 4(b)): if the requested information cannot be fetched in the cloud or user wants to send command to STR, the cloud services will forward the request/command to GOS (3d), which will forward it to STR (3b). After receiving request/command, the STR will begin to execute or return the data step by step (3a, 3c, and 3f).

(2) Disconnected Situation (the right part of Figure 4(a)): In this case, GOS will occasionally disconnect with the cloud services, which makes the network be temporary divided into two parts. In order not to interrupt the execution and management processes, two master sources exist simultaneously in this situation: STR and the client application. Both of them could update the transportation data during the disconnected stage. When the network is recovered, the data collected from both sources will be synchronized in the cloud and then disseminated to the other entities. The detailed working logics in this situation are presented in the following:

- Update transportation data (see arrows 4a and 4e): In this case, the STR continues updating its data to GOS (4a). However, since GOS cannot forward the data to the cloud, it will temporary store these data in its database. Meanwhile, users could also actively update the transportation data collected manually through the client application (4e). These data will then be stored in the cloud.
- Synchronize data from two master sources (see arrows 5c, 5g, 5f, 5d, and 5b): As long as the network is recovered, GOS will upload the data into the cloud platform (5c). Data inconsistency may occur here when synchronizing the data stored in the cloud (updated by users through the cloud client) and uploaded by GOS. Therefore, the cloud services will run the data reconciliation process to generate consistent transportation data (5g), and then disseminates the result to the others step by step (5f, 5d, and 5b).

These synchronized data will then be sent to decision support services to support the management and operation activities in prefabrication transportation.

5.2. *Data reconciliation method*

Considering the management and operation scenarios in prefabrication transportation, and make it easy to be implement and execute in the cloud-based fleet management platform, the transportation data reconciliation method mainly considers two factors, one is the confidence value of the data source, and the other is the last modification time (timestamp). Based on this idea, the proposed data reconciliation method can be depicted in Algorithm 1.

Basically, it contains three steps. The first (line 1–5) is examining the data validity, including its integrity and format. If it is valid, its hash value will be generated using a weak hash algorithm, and then the second step (line 6–8) could decide whether a data reconciliation is needed by checking its hash value in the cloud. The third step (line 9–15) is the data reconciliation process that updates the data through comparing the confidence value and timestamp between the newly collected data and the existing data stored in the cloud.

In Algorithm 1, the basic operations include calculating hash value and comparing the confidence value and timestamp, no loops and extra spaces are needed. Therefore, both the time complexity and space complexity are *O(1)*. It makes this algorithm easy to implement and execute in the platform or even on mobile devices.

Algorithm 1: Transportation Data Reconciliation

Require: D_n–The newly collected transportation data
Require: D_c–The corresponding transportation data in cloud

if D_n is validate
  Hash(D_n) → D_n.*hashvalue*
else
  return
end if
if D_n.*hashvalue* equals to D_c.*hashvalue*
  return
end if
if D_n.*confidence* is bigger than D_c.*confidence*
  D_n → *CloudData*
else if D_n.*confidence* equals to D_c.*confidence*
  if D_n.*timestamp* is later than D_c *timestamp*
    D_n → D_c
  end if
end if

6. Case study

In this section, a real-life case study will be given to demonstrate the management and operation processes of prefabrication transportation through the proposed cloud-based fleet management platform, and evaluate its effectiveness and efficiency.

6.1. *Scenario description*

The case is based on a real public housing project 'Tuen Mun Area 54 Site 2, Phases 1 & 2', which is located near Siu Hong Station, Tuen Mun, New Territories, Hong Kong, and conducted by HKHA (Project Website: http://www.autom.hk/bimp/). Gammon Construction Ltd. (Gammon) is the general project contractor who is in charge of the construction site and taking execution control for the overall project. Wing Hong Shun Ltd. (WHS), a prefab manufacturer located in Huizhou, Guangdong Province, is the precast components provider, and Yingyun Transportation Ltd. (Yingyun) is one of the major transportation service providers in this project.

For the prefabrication transportation of this project, Yingyun has allocated 14 drivers, 14 tractors, 29 trailers, and 2 resident managers at WHS and Gammon separately. Meanwhile, it also provides temporary warehousing service in Hong Kong near the construction site. In this case, WHS creates transportation orders three to five days before due date based on the project progress reported by Gammon, and then releases them to resident manager of Yingyun. Yingyun will then make detailed transportation plans and schedules to ensure JIT delivery. Yingyun usually picks up the orders from WHS one to three days in advance and stores them in its temporary buffer warehouse. After the resident manager at Gammon reporting the availability of buffer space at construction site, these orders will then be delivered from the buffer warehouse to the site.

Besides this project, Yingyun is also conducting many other transportation tasks paralleled. Due to the variety of its customers and limited budget, there is still no information systems adopted at Yingyun for its transportation management.

6.2. *Platform implementation*

According to the framework and technologies discussed in previous sections, the cloud-based fleet management platform is developed under Java Runtime Environment (JRE) and deployed in our private cloud. The cloud contains seven physical servers with ESXi installed on each of them. A vCenter is used to manage all these ESXi hosts while OpenStack is adopted to manage the computing, storage, and network resources. Meanwhile, Apache 2.4 is selected as the HTTP server to drive cloud services, as well as the web-based application. In addition, the mobile application is also developed for Android devices to access the cloud services. This configuration makes the platform could handle dynamic demands, resilient to disruptions, and ensure stable services to end users.

For transportation service providers, besides the authorization process, they could use the platform through two major steps: platform configuration and platform execution. In the following of this part, we will use Yingyun as the case company to demonstrate the detailed processes of the two steps.

6.2.1. *Platform configuration*

The configuration process refers to configuring company-specific information into the platform. It should be conducted from both the hardware aspect and software aspect.

From the hardware aspect, all the transportation resources involved in this project will be equipped as STRs. To save the implementation cost, both trailers and tractors are equipped with small round Near Field Communication (NFC)-enabled RFID tags (cost about $0.08 per tag), as illustrated in Figure 5. For each trailer, the tag is attached near its right tail light. For the tractor, the tag is stuck near its dashboard, where is easy for drivers to scan.

From the software aspect, managers of Yingyun could login the platform through any networked devices with Internet browser that supports JavaScript, and register all the information of STRs and drivers, as shown in Figure 6. Meanwhile, they can also make pre-assignment of drivers to specific tractors by their proficiency on different types of tractors. Besides, for the drivers of Yingyun who will participate in the prefabrication transportation, they should install the mobile application in their own phones (Android phone with NFC and GPS functions is

Figure 5. Hardware configuration for STRs (Trailers and Tractors).

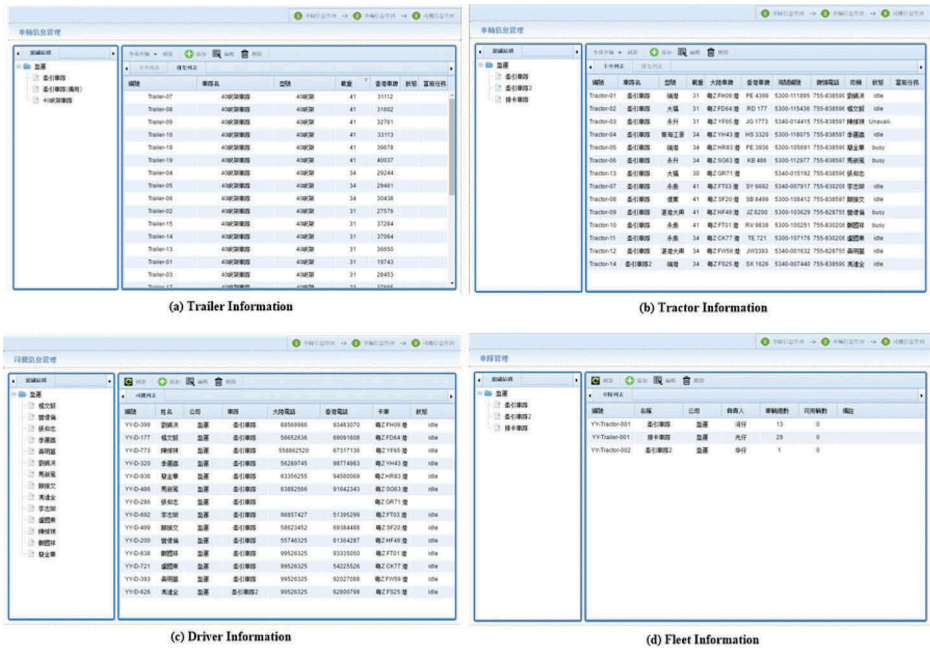

Figure 6. Information registration of STRs and drivers.

required, usually costs about $200). Their phones will serve as mobile gateways during the execution of the platform, and responsible for collecting real-time transportation data from STRs.

6.2.2. *Platform execution*

The platform execution process is based on the management activities in prefabrication transportation, and can be divided into three phases, as shown in Figure 7.

6.2.2.1. ***Order management.*** The platform provides an order management module for all involved stakeholders in prefabrication transportation (The upper layer of Figure 7). For managers of Yingyun, they could login the platform and check the status of all the transportation orders, and release selected orders for scheduling and execution. The platform also provides interfaces for prefab manufacturers (e.g. WHS) to import their transportation demands from Excel files, XML files, or databases. Besides, all the authorized managers, no matter from Yingyun, WHS, and Gammon, could login the platform and monitor the real-time status, locations, and routs of their ongoing transportation orders, and check the information of historical orders.

6.2.2.2. ***Transportation scheduling.*** Once the transportation orders are released from the order management module, the schedulers of Yingyun could begin to make transportation plans and schedules through the cloud platform (The middle layer of Figure 7).

Three basic management tools are provided in this module. Firstly, the order evaluation tool helps schedulers to evaluate both priorities of these orders and the capacity of available fleet. Secondly, the transportation planning tool can assistant schedulers to make transportation plans and schedules. They can also adjust the result manually based on their experiences, or configure their own rules for making decisions. Thirdly, after transportation orders are divided into atomic transportation tasks, the task assignment tools could automatically assign these tasks to drivers. Logistics managers can also assign these tasks through drag-and-drop

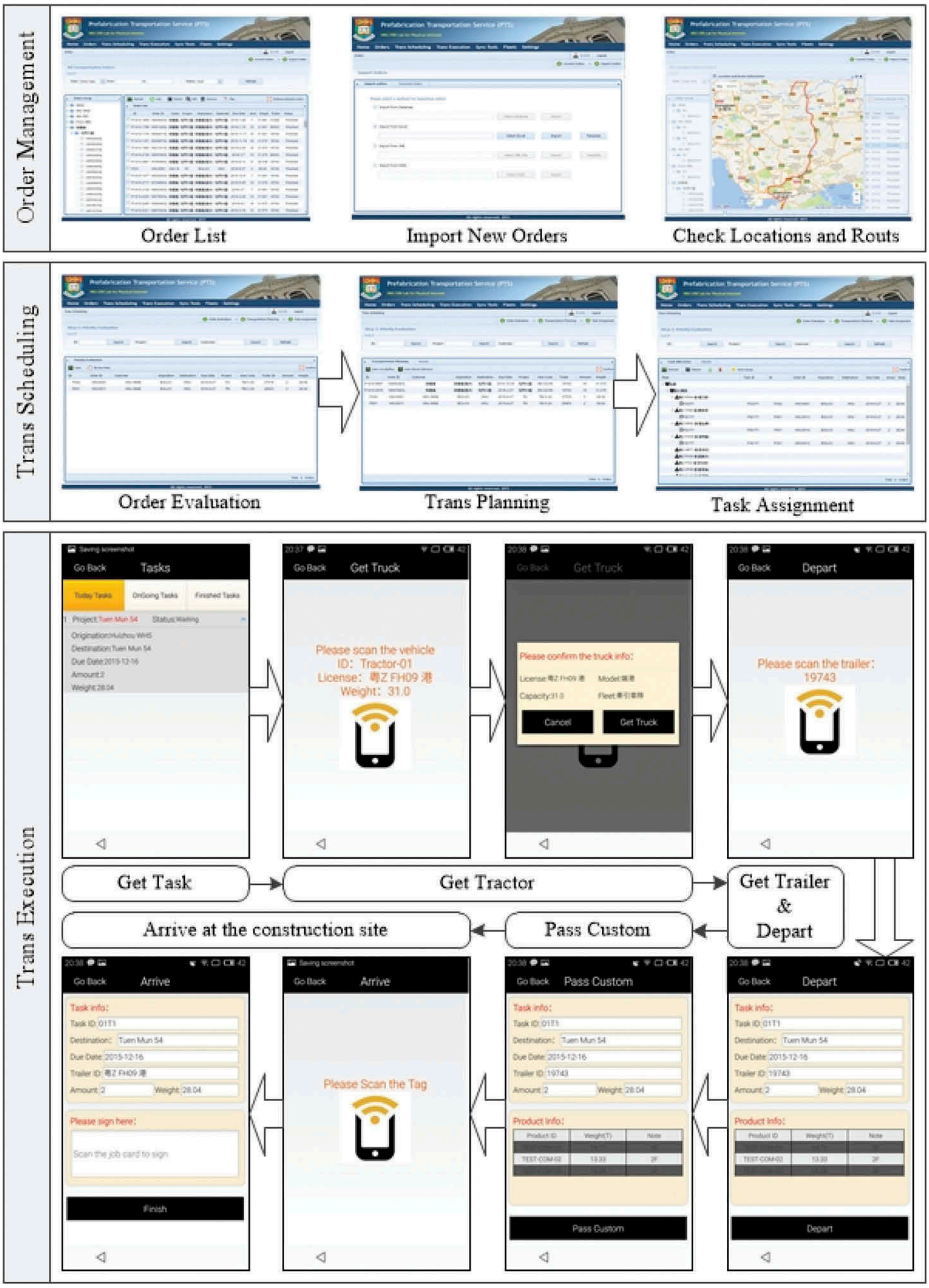

Figure 7. Management and operation processes of prefabrication transportation.

operations in the platform without any other inputs. After all these tasks are well assigned, they could be released to drivers for execution.

6.2.2.3. *Transportation execution.*

After these transportation tasks are released to drivers, the transportation execution stage begins. The general working logics of this stage are shown in the bottom of Figure 7.

For the drivers in Yingyun, they can login the mobile application with the pre-assigned accounts to use the platform services. They could check their pending tasks and select one to conduct. Then the mobile application will show them which tractor and trailer to get. After scanning the corresponding tags attached on tractor and trailer, drivers could check the information again and then move to the next step. Meanwhile, the tractor, trailer, and the mobile phone will also be bound together through the two scanning processes, which makes it possible to extract the transportation data, including time, location, rout, and speed of the ongoing tasks, through the sensors of mobile phone during the task execution process. The mobile application also provides a tool for drivers to report the status of passing the custom. After drivers have arrived at the destination, they can scan the tags on the trailer again for receivers to check the task information. If it is correct, receivers could sign through the phone, which indicates the transportation task is well finished.

All the transportation data collected during the execution phase will be shared in real-time manner to authorized project contractors to generate real-time n-Dimensional BIM model, project progress report, and real-time status of prefab components, as shown in Figure 8.

6.3. *Discussions*

During this case study, totally 190 transportation orders (90 order groups) have been imported to the platform by WHS. Taken these orders, Yingyun has generated and executed 345 transportation tasks

(a) nD BIM model

(b) Project Progress

(c)Real-time Status of Each Prefab Component

Figure 8. Transportation information sharing for project contractors.

through the platform. These transportation tasks have covered the whole prefabrication transportation process from the 5th floor to the 37th floor of block 5 in the project. Many advantages of adopting the cloud-based fleet management platform have been shown up through the case.

Firstly, compared with traditional method, TMSS greatly decreases the cost for transportation companies to use the IoT system. According to our investigations, it would cost over $70,000 to customize a fleet management system from 3rd party companies with more than three months' lead time. However, through TMSS, Yingyun only needs to pay the platform about $750 per year for rich up-to-date fleet management services, and could begin to use the platform once paid and registered. Meanwhile, in our case, the extra hardware investment (RFID tags for tractors and trailers) for Yingyun is less than $5.

Secondly, the platform is easy to be adopted by transportation service providers. On one hand, the platform configuration process is simple, as in this case, it only took less than half a day to finish both the hardware and software configuration. On the other hand, the operation procedural for the web-based system and mobile application is clear and easy to follow, no special professional knowledge is required to use the platform.

Thirdly, the management cost has been reduced by means of less paper-works and phone calls. Through using the platform, most of the information could be checked through the web-based application or mobile apps, the printed hard copies have been reduced from 5 papers per task to 3 papers per task. Besides, since the platform provides a medium for all stakeholders to share the information digitally in real time, the number of phone calls and the workload of resident managers at WHS and Gammon have also been greatly reduced. It is even possible to cancel the positions of resident manager in the future to further save the cost.

Fourthly, the efficiency of the transportation management processes has been greatly improved. Many repetitive manual works have been replaced by the platform through automatic tools, such as transportation scheduling and task releasing. Besides, through the real-time information sharing, the average waiting time for drivers to pick up the transportation orders at WHS has also been reduced from 2 hours to 1.2 hours, and the on-time delivery rate has been improved from 92.5% to 99.7%.

Despite the benefits acquired, there are also some limitations. One of the most important one is that the security and privacy issues have not been well addressed. During the implementation of the platform, a lot of sensitive data will be collected from prefab manufacturers, transportation service providers, project contractors, and project owners. The security and privacy issue would be one of the most important concerns for them to use the platform. Currently, Apache Shiro™ is adopted to provide basic security control, while in the future, more strict security and privacy control strategies (Basu, Sengupta, and Mazumdar 2016; Casola et al. 2017; Yang et al. 2017) should be considered. Besides, the scalability and compatibility of the platform should also be further tested in many other prefabricated construction projects.

7. Conclusions

Transportation plays an important role to harvest the benefits of prefabricated construction, and its efficiency directly determines the success of the whole construction process. In order to facilitate the management and operation of prefabrication transportation for various transportation service providers with relatively lower cost, this paper proposed the concept of TMSS, and built a cloud-based fleet management platform through integrating IoT and cloud technology. Besides, to realize sufficient and accurate transportation data collection, the relation-based data extraction approach and data synchronization mechanism is proposed. The platform has been verified through a real-life prefabricated construction project in Hong Kong, and many advantages could be gained by all the involved stakeholders.

The contributions of this paper lie in the following aspects. Firstly, TMSS is proposed as a new paradigm for transportation companies to adopt the cutting-edge IoT technologies for its management and operation processes. TMSS is more flexible and economical, and enables the sharing of information among all the authorized stakeholders. This paradigm can also be applied in many other areas, such as warehouse management and manufacturing execution management. Secondly, the relation-based data extraction approach provides the opportunity to get rich information under limited sensing devices. It could further decrease the investment of smart devices for transportation companies to use the platform. Thirdly, based on the scenarios of prefabrication transportation, this paper proposed a mechanism for transportation data synchronization, which could ensure the data consistence and the smooth execution of the platform under instable networks. The approach can also be extended in many other scenarios.

In the future, this research can be further extended from the following aspects. Firstly, the decision-making models for different stages of prefabrication transportation should be further studied to figure out the best solutions. Secondly, although generation rule is adopted to avoid repetitive configurations for using relation-based data extraction, automatic tools should also be developed to further decrease manual works and make the method easily adapt to more complex scenarios. Thirdly, data analytical tools should be included for mining knowledge from the mass real-time transportation data collected from STRs. Fourthly, the business mode of the TMSS, including its pricing mechanism should be further researched to implement this idea to the wide public.

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ORCID

Gangyan Xu http://orcid.org/0000-0001-9537-9006
George Q. Huang http://orcid.org/0000-0003-3592-7917

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