www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

LEVERAGING CONSTRUCTION INSPECTION AND DOCUMENTATION FOR ASSET INVENTORY AND LIFE CYCLE ASSET MANAGEMENT

REVISED: April 2016
PUBLISHED: May 2016 at http://www.itcon.org/2016/5
EDITOR: Amor R.

Chenxi Yuan, Ph.D. student,
Division of Construction Engineering & Management, School of Civil Engineering, Purdue University
Email: yuan89@purdue.edu

Timothy McClure, Ph.D. student,
Division of Construction Engineering & Management, School of Civil Engineering, Purdue University
Email: tmcclur@purdue.edu

Phillip Dunston, Professor,
Division of Construction Engineering & Management, School of Civil Engineering, Purdue University
Email: dunston@purdue.edu

Hubo Cai, Associate Professor,
Division of Construction Engineering & Management, School of Civil Engineering, Purdue University
Email: hubocai@purdue.edu

SUMMARY: *Accurate and complete construction records and as-built data are key prerequisites to the effective management of transportation infrastructure assets throughout their life cycle. The construction phase is the best time to collect such data. Assets such as underground drainage and culverts are visible and physically accessible only during construction. For assets such as guardrails, signals, and pavement, it is safer and more efficient to collect their data during the construction, before the road segment is open to traffic, than after construction. This paper presents a mobile application that is centered on construction inspection activities to leverage the construction inspection and documentation practice for asset inventory. Pay item is a specific unit of work with an estimated price, based on which a contractor is paid during construction. Therefore, the newly developed mobile application utilizes pay items as the bridge to match plan assets, i.e., physical structures prescribed in design documents, with corresponding assets in asset management database. Based on the match, an inspection activity-centered mechanism is created to facilitate the automatic conveyance of construction documentation data to asset management database. Implemented on a platform of mobile device, the application has been conceptually tested using an example asset—small culverts in a construction project of the Indiana Department of Transportation. It was validated that the newly proposed mobile application design scheme could leverage the existing construction inspection and documentation work to eliminate the individual data collection efforts for asset inventory purposes in current practice.*

KEYWORDS: *Asset data collection, construction documentation, field inspection, pay items, asset inventory of transportation infrastructure.*

REFERENCE: *Chenxi Yuan, Timothy McClure, Phillip Dunston, Hubo Cai (2016). Leveraging construction inspection and documentation for asset inventory and life cycle asset management. Journal of Information Technology in Construction (ITcon), Vol. 21, pg. 72-85, http://www.itcon.org/2016/5*

1. INTRODUCTION

Having accurate and complete in-place data, i.e. the construction records and as-built data, of transportation infrastructure assets is a key prerequisite to their effective management, operation, and maintenance (WERD 2003; Gordon et al. 2011). Such data reflect the nature of infrastructure assets: materials and assemblies that were used, construction means and methods, location, quality as measured by inspections and testing, and performance measures (NCHRP 2009; AASHTO-AGC-ARTBA Joint Committee 2006). They provide reliable information for life cycle performance prediction and decision-making at strategic, network, and project levels (Flintsch et al. 2006; Harrison 2005; Markow 2010).

The construction phase is the best time to collect such data. Assets such as underground drainage and culverts are only visible and physically accessible during construction. Once backfilled, compacted, and covered by concrete and/or asphalt, they are neither visible, nor accessible, except the outlets. As vegetation grows and covers these outlets, finding them in the field is also challenging. For instance, Indiana Department of Transportation (INDOT) spent thousands of crew hours in a summer just to locate and inventory outlets along major highways. Unfortunately, it is almost impossible to inventory all the underdrains because they are not visible anymore and to do so, we might have to run ground penetrating radar (GPR) scans along all major roads, and collect and process huge amount of data with no guaranteed accuracy. Even for assets that are still visible and accessible after construction, such as guardrails, signals, and pavement, it is much safer and more efficient to collect data during construction, before the road segment is open to traffic, than after construction.

In the current practice, the construction documentation process and the asset in-place data collection process in state highway agencies (SHAs) are two separate processes (Yuan et. al 2016). The construction documentation process focuses on construction pay item—a specific unit of work with an estimated price, based on which a contractor is paid during construction. Resulting documentation, while extremely information-rich, covering every single construction detail, is heterogeneous in format (digital versus paper) and data structure. To meet the data requirements for the operation and maintenance (O&M) and the life cycle management of assets, a separate process for collecting asset in-place data—asset inventory—exists in SHAs. Unfortunately, this process is typically carried out after construction is complete and the road/bridge facility is open to traffic. At that time, many underground assets are covered, not accessible anymore; collecting asset data with on-going traffic is neither effective, nor safe.

The separation of the construction documentation and the asset in-place data collection processes in the current practice leads to three problems: duplicate data collection efforts, low productivity, and information loss. There is a need to integrate the construction documentation process and the asset in-place data collection process to collect accurate and complete construction records and as-built data of transportation infrastructure assets during the construction phase, and facilitate its usage in the downstream O&M phase. Had such a system in place, the duplicate data collection efforts, such as those by INDOT to inventory its outlets along major highways, could be eliminated to save costs for SHAs.

Having investigated current field data collection software as well as collaborating with INDOT for a mobile application prototype, the authors propose a new application design scheme that is centered on construction inspection activity to leverage the construction inspection practice for asset inventory. Observing that construction inspection and documentation at many state highway agencies is based on pay items, the proposed framework utilizes pay items as the bridge to match plan assets, i.e., the physical structures prescribed in design documents (plans/drawings), with corresponding assets in asset management database. Based on the match, an inspection activity-centered mechanism is created to facilitate the automatic conveyance of construction documentation data to asset management database. The design scheme is being tested and validated on a platform of mobile device using one type of assets—small culverts in a construction project of the Indiana Department of Transportation (INDOT).

2. BACKGROUND

Transportation asset management (TAM) is a data-driven decision making process. Transportation agencies have been using information management systems to operate and maintain infrastructure asset data since 1990s (WERD 2003; Nemmers 1997; FHWA 1999). In U.S., SHAs have implemented individual asset information management systems, such as highway performance management system (HPMS), pavement management system (PMS), and bridge management system (BMS) to host different components of transportation assets (Flintsch 2006). Generic framework was also proposed to host multiple types of assets in a single information system, such as Model Inventory of Roadway Elements (MIRE) (Lefler et al. 2010). Building information modelling (BIM), owing to its object-oriented characteristics, enables the use of emerging technologies for information management throughout the project's lifecycle in infrastructures (Su et al. 2011; Hill 2012; Wang et al. 2014; Abanda et al. 2015; Shou et al. 2015; Davenport and Voiculescu 2015). Especially, cloud BIM and mobile BIM, which incorporate existing emerging mobile technologies, can seamlessly collect, track, and share field data during construction, and greatly facilitate the construction inspection and documentation process (Wong et al. 2014, Redmond et al. 2012, Lin et al. 2014, Delcambre 2014).

With the rapid development of these asset information modelling and management systems as well as the increasing need for accelerated project delivery with accurate data, Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), American Road & Transportation Builders Association (ARTBA), and Associated General Contractors of America (AGC) have been jointly promoting Civil Integrated Management (CIM) into highway projects. The ultimate goal of CIM is to collect, organize, and manage accessibility to accurate data and information in electronic document format through the whole infrastructure life cycle (Guo et al. 2015; FHWA 2012; Parve 2014). Specifically, CIM aims to set up a practical framework across state department of transportations (DOTs) to efficiently manage asset data evolvement in the data life cycle stages (the vertical axis in Figure 1), and effectively accumulate the information through the infrastructure life cycle (the horizontal axis in Figure 1).

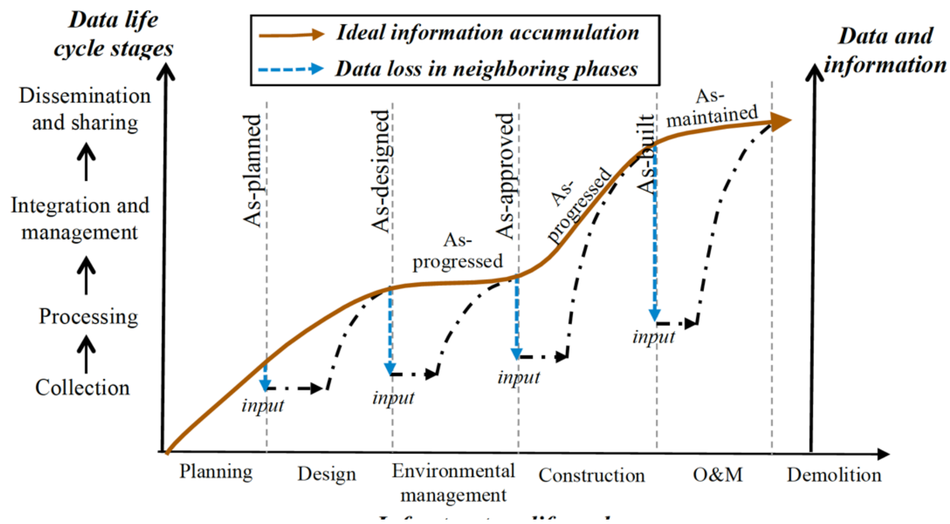


FIG. 1: Integration of data life cycle and infrastructure asset life cycle

Figure 1 illustrates that asset data has its own life cycle phases: data collection, processing, integration and management, and dissemination and sharing. This data cycle repeats throughout the life cycle stages of infrastructure. The solid brown curve in Figure 1 illustrates the ideal information accumulation trend in life cycle asset information management. It ensures the continuous accumulation of asset information; that is, all data gathered in the preceding infrastructure phase is passed to the following phase. The dashed blue lines illustrate that in the current practice, there is a big drop between two neighbouring infrastructure life phases, leading to data loss and consequently, duplicate data collection efforts that shall be eliminated. In this paper, we focus on the data flow between construction and O&M phases. For instance, the deviations from as-approved plan drawings during pipeline installation are usually redlined by site engineers; however, not all these changes are recorded quantitatively in the final report and the construction details will not flow into the O&M for future use. Another example is the Dynamic Cone Penetration (DCP) testing during soil compaction. Field engineers only need to record "Pass/Not Pass" without any detailed information regarding testing location and testing results to O&M, which are critical to predicting pavement performance over time and making informed decisions regarding maintenance and rehabilitation strategies.

3. CURRENT PRACTICE AT INDOT

At INDOT, the construction documentation and asset inventory are two separate processes. Figure 2 illustrates the data flow throughout infrastructure life cycle stages, highlighting the data blockage issue. In the design phase, *ProjectWise* is used as the document management and access solution to meet file management needs. Upon the completion of design, plans and drawings are passed into the construction stage as PDF files. *SiteManager* is the tool used at INDOT's construction projects for managing construction contracts and documenting construction records. Because design files are received in PDF format, construction engineers red-line paper drawings for as-built. No mechanism currently exists to allow the flow of construction records into road inventory and asset management systems such as the work management system (WMS), the bridge management system (BMS), and the pavement management system (PMS*)*.

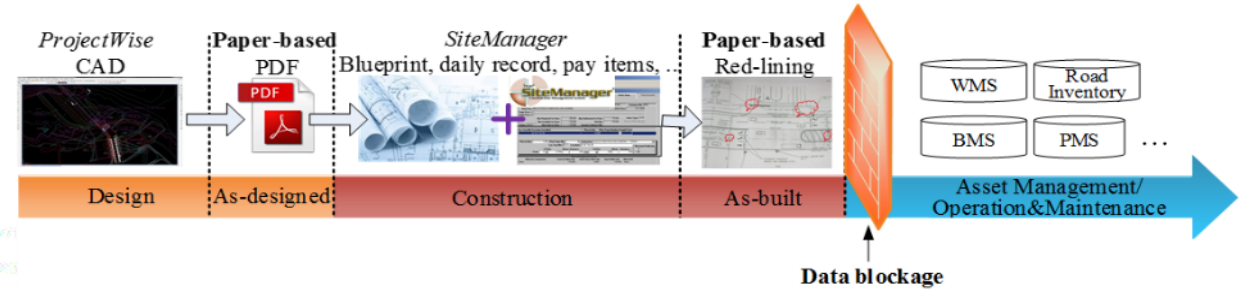


FIG. 2: Asset data flow in current INDOT practice

To overcome the data blockage in the current practice, a solution is proposed (see FIG. 3), in which the paper-based data are substituted by electronic data and a mechanism is created to facilitate the flow of data items collected in construction documentation to asset management information systems. INDOT is presently in the process of adopting electronic design files to replace paper-based PDF files and implementing mobile application for field construction documentation. The study presented in this paper focuses on creating the mechanism to automate the flow of electronic as-built data into asset information systems. Specifically, this paper creates a mechanism to leverage the construction documentation process to generate as-built asset data and channel the flow of construction records into asset management information systems.

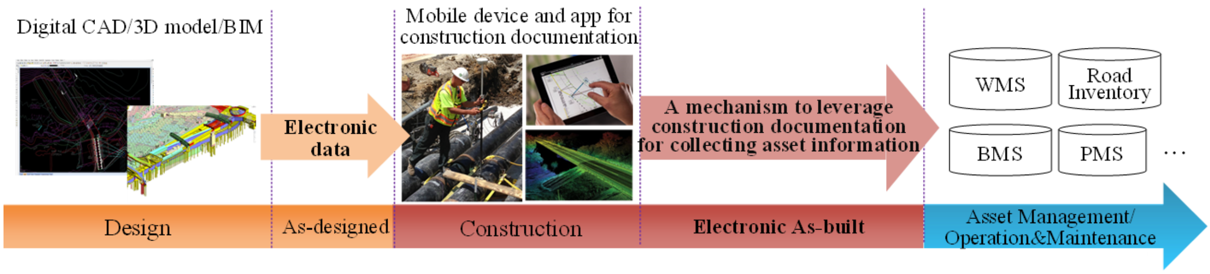


FIG. 3: Suggested asset data flow

Most SHAs including INDOT have a comprehensive list of bid items, or pay items. Each pay item has a unit price and a quantity, and multiplying these two leads to the cost of the corresponding pay item. The project price is the total cost of all pay items. Construction documentation is typically centered around pay items. However, project plans specify items to be built, i.e. plan assets and later as-built items. This discrepancy between construction documentation and the specification of as-built items leads to a technical challenge in the suggested asset data flow: bid items and as-built items are not always a one-to-one match. For instance, a bid item of "pipe installation" might cover several pipe segments and each segment is an as-built item itself; an underdrain pipe segment covers several bid items such as "excavation," "place aggregate for underdrains," "place geotextiles for underdrains," "place pipe for underdrains," and "backfill" and possibly "inspection." In our study, we examined and detailed the construction process for as-built items to address this technical challenge.

4. METHODOLOGY

In this section, we first examine the characteristics of construction inspection and documentation process, and then propose a conceptual logic workflow of construction inspection and documentation to channel data flow from plan asset to asset management systems. Afterwards, an entity-relationship (ER) diagram is created and validated to support mobile application development.

4.1 Construction inspection and documentation

The construction inspection is an activity-centered process; that is, construction inspection starts with the notice of a schedule of activities from contractor. However, construction documentation is pay item-centered; that is, construction engineers document construction data based on pay items in the bid documents, e.g., contract information book (CIB) at INDOT. Because of the misalignment between inspection and documentation, construction engineers have to mentally link construction activity (received notification), plan asset (physical components), and pay items (for documentation) to determine the appropriate pay items to document the quality and quantity of construction work in current field inspection practice. Table 1 provides the typical inspection and documentation process for the installation of a culvert pipe segment. Figure 4 graphically illustrates the process.

TABLE 1. Example of construction inspection process and corresponding documentation

Steps in a construction inspection process	Case description
1. Schedule of activity from contractor	1. Install concrete pipe by Main Street, Structure 25
2. Review plans/specs for activity requirements	2. Pipe 18" RCP, placement method, and backfill requirements per Spec. Section 715
3. Inspect activity to insure requirements are met	3. Pipe excavated, bedded, installed, and backfilled. Quantities measured.
4. Record pay item quantities in SiteManager based on associated plan asset(s)	4. Structure 25 on plan—2 pay items: 149' 18" Type 1 pipe and 95cy Structure Backfill Type 1.

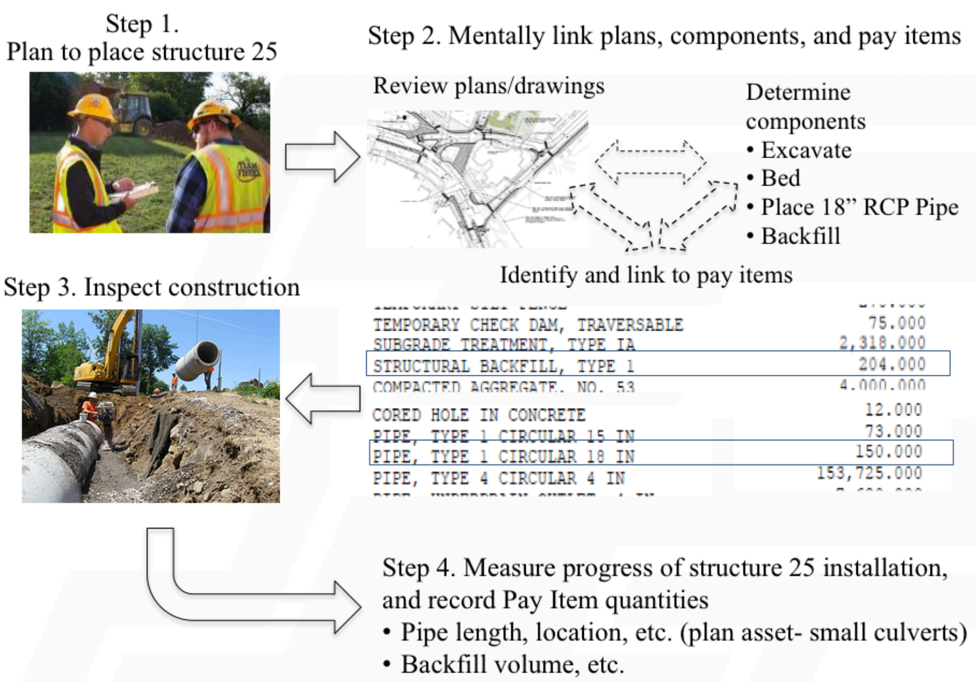


FIG. 4: Typical field inspection process

4.2 Conceptual workflow for leveraging construction documentation and asset inventory

The construction inspection process shall guide documentation in the field. Figure 5 illustrates the conceptual workflow of construction documentation, following the activity-centered construction inspection process, assuming that design documents and construction records are both digital. The process starts with picking a plan activity—Step 1, which aligns with Step 1 in Figure 4. Step 2 in Figure 5 aligns with Step 2 in Figure 4, in which all the mental linking processes are automated; that is, upon the selection of the plan activity, relevant plan asset (Structure 25) information is automatically retrieved and associated pay items are automatically determined. This new arrangement allows construction engineers to verify the link among construction activity, plan assets, and pay items rather than mentally linking process. Moreover, relevant plan asset information (drawings, specifications, and construction schedule tables) is available to construction engineers, shifting the entire field inspection and construction documentation practice into a "check-and-verify" mode. Additional data for asset management will be collected (compartment 2.3 under Step 2) during field inspection. All relevant data flow into asset management upon the completion of construction documentation. In this example, the plan asset is Structure 25 (pipe); the corresponding asset type in WMS is Small Culvert, and the related pay items include "211-09264 Structural Backfill, Type 1" and "715-05121 Pipe, Type 1 Circular 18 IN."

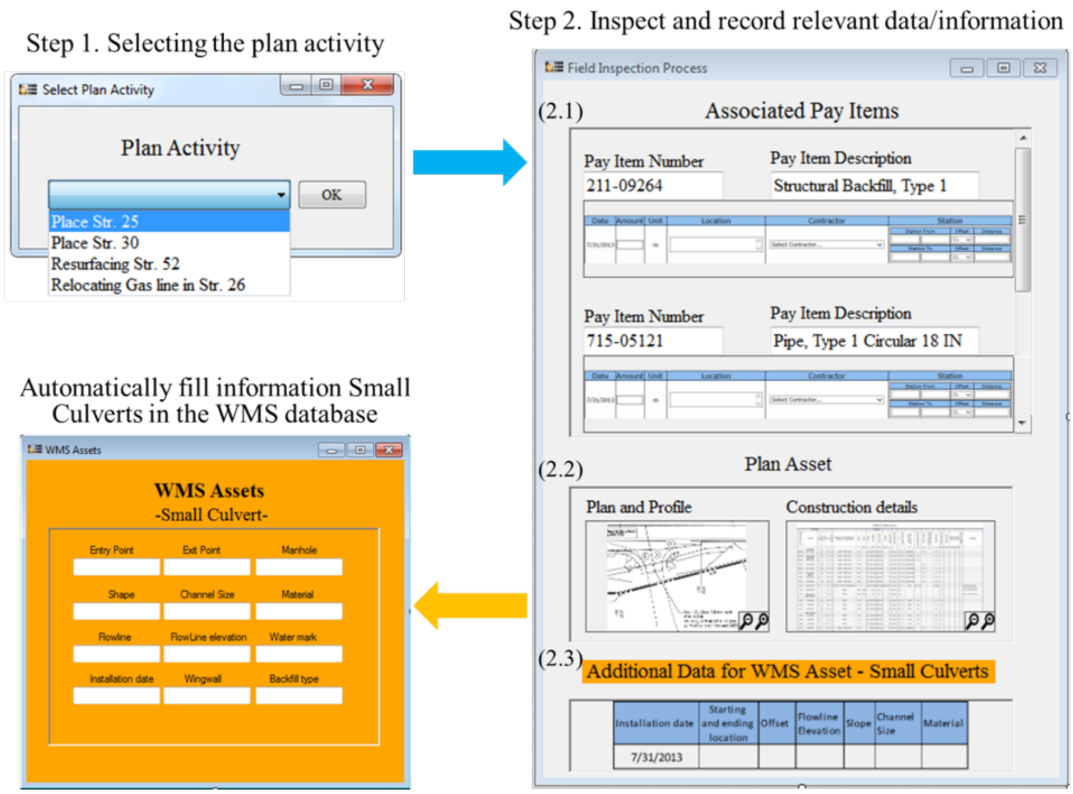


FIG. 5: The conceptual user interface for the construction inspection and documentation

4.3 Framework for linking plan assets and WMS assets to enable the flow of construction data into asset management

To facilitate the conceptual work flow illustrated in FIG. 5, we created an entity-relationship (ER) model (see FIG. 6) for linking plan assets, construction activities, pay items, and WMS assets. Some sample attributes are listed for each entity. Following eight bullets describe the entities and their relationships in the ER model as follows.

- A construction process contributes to/results in a WMS asset.
- A construction process is composed of one or more construction activities.
- A construction activity is charged to one or more pay item(s) in CIB.
- A pay item in CIB is associated with a plan asset.

- Pay item in CIB is a subset of pay item and pay item refers to the comprehensive pay item list.
- Pay item is classified into pay item category; a pay item category is a list of pay items corresponding to a particular type of WMS asset.
- Underdrain, guardrail, attenuator, and small culvert are sample subtypes of WMS asset; and any subtype of WMS asset corresponds to a particular pay item category.
- Plan asset might be related to another plan asset. For instance, attenuator can be viewed as one component of guardrail if the attenuator is used as the end treatment of the guardrail.

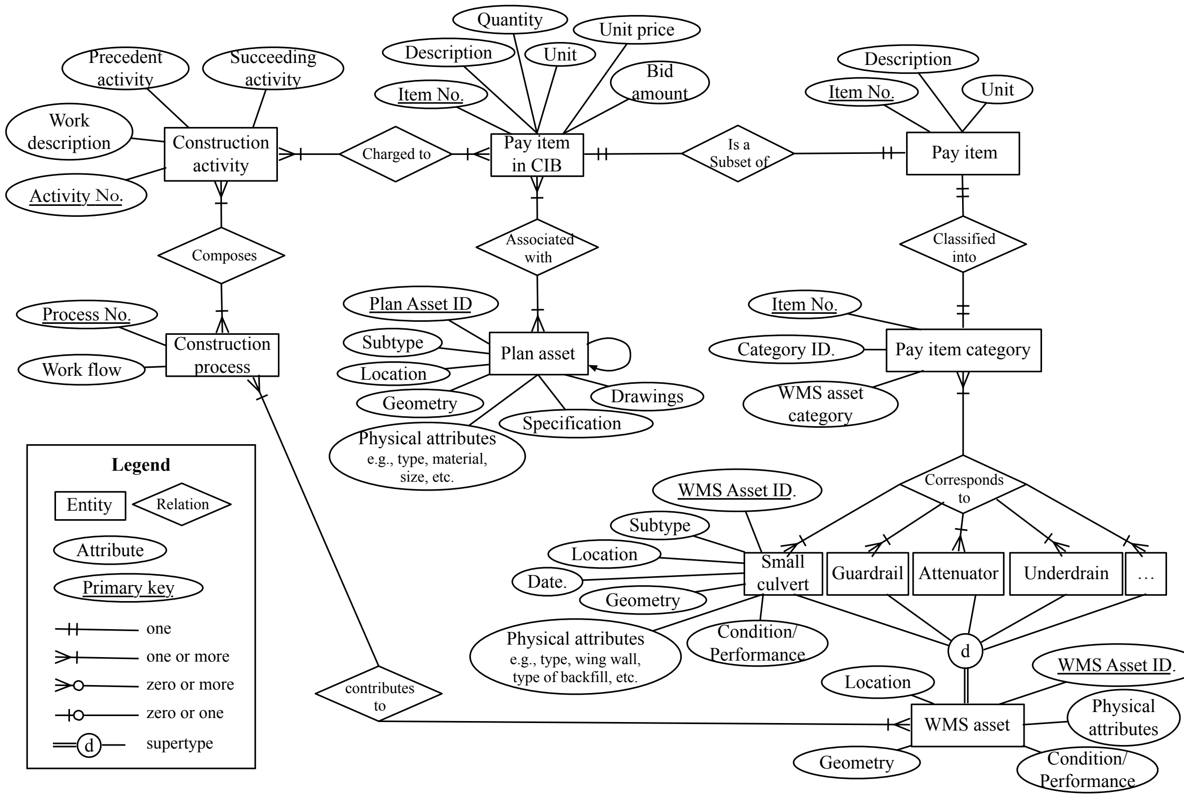


FIG. 6: Entity-relationship (ER) model for construction process, plan asset and WMS asset

Such an ER model enables the linking mechanism. Following subsections describe how to establish the relations and the linking mechanism, using small culvert data from an INDOT project (contract number *IR-30143-A*) for the illustration purpose.

4.3.1 Linking Plan Assets to Pay Items in the Contract Information Book (CIB)

The goal in this step is to link every pay item in the CIB to plan assets—physical structures prescribed in design documents (plans/drawings). This goal is achieved by interviewing INDOT construction engineers and examining four INDOT standards—INDOT 2014 CAD Standards Manual, INDOT 2013 Design Manual, INDOT 2014 Standard Specifications, and INDOT 2014 Standard Drawings. INDOT standards prescribe how and where plan assets are specified in plans/drawings. Knowledge and experience of INDOT's construction engineers help determine the association between plan assets and pay items. Together, they enable the retrieval of plan asset information for every pay item and vice versa.

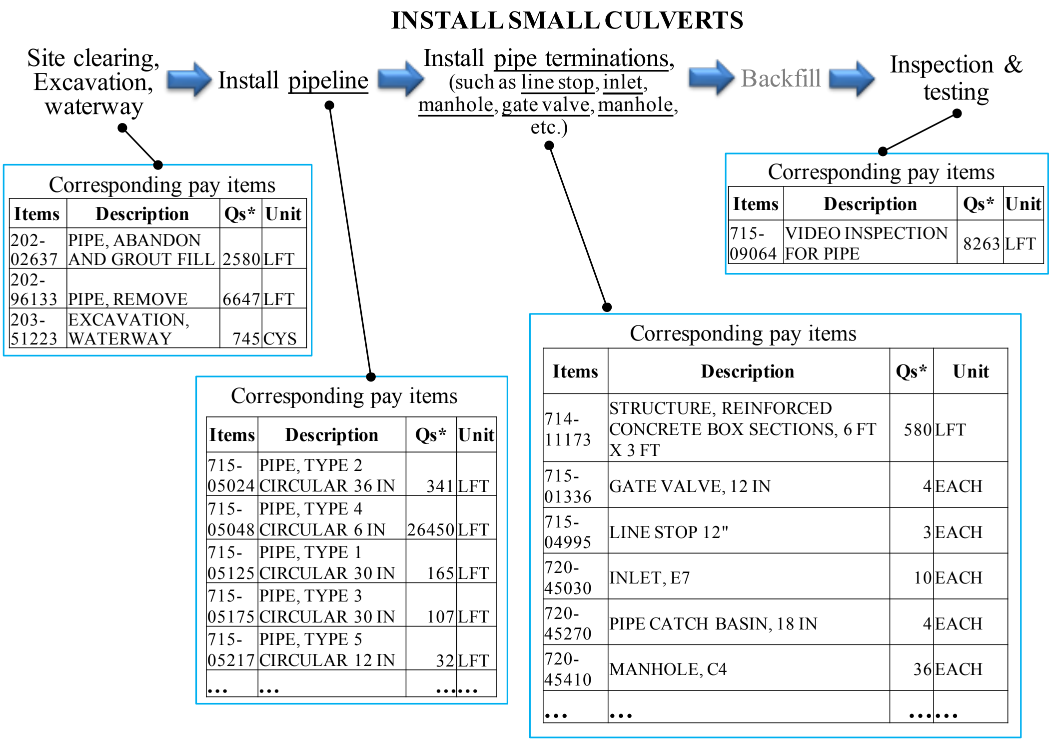
While the association between plan assets and CIB pay items is established upon the completion of design and before project letting, that information is not being passed to construction in the current practice. As a result, to validate this linking process, the team had to start with two separate lists: plan assets and CIB pay items. The association between them had to be re-established. According to INDOT standards, there are schedules/tables in plans for plan assets such as underdrains, small culverts, guardrails, and attenuators, which can be used as references for associating the plan assets and CIB pay items. Figure 7 provides an excerpt of the structure table, which is related to one of the plan assets – small culverts.

STRUCTURE DATA																								
	LOCATION					DESCRIPTION					FLOW LINE													SCOU[R]
STRUCTURE NUMBER	STATION	LEFT	RIGHT	CROSS	SIZE	PIPE TYPE	MANHOLE, INLET, CATCH BASIN, OR SPECIALTY STRUCTURE AND TYPE	LENGTH	VIDEO INSPECTION LENGTH	SKEW	COVER	UP STREAM	DOWN STREAM	SERVICE LIFE	SITE DESIGNATION	pH	BACKFILL METHOD	STRUCTURE BACKFILL	TYPE	FLOWABLE BACKFILL	TYPE	GEOTEXTILES	REVETMENT RIPRAP	SUMP DEPTH	GEOTEXTILE
					IN.			LFT	LFT		LFT	ELEV.	ELEV.	YRS				CYS		CYS		SYS	TON	IN.	SY
LINE "PR-S-B"																								
105	13+50.00		X		15	3	PIPE	115.0			4.4	831.58	830.10	75	NA	7	2	12.95					1.6		
106	14+50.00	X			30	3	PIPE	109.0			6.9	831.31	830.98	75	NA	7	2	34.97					6.3		7
	LINE "B"																								
202	242+25.00	X			18	2	INLET, TYPE N-12	104.0			2.9	821.02	820.00	75	NA	7	1/3	19.07/16.38					1.5		2

FIG. 7: An excerpt of the structure data table for small culverts

4.3.2 Decomposing the construction process and linking construction activities to pay items in CIB

FIG. 8 illustrates one of the typical construction process for plan assets (underscored) of small culverts and their associated pay items in CIB. A plan asset might have more than one associated pay items. For instance, "Install pipeline" might correspond to many different types of pipe with varying dimension (only a few are listed). "Install pipeline" and "Install pipe terminations (such as line stop, inlet, manhole, gate valve, etc.)" directly contribute to new assets. Activities such as "Site clearing, Excavation, waterway" and "Inspection & testing" are part of the construction process, but they do not generate/lead to assets. The framework only channels the flow of construction documentation data of construction activities that directly result in assets into WMS database.



Items	Description	Qs*	Unit
202-02637	PIPE, ABANDON AND GROUT FILL	2580	LFT
202-96133	PIPE, REMOVE	6647	LFT
203-51223	EXCAVATION, WATERWAY	745	CYS

Items	Description	Qs*	Unit
715-05024	PIPE, TYPE 2 CIRCULAR 36 IN	341	LFT
715-05048	PIPE, TYPE 4 CIRCULAR 6 IN	26450	LFT
715-05125	PIPE, TYPE 1 CIRCULAR 30 IN	165	LFT
715-05175	PIPE, TYPE 3 CIRCULAR 30 IN	107	LFT
715-05217	PIPE, TYPE 5 CIRCULAR 12 IN	32	LFT
…	…	…	…

Items	Description	Qs*	Unit
714-11173	STRUCTURE, REINFORCED CONCRETE BOX SECTIONS, 6 FT X 3 FT	580	LFT
715-01336	GATE VALVE, 12 IN	4	EACH
715-04995	LINE STOP 12"	3	EACH
720-45030	INLET, E7	10	EACH
720-45270	PIPE CATCH BASIN, 18 IN	4	EACH
720-45410	MANHOLE, C4	36	EACH
…	…	…	…

Items	Description	Qs*	Unit
715-09064	VIDEO INSPECTION FOR PIPE	8263	LFT

*Qs: Quantities

FIG. 8: Typical construction process of small culverts and associated pay items in CIB

4.3.3 Classifying pay items to corresponding subtypes of WMS asset

This step aims at pre-compiling a list of relevant pay items for every subtype of WMS asset. Some pay items are relevant to more than one asset; therefore, they can appear in many lists. INDOT standard specification and knowledge on construction led to a list of keywords for each subtype of WMS asset. Searching the comprehensive list of pay items using these keywords resulted in a list of possible pay items for each WMS asset subtype. Table 2 lists the keywords for small culverts. Their search resulted in a total of 1222 (mainly due to a wide variety of pipe types) possible pay items. Table 3 lists a few of them.

TABLE 2. Key words for pre-compiling pay items for WMS assets

Priority Asset	Keywords	Items Manually Removed/*Added*
Culverts	Excavation, waterway; pipeline—pipe; pipe connectors—stop, valve, cap, casting, pump, plug, blind flange, butterfly debris screen, dripline, ductile iron fitting, gate, riser, connection, join; pipe terminator—manhole, hatch, monitoring well, catch basin, inlet, drain(age), end section, flushing, head(er), protection; structural plate pipe and concrete box structure—structure plate, box; side ditch, riprap, backfill, grout, slope wall, trench, sewer, stormwater	Removal—A number of irrelevant items were removed; *Adding—Items of "Best management practice," "Force main," "Life station," "Maintenance," and "trash rack" were added.*

TABLE 3. Relevant pay items of small culverts

SECTION	ITEM	DESCRIPTION	UNIT
202	202-02637	PIPE, ABANDON AND GROUT FILL	LFT
202	202-02772	CASTING, REMOVE	EACH
202	202-02859	GRATED BOX END SECTION, REMOVE	EACH
202	202-96133	PIPE, REMOVE	LFT
203	203-51223	EXCAVATION, WATERWAY	CYS
607	607-06175	GUTTER, CONCRETE, A	LFT
607	607-06335	PAVED SIDE DITCH, A	LFT
614	614-06470	HEADER, CEMENT CONCRETE, A	LFT
616	616-05688	RIPRAP, CLASS 1	TON
714	714-02584	STRUCTURE EXTENSION REINFORCED CONCRETE BOX SECTIONS, 8 FT X 3 FT	LFT
715	715-01336	GATE VALVE, 12 IN	EACH
715	715-01344	PIPE END SECTION DIA 60"	EACH
720	720-01987	CATCH BASIN, A10	EACH
720	720-45005	INLET, A2	EACH
720	720-45400	MANHOLE, A4	EACH
721	721-43000	AUTOMATIC DRAINAGE GATE, 12 IN	EACH
723	723-10156	STRUCTURE, REINFORCED CONCRETE THREE-SIDED SECTIONS, 228 IN X 120 IN	LFT
725	725-08291	PIPE LINER, CURED-IN-PLACE, 24 IN.	LFT
…	…	…	…

4.3.4 Matching pre-compiled list of pay items to pay items in CIB

The matching itself is straightforward because every pay item in CIB and in the pre-compiled lists has a unique identifier/number. A side-by-side matching results in a list of pay items that is in both the project CIB and the precompiled list corresponding to a specific WMS asset subtype. Still taking the INDOT project with contract number IR-30143-A as an example, there are a total of 66 matched pay items for the WMS subtype of small culvert. Table 4 lists a portion of those matched items. These matched pay items function as the bridge to connect plan assets to WMS assets such that data items of plan assets documented in construction can automatically flow into WMS.

TABLE 4. Matched pay items for small culverts

Pay Item	Description	Unit	Quantity
616-05688	RIPRAP, CLASS 1	TON	8
616-06405	RIPRAP, REVETMENT	TON	4219
714-11173	STRUCTURE, REINFORCED CONCRETE BOX SECTIONS, 6 FT X 3 FT	LFT	580
715-01336	GATE VALVE, 12 IN	EACH	4
715-04995	LINE STOP 12"	EACH	3
715-05024	PIPE, TYPE 2 CIRCULAR 36 IN	LFT	341
715-05048	PIPE, TYPE 4 CIRCULAR 6 IN	LFT	26450
715-05125	PIPE, TYPE 1 CIRCULAR 30 IN	LFT	165
715-05169	PIPE, TYPE 3 CIRCULAR 15 IN	LFT	582
715-05203	PIPE, TYPE 4 CIRCULAR 4 IN	LFT	30447
715-09064	VIDEO INSPECTION FOR PIPE	LFT	8263
715-10238	PIPE ROADWAY DRAIN CASTINEXTENSION	EACH	4
715-46005	PIPE END SECTION, DIA 15"	EACH	27
715-98961	FORCE MAIN SANITARY SEWER, 2.5"	LFT	225
716-07633	PIPE INSTALLATION, TRENCHLESS, 24 IN	LFT	210
719-05438	PIPE, DRAIN TILE TERMINAL SECTION, 4 IN	LFT	40
…	…	…	…

The design and implementation of the ER model enables the conceptual workflow as illustrated in FIG. 5. Construction engineers use a field application to select a construction activity. Based on the links between construction activity and CIB pay item and between CIB pay item and plan asset, the application retrieves and displays plan asset information and lists associated pay items for documentation. Based on the matching of CIB pay item to categorized pay items that correspond to WMS asset subtype, when construction engineers record data items for a pay item, the application sends the relevant data items to the appropriate locations in WMS database, resulting in asset data items collected during the construction documentation practice.

The framework is valid because 1) matched pay items are sets of common pay items that appear in the CIB and in the pre-compiled lists, 2) every pay item in the CIB is associated with plan asset(s) and/or plan asset component(s), and 3) every pay item in a pre-compiled list belong to the corresponding WMS asset subtype. Consequently, plan assets are connected to specific WMS assets, and relevant data items collected in construction documentation automatically flow into corresponding WMS asset.

5. IMPLEMENTATION WITH A CASE ILLUSTRATION

The recommended mobile application was tested using data from the INDOT construction project (contract number: IR-30143-A), which includes both rehabilitation and new construction of roadways on US-31. The case illustration focused on the new construction part (about 18 miles long), with a total of 445 pay items in CIB. The case chosen was a construction activity to install a small culvert.

Figure 8 illustrates the IPad-style application user interface to facilitate the construction inspection and documentation process for the scenario of "*Installation of structure 202 with length of 104 LFT, crossing US-31 (South Bound) Line "B", at station 242+25.00*." The user interface has ten compartments. The construction engineer selects the contract number and project number in Compartment 1 and 2. The available items in both compartments depend on what projects the construction engineer is working on. The construction engineer selects the activity of "Install Small Culverts" in Compartment 3, Compartment 4 lists all pay items associated with the plan assets covered under the activity, such as pipe, pipe end section, inlet, and manhole. The construction engineer then selects "PIPE, TYPE 2, CIRCULAR 18 IN," and Compartment 5 displays the data items to be collected for the construction documentation purpose. Compartment 6 shows construction records corresponding to data items collected in Compartment 5. Compartment 7 shows information in the plans/drawings of the associated plan assets. Compartment 8 lists all data items that will flow into WMS. Table 5 lists all the data items collected for WMS assets following this newly proposed workflow for all associated WMS assets under this inspection scenario.

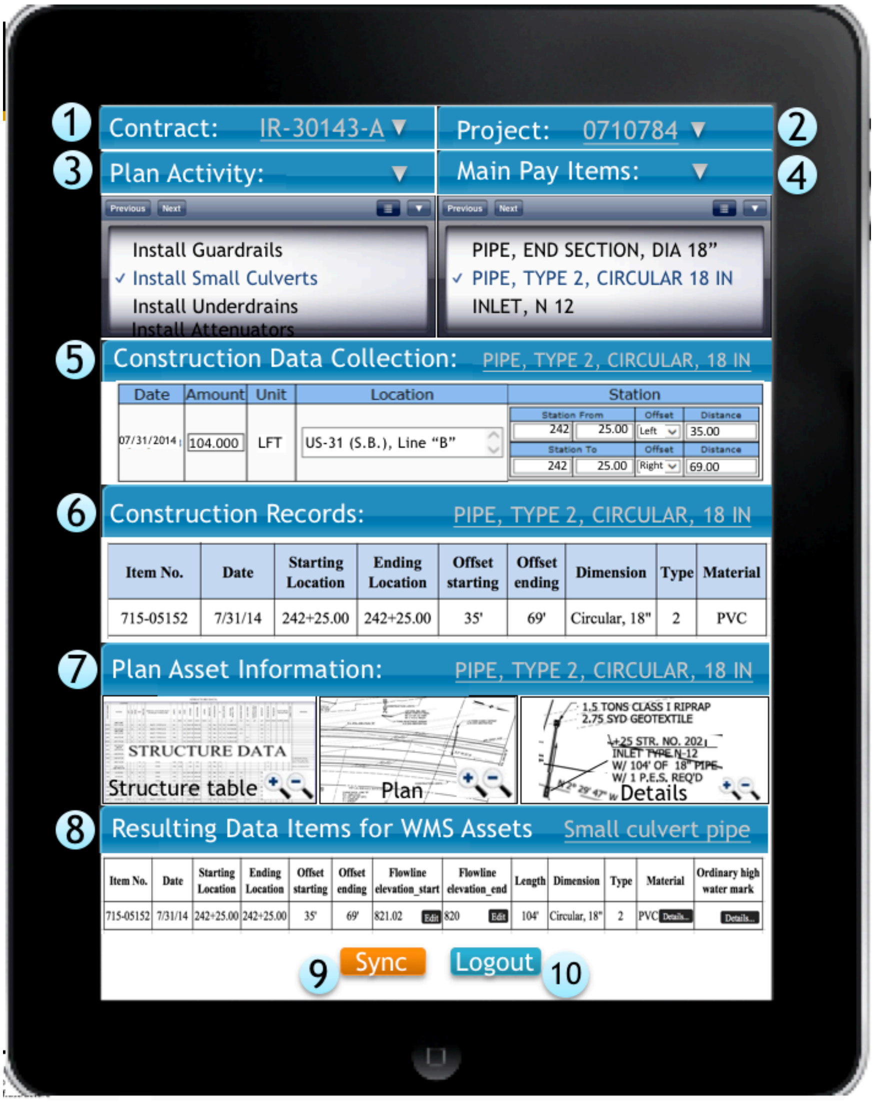


FIG. 8: Mock-up screen for collecting data: installation of small culvert pipeline

The mobile application prototype works in such a way that (1) construction engineers document construction inspection in an offline mode (considering the low stability and accessibility to wireless network). Collected data sits in the cache of the mobile device, and (2) construction engineers come back to field office, connect the mobile device to internet, and click the “Sync” button to send data to the destination server databases.

TABLE 5. Small culvert data collected through construction documentation

(a). Small Culverts Assets – Pipelines

Date	Starting location	Ending location	Offset starting	Offset ending	Flowline elevation starting	Flowline elevation elevation	Length	Dimension	Type	Material
7/31/14	242+ 25.00	242+ 25.00	35'	69'	821.02	820	104'	Circular, 18"	2	PVC

(b). Small Culverts Assets – Pipe end termination

Date	Location	offset	Type	Dimension	Wingwall(Y/N)
7/31/14	242+25.00	69'	End Section	Pipe 18"	N

(c). Small Culverts Assets – Inlet end terminations

Date	Location	offset	Type	Dimension	Wingwall(Y/N)
7/31/14	242+25.00	35'	Inlet	N-12	N

6. CONCLUSIONS AND FUTURE WORK

The construction phase is the best time for collecting complete and accurate in-place data of infrastructure assets. In the current practice at SHAs, the construction documentation and asset in-place data collection are two separate processes, leading to information loss and duplicate efforts on data collection. This study designs a mobile application to leverage the construction inspection and documentation process for asset inventory during construction. The mobile application uses pay items as the bridge to connect plan assets with assets in asset management databases. It enables the automatic flow of plan asset data collected in construction documentation into asset management systems. The proposed field application was tested using an INDOT construction project. The case illustration proved that the proposed application scheme worked for small culverts, and should also work for other WMS assets as verified in Methodology. And the case illustration received positive feedback from both construction and O&M units at INDOT.

Currently, INDOT is using the IPad application for field data collection and documentation. Our proposed framework extends their current application to asset inventory by creating a mechanism to channel the construction data into asset management system. Meanwhile, this study offers to be a valuable tool to construction documentation and asset inventory for asset management in SHAs. It follows the general construction procedure and eliminates the need (in the current practice) to mentally link construction activities to plan assets and pay items, which is expected to improve the efficiency in construction documentation. Taking advantage of electronic design files, the newly developed framework allows 1) bringing relevant plan asset information to construction engineers in real time, and 2) leveraging the construction documentation process to collect in-place asset information. Upon the completion of construction projects, accurate and complete construction records and as-built data automatically flow into asset management and road inventory information systems to facilitate life cycle asset management.

The newly created entity-relationship scheme fits the current practice of many SHAs in construction inspection, documentation, and asset management. Thus, the newly created method and the findings have boarder impact for future infrastructure inventory and life cycle asset management.

Although the mobile field application is convenient, attributed to the portability of device, limitations such as the the cache capacity of the hardware, battery duration, additional training efforts, and plan asset information retrieval performance from 2D drawings, still exist and call for future studies in various aspects. Since the mobile application is still under enhancement and further development, we do not have quantitative performance data at this stage. Upon the rolling out of the enhanced version of the mobile application, we expect to perform a number of case studies to compare the use the mobile application to the conventional way of inspection, documentation, and asset inventory for quantitative assessment on the time/cost savings, and a survey to evaluate its efficiency in the practice, in various aspects including percentage of information loss, time saving for field construction engineers in construction documentation, and communication time saving between operation and maintenance personnel (i.e. retrieving data on an as-needed basis).

Furthermore, implementing the linking mechanism requires a detailed assessment of data needs and the classification of pay items corresponding to WMS asset subtypes. Both tasks are time consuming. The implementation of the newly created mobile application also calls for a realignment of the business process. Having SHA staff buy-in is critical to its success.

7. ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of INDOT through Joint Transportation Research Program (JTRP) project SPR-3707 and the guidance of the study advisory committee (SAC). Any opinions, findings, and conclusions in this paper are those of the authors and do not necessarily reflect the views of Purdue University or INDOT.

REFERENCES

AASHTO-AGC-ARTBA Joint Committee (2006). *Asset Management Data Collection Guide: Task Force 45 Report*. 2006.

Abanda, F. H., et al. (2015). *A critical analysis of Building Information Modelling systems used in construction projects.* Advances in Engineering Software 90: 183-201.

Chen, P. P. S. (1976). The entity-relationship model—toward a unified view of data. ACM Transactions on Database Systems (TODS),Vol. 1, No. 1, 1976.

Construction, M. H. (2012). *The business value of BIM for infrastructure: Addressing America's infrastructure challenges with collaboration and technology*. http://analyticsstore. construction.com/index.php/2012-business-value-of-bim-in-north-america-smartmarketreport.html. September 5, 2012.

Davenport, C. and Voiculescu, I. (2015). *Mastering AutoCAD Civil 3D 2016*. Autodesk Official Press, John Wiley & Sons.

Delcambre, B. (2014). Mission numérique bâtiment. http://www.territoires.gouv.fr/IMG/pdf/rapport_mission_numerique_batiment.pdf. December 2014.

FHWA (1999). *Asset Management Primer.In, U.S. Department of Transportation Federal Highway Administration Office of Asset Management*, 1999.

FHWA (2012). *CIVIL INTEGRATED MANAGEMENT (CIM).* http://www.efl.fhwa.dot.gov/files/technology/dv/CIM-Poster-04.12.pdf. April, 2012.

Flintsch, G., and J. Bryant (2006). *Asset management data collection for supporting decision processes*. In, US Department of Transport, Federal Highway Administration, Washington, DC, 2006.

Gordon, M., G. JasonSmith, P. D. Thompson, H.-A. Park, F. Harrison, and B. Elston (2011). *AASHTO Transportation Asset Management Guide, Volume 2: A Focus on Implementation*. American Association of State Highway and Transportation Officials. Prepared under NCHRP Project, 2011, 08-69.

Guo, F., C. T. Jahren, and Y. Turkan (2015). *Electronic document management systems for transportation construction industry*. 2015.

Harrrison, F. (2005). *NCHRP Report 545: Analytical Tools for Asset Management.* Washington DC, 2005.

Lefler, N., F. Council, D. Harkey, D. Carter, H. McGee, and M. Daul (2010). *Model inventory of roadway elements-MIRE, Version 1.0*., 2010.

Lin, Y. C., Su, Y. C., Chen, Y. P. (2014). *Developing mobile BIM/2D barcode-based automated facility management system*. The Scientific World Journal, August 28, 2014.

Markow, M. J. (2010). *Target-setting methods and data management to support performance-based resource allocation by transportation agencies: volume I: research report: volume II; guide for target-setting and data management*. Transportation Research Board (TRB), Washington, D.C., 2010.

NCHRP(2009). *An Asset-management Framework for the Interstate Highway System.* Transportation Research Board, 2009.

Nemmers, C. (1997). *Transportation asset management.* Public roads, Vol. FHWA, Vol. 61, No. 1, 1997.

Parve, L. (2014). *Supporting 3D/4D Construction Applications in Preconstruction*. FHWA 3D Engineered models webinar series. http://www.fhwa.dot.gov/construction/3d/webinars/webinar04.pdf. 2014.

Redmond, A., et al. (2012). *Exploring how information exchanges can be enhanced through Cloud BIM*. Automation in Construction 24: 175-183

Shou, W., et al. (2015). *A Comparative Review of Building Information Modelling Implementation in Building and Infrastructure Industries.* Archives of Computational Methods in Engineering 22(2): 291-308.

Su Y., Lee Y., and Lin Y. (2011). *Enhancing maintenance management using building information modeling in facilities management.* Proceedings of the 28th international symposium on automation and robotics in construction.

Wang, W. C., Weng, S. W., Wang, S. H., and Chen, C. Y. (2014). *Integrating building information models with construction process simulations for project scheduling support*. Automation in construction, Vol. 37, 68-80.

WERD (2003). *Data Management for Road Administrations—A Best Practice Guide*. Western European Road Directors, Sub-Group Road Data, Conference of European Road Directors (CERD), Europe (www.roaddata.org), 2003.

Wong, J., Wang, X., Li, H., Chan, G., Li, H. (2014). *A review of cloud-based BIM technology in the construction sector.* The Journal of Information Technology in Construction 19, 281-291.

Yuan, C., McClure, T., Cai, H., and Dunston, P.S. (in press). *Survey on the Practice Hurdles in Collecting, Managing, and Sharing Transportation Infrastructure Asset Data.* Construction Research Congress 2016.