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Project controls for electrical, instrumentation and control systems: Enabling role of digital system information modelling

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ABSTRACT

Accurate assessment of a project's progress enables managers to control and manage costs and schedule. Automating the processes to monitor and inspect the progress of works in construction, and ensure that the data acquired and retrieved are able to produce an accurate 'as-built' model is an issue that has received ubiquitous attention in the literature. Emphasis has been placed on utilizing technologies such as mobile augmented reality, laser scanners, and computer visions to monitor and control physical objects that possess geometrical properties. Connected systems such as Electrical, Instrumentation and Control Systems (EICS), however, do not possess geometrical properties and as a result have been overlooked, receiving limited attention. This paper utilizes a digital System Information Model (SIM) to enable a project control system based on human-machine interactions, to be developed, in order to monitor progress during the construction of connected systems. By incorporating the design, schedules, activities, and tasks into a digital, cloud-based model, the system enables different parties involved in a project to synchronously work together. Information can be recorded, distributed and shared in real-time therefore significantly improving decision-making, the approvals process, and management of information. A SIM is discipline-specific and there is a need to ensure its interoperability with building information modeling software. Therefore, a bi-directional link between the SIM and the project's overall schedule and three-dimensional model needs to be developed in the future.

1. Introduction

To be able to monitor and control time, cost, quality and safety in real-time during the construction of an asset can provide contractors with the capability to better manage, forecast and deliver their projects [5,10,11,17,27]. Digital technologies such as augmented reality, laser scanning, photogrammetry, and computer vision enabled by the adoption of Building Information Modelling (BIM) are beginning to be used in construction to better manage projects and the operations and maintenance of assets [4,7,9,12,30,31]. Such monitoring has typically focused on utilizing geometric properties, which has enabled the progress of a physical structure and its materials during construction to be monitored.

Cloud-based systems, for example, such as the Autodesk BIM 360™ suite, that can support progress monitoring during the construction of projects (e.g., [27]), are reliant on physically modeled objects in order to assign properties such as construction sequence, or status. Progress monitoring can also be extended to operations and maintenance. However, rather than maintaining building information models that have been handed-over to asset owners, there has been a tendency to use laser scanning to recreate the 'as-built' [3]. While software solutions such as BIM 360™ Field and dRofus can capture and utilize semantic information, they are unable to adequately support information contained in connected systems (i.e. electrical, control and instrumentation) as they focus on operations on discrete objects [26].

Due to the complexity of these connected systems, and the absence of geometry, automatic project progress monitoring is not attainable with prevailing digital technologies. This has resulted in an absence of research examining the performance of connected systems during construction even though they are core to the functioning of an asset. As connected systems are invisible and intangible they tend to be overlooked with preference given by researchers to the examination of physical objects through three-dimensional (3D) representations that provide a visual context. But, as assets become more reliant on automation and digital technologies their importance will increase exponentially and therefore there is a need for research to focus on future-

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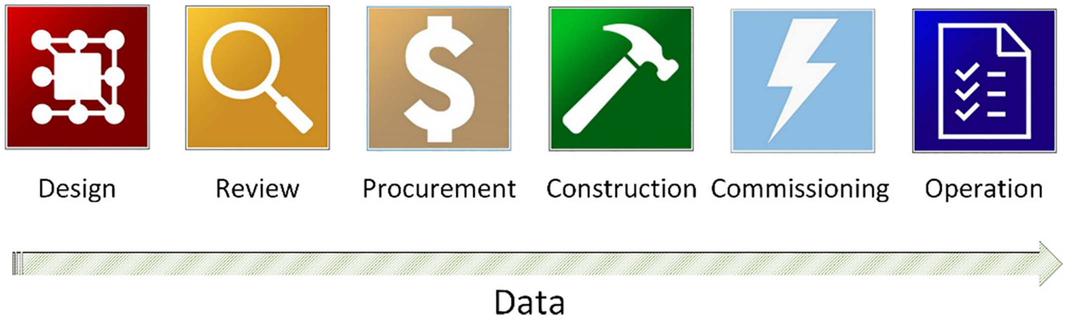

Fig. 1. SIM functional modules.

proofing the information that is attributed to connected systems [26]. This is an area that has been neglected by the construction and engineering management literature.

Against this contextual backdrop, this paper utilizes a digital System Information Model (SIM) to enable a project control system based on human-machine interactions, to be developed, in order to monitor progress during the construction of connected systems. By incorporating the design, schedules, activities, and tasks into a digital model that is cloud-based, the system enables different parties involved in a project to synchronously work together. Information can be recorded, distributed and shared in real-time therefore significantly improving decision-making, the approvals process, and management of information.

In the next section of this paper, the concept of a SIM is briefly introduced before introducing the project control system for progress monitoring of connected systems, which is demonstrated using a case study. The literature is replete with studies that have examined progress monitoring in construction using digital technologies. A detailed review of progress monitoring, particularly from automated and real-time perspectives, can be found in a number of studies, for example, Kim et al., [14]; Golparvar-Fard et al. [12], Kopsida et al. [15], Matthews et al. [27], Li et al. [17] and Kropp et al. [16]. The research not only presents a real-life application of a SIM being used to monitor progress in real-time but also provides a platform for a new line of inquiry to examine the performance of connected systems during their construction, specifically in the context of electrical, instrumentation and control systems (ECIS).

2. System information modelling

The concept of SIM has been examined from a number of perspectives in construction such as retrospective 'as-built' generation [20], life-cycle management [32], enabling digital asset management [21], retrospective constructability assessment [22], and analysis of tender documentation quality [24]. A SIM is a derivative of BIM, but 'Building' is replaced with 'System' to represent the process of modeling complex connected systems, such as electrical, control, power, and communications, which do not possess geometry [21]. A SIM takes a discipline-specific perspective but can be integrated with when a consolidated point of truth is formed [26].

A SIM model is a digital representation of the physical system to be constructed. The object modeled in a SIM has a 1:1 relationship to its real-world counterpart. Thus, a SIM is object-oriented, and children are able to inherit information from parents. In this instance, the parent/child relationship in object-oriented programming (OOP) should be viewed as a concept of 'inheritance' rather than one of the containers and contained elements. When manipulating the SIM, a parent is one object, and a child is another object contained within. However, within an OOP, it is necessary to consider classes than the individual objects themselves. In OOP, a parent is one class, and a child is another that inherits all of the attributes and functions that are assigned to the parent. The upshot is that data re-entry can be eliminated when changes are required to a model. Effective information management 'Input once, user forever' can be achieved, which can consequently reduce errors, omissions, and redundancy that prevail when connected systems are documented using Computer-Aided-Design (CAD) with the output being typically in a paper format. According to McKinsey [28], employees spend 1.8 h every day or 9.3 h per week on average as a result of searching and gathering information from documents. This is even higher in the case of mega-projects when data and information gathering can become a momentous task.

Designing within a SIM environment enables the data to be predefined, structured and gradually created in a digital model throughout all phases of a project. The digital SIM is established using a Structured Query Language (SQL) database that enables modeled objects to be dynamically interconnected. Software applications such as Digital Asset Deliverable (DAD), can be used to manage the data of a SIM.

To enable a SIM to be used on different phases of a project, dedicated functional modules are developed [32]: (1) Design; (2) Review: (3) Procurement; (4) Construction; (5) Commissioning; and (6) Operation (Fig. 1). User groups provided with access rights are created for each functional module. For example, a design team can be granted with an 'Edit' right to the 'Design Module' and the review team is granted with 'Check' and 'Approve' rights in the 'Review Module'. In protecting the design from unauthorized changes, only the design team is able to modify the 'Design Model'. Thus, users from other functional modules are able to attach data to the design model without affecting its integrity.

When a SIM is used to model ECIS, which is a connected system, physical equipment is modeled as components and cables as connectors. Components are classified by their 'Location' and 'Type' and connectors are classified by 'Type' (Fig. 2). This classification is very similar in nature to other object-oriented software applications that enable BIM to be undertaken. Users can define new attributes to suit their specific needs and attach them to the model. Various supplementary documents can also be attached to the model such as pictures, pdf. files, and datasheets.

A SIM model can be accessed either locally using a Personal Computer (PC) or remotely with a mobile device such as a Tablet. A cloud-based service can enable the users to synchronize their information to the central database. Then, this can enable engineers to gain instant access to information so that can oversee a project's progress and make prompt decisions should deviations from what has been planned to begin to occur.

3. Case study

A case study can be used to examine issues such as 'why' and 'how' and acquire an understanding about 'practice' (i.e. the actual activity, events or work) [21–23]. As a result, a case study can provide practical insights about industry-specific problems that are being addressed and therefore enable learning and changes in practice to occur. A case study

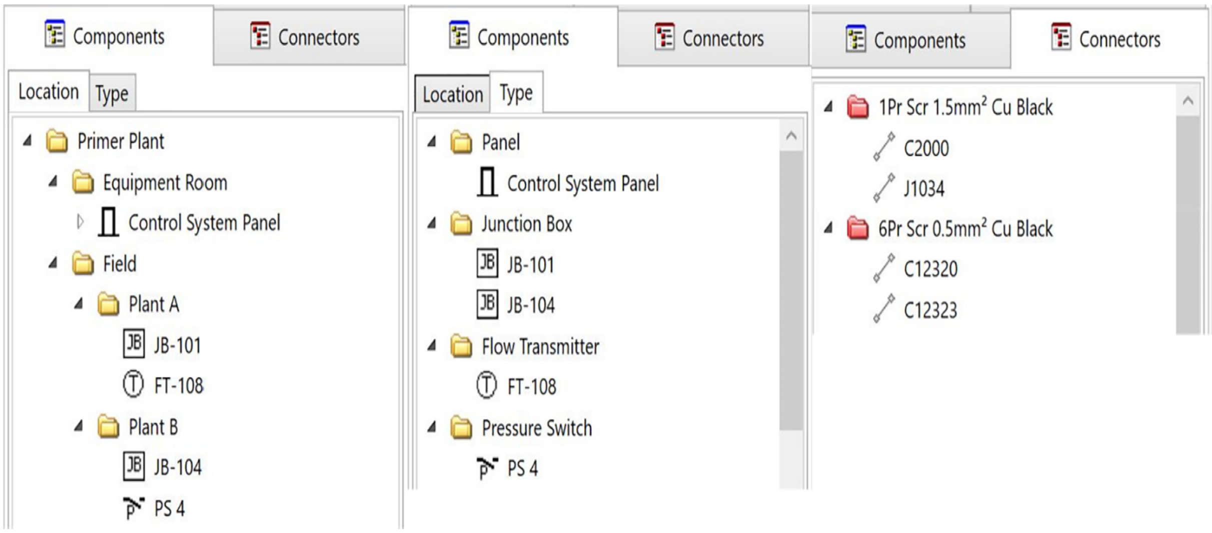

Fig. 2. Component and connector classifications.

approach was therefore adopted to contribute to examining 'how' a SIM is used during construction to monitor the progress of the installation of connected systems. Parallels can be drawn here with several studies such Davis and Harty [8] Matthews et al. [27] and Li et al. [17] that examined the implementation of BIM during construction for project controls. The justification of 'why' a SIM should be used to enable the digitization of EICS assets at each phase of their life-cycle has been empirically examined in a number of studies (e.g., [20–22,24,25,32]). Key benefits of using a SIM emerging from previous research include:

- a reduction in costs to create documentation and a digital model;
- elimination of information redundancy;
- consolidated point of truth;
- improved access, usability, and manageability of information; and
- engendering collaborative work environment.

While it has been demonstrated that a SIM can provide significant cost and productivity savings during the design process, there has been no research that has examined how it can be used in construction. Drawing on practice and the experiences from a real-life project the purpose of this case study is to examine the use of a SIM in construction as a project controls mechanism and how semantic information needs to be used to monitor the progress of ECIS during their installation. Thus, the case study provides a basis for organizations to consider a new technological solution and workflow to monitor the progress of ECIS in real-time. Monitoring ECIS progress in real-time can ensure that an 'as-built' documentation provided at handover reflects that what has been constructed and installed. Having access to the right information at the right time during the assets operation and maintenance can provide help reduce costs and improve productivity. In plant operations, ECIS typically account for 60% of maintainable items and are for critical to ensuring the safe and efficient operation of an asset [2]. Thus, it is imperative that 'as-built' documentation is error-free and reflects precisely what has been installed [2], though this seldom the case for EICS 'as-builts' [24,25].

To acquire an understanding about how the SIM was being used for project controls and ensure the reliability of the information at handover, a triangulated approach to data collection was adopted to overcome problems associated with bias and validity [19]. This approach also enabled the researchers to gain an understanding of the case study's context and documentation that was made available. Cohen and Manion [6] define the process of triangulation as an "attempt to map, or explain more fully, the richness and complexity of human behavior by studying more than one standpoint" (p.254). Thus, multiple viewpoints were obtained from within the engineering organization to obtain a balanced understanding of the design and development of the project control system. Unstructured interviews and observations over a three-month period in the engineering organization's office were undertaken to seek explanation and clarification about issues that were identified from the documentary sources provided, which enabled intrinsic biases that may have arisen to be overcome. Interviews provided the researchers with a mechanism to ask questions and seek clarification with engineers involved with the selected case study project.

3.1. Case selection

The authors have been collaborating with an EICS organization for a number of years examining issues associated with the design, development, and implementation of SIM. However, the adoption of a SIM as a mechanism to be used for project controls has been limited. The EICS organization was provided with an opportunity to deploy a SIM on an energy infrastructure mega-project which provided the researchers with an opportunity to examine its development and implementation in practice.

3.2. Case background

A client-initiated, with the support of their Government, a US$27 billion economic development on the southern coast of the Red Sea. As part of this development an oil refinery (US$4 billion), port terminals (US$1.4 billion) and a 2400 MW power plant (US$2.5 billion) are required. The refinery will cover an area of 12 km^2 and have a processing capacity to process approximately 400,000 barrels per day of heavy and medium crudes to produce gasoline (75,000 bpd), ultra-low-sulphur diesel (100,000 to 160,000 bpd) and fuel oil (160,000 to 220,000 bpd).

An Engineering Procurement Construction Management (EPCM) organization was awarded a contract by the client to provide Front-End Engineering and Design (FEED), and Project Management Services (PMS). When the FEED was complete the project was divided into a total of 13 Engineering Procurement and Construction (EPC) packages, which included a marine terminal, utility facility, and building; sour water stripper unit and amine regeneration unit; naphtha and aromatics (benzene and paraxylene) units; two tank farms packages; crude distillation and vacuum unit; hydrocracker and diesel hydro-treater packages. The EICS organization who has been working with the authors was contacted by the EPC which is responsible for delivering the utility and building facility to create a platform enabled by a digital SIM for the purpose of project controls. As a result, the specific 'Construction

Functional Module (CFM)' that forms an integral part of the SIM was enacted so that cost, time and quality information directly observed by onsite engineers was provided directly to project managers. The workflow of the CFM followed the Deming Cycle Plan➔Do➔Check➔Act (PDCA) cycle [21–23]. In the next section of the paper, the CFM that was created to enable EICS works to be monitored in a digital environment in the case study project is presented.

4. Enacting SIM in construction

The SIM's 'Construction Portal' provided a comprehensive all-in-one solution for having access to design information of the construction objects, together with their associated activities and progress information which was updated every time a specific activity was completed. This meant that engineers on-site were able to access the SIM design through a construction portal in real time. When activity was completed, the engineer immediately updated the status enabling information to be made available instantly to the project manager.

The project's schedule was created using Oracle's Primavera P6 software and developed by the EPCM organization. Input from both the construction contractor and the project management team to ensure the client's specifications and expectations could be met within the allocated time period were also required to create the schedule. It was extracted from P6 as a CSV file and then imported into SIM. The agreed sequencing of construction tasks and monitoring activities reflected a reasonable workflow that adhered to the contractors and project management team's quality control procedures. The workflow was digitally created, evaluated and modified until a satisfied procedure was determined. A date attribute was created in the SIM and assigned to the objects and activities. The scheduled date (created in P6) for each activity was assigned to the corresponding activity as the 'Planned Date' in the SIM. The actual date the engineer completed the activity was recorded in the SIM as an 'Actual Date' attribute, which enabled a project manager to view differences. An overview of the 'Construction Portal' that was established for the project is presented in Fig. 3 and the progress dashboard in Fig. 4.

The PDCA workflow of the 'Construction Portal' provided site engineers and managers with the ability to continuously monitor and improve their decision-making as they had access to real-time data. The digital design data stored in the SIM formed the foundation for the construction portal's application. Having accurate and coherent design data enabled construction activities to be scheduled effectively and efficiently. There was no requirement to manually cross-check and validate the information contained in the SIM as it acted as a consolidated point of truth, which enabled the scheduling of activities to be completed at minimum cost and time.

The construction activities were created in a hierarchical structure that reflected the actual workflow adopted in the project. A typical structure included 'Work step', 'Work class', and 'Discipline' (Fig. 3). The created construction activities were then allocated to a 'Work Package' and assigned to an engineering team. The number of components, cable length and cable terminations were used to measure the works that were completed.

To reflect the actual workload of different disciplines a set of Relative Weight Factors (RWF) were created. In this project, the RWF for the electrical discipline was defined as 4.68% and 5.96% for the instrumentation discipline. This indicated that the electrical and instrumentation work accounted for 4.68% and 5.96% respectively of all the work to be finished in the project. The total construction person-hours for the project was 25,550,000, with the electrical and instrumentation consuming 1,195,740 and 1,522,780 respectively. The RWFs for the 'Work steps', 'Class' and 'Discipline' were defined according to the features of the project and the type of activities undertaken (Fig. 4). Progress was calculated using the equations created in the construction portal (Fig. 5). For example, the progress of 'Cable Pulling' was calculated using the following equation:

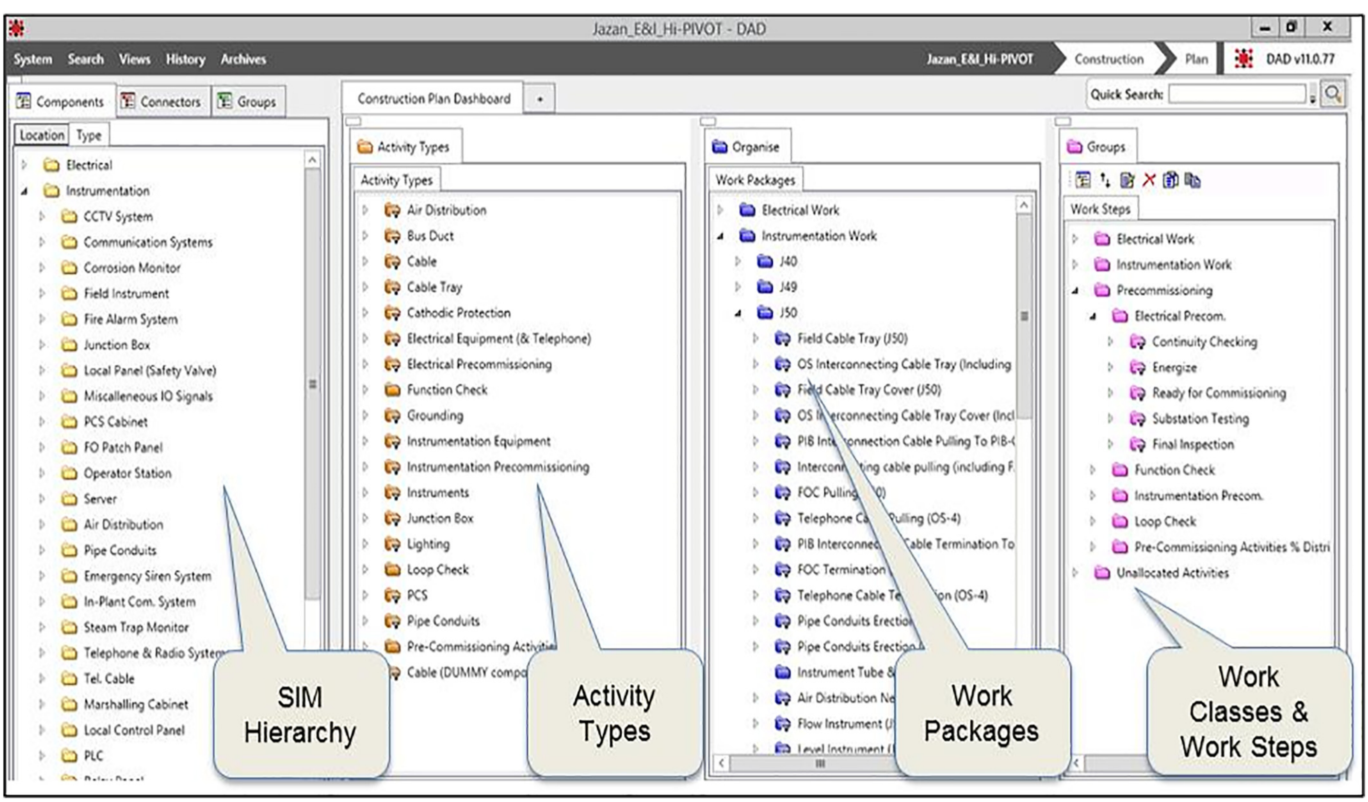

Fig. 3. Overview of the construction portal.

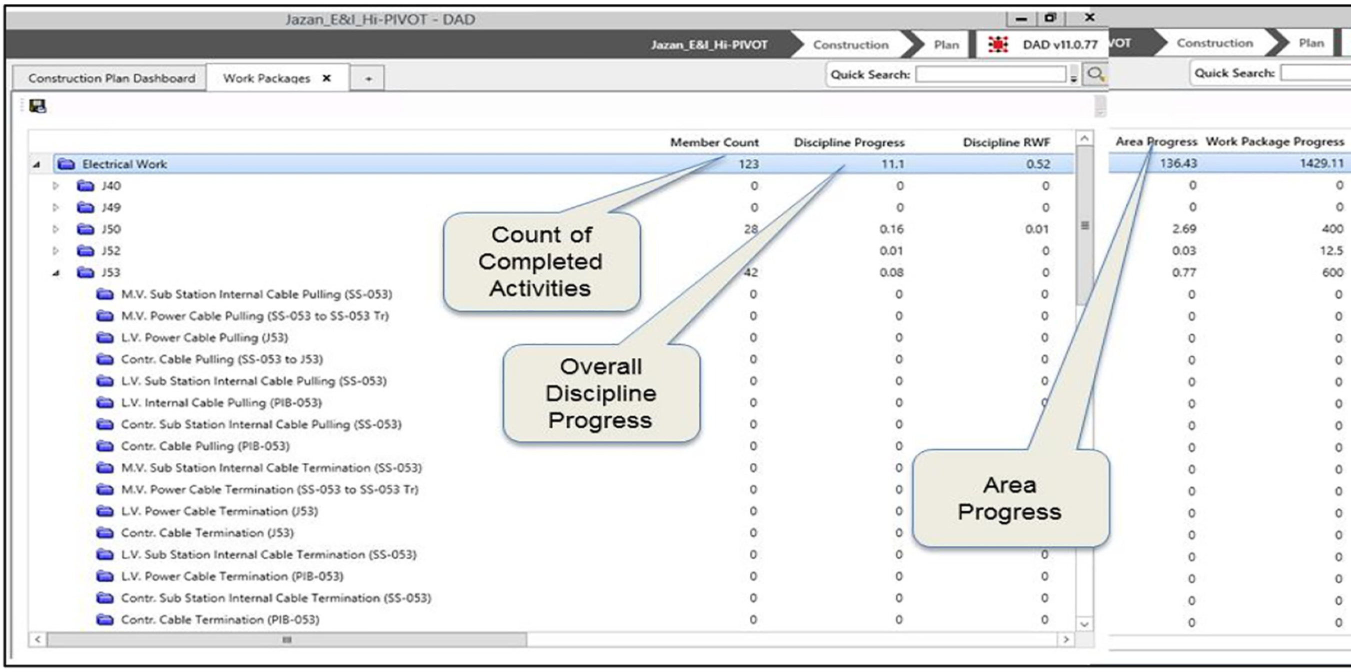

Fig. 4. Construction progress dashboard.

$$\frac{\text{length}}{\text{cable length in WP}} \times \text{cable pulling flag} \times \text{No. of steps in work class} \times \text{work step WF\%} \quad (1)$$

and the cable termination progress can be calculated as:

$$\frac{\text{termination}}{\text{sum of terminations in WP}} \times (1-\text{cable pulling flag}) \times \text{termination flag} \times \text{work step WF} \quad (2)$$

$\% \times$ No.of steps in work class

With this in mind, the project manager was able to monitor work

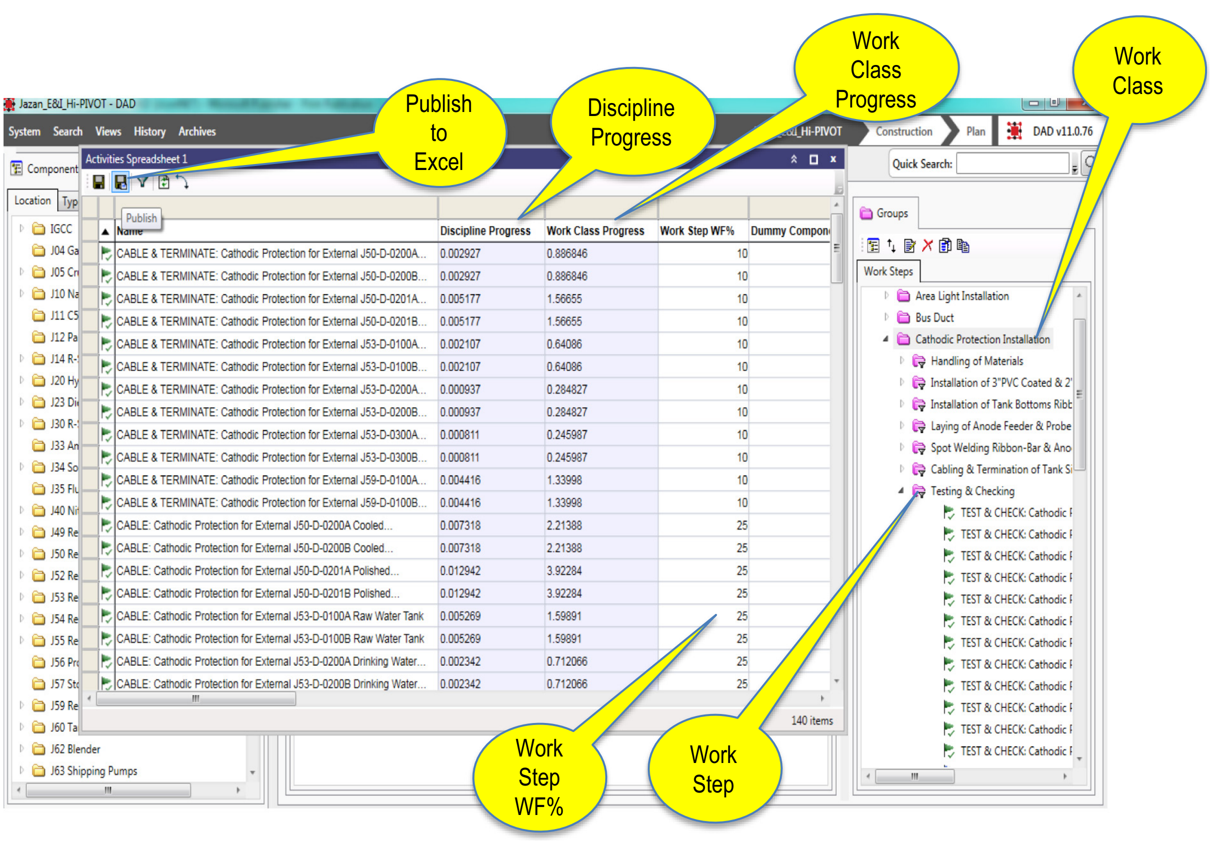

Fig. 5. Understanding construction progress.

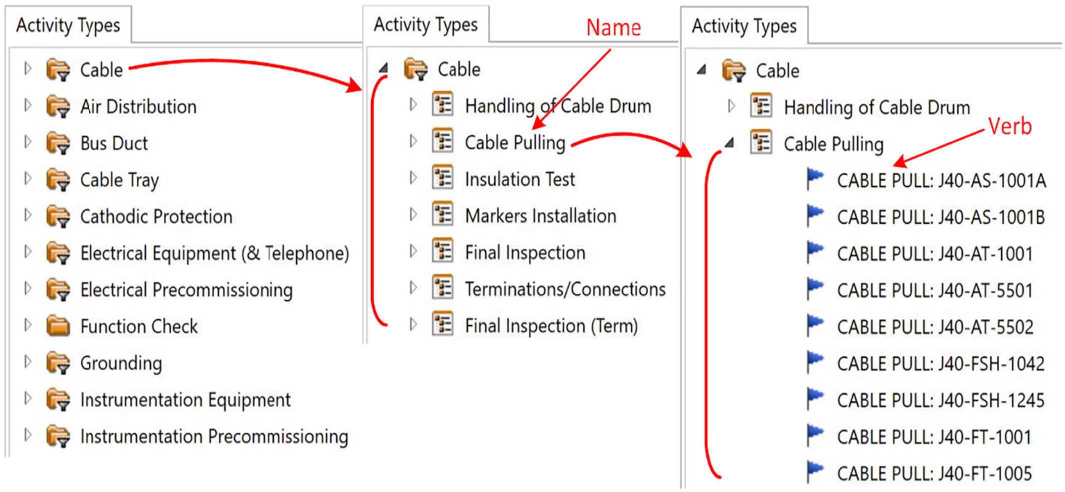

Fig. 6. Activity definition and assignment.

progress and the according man-hours consumed.

4.1. Activity definition and job assignment (plan)

In the CFM, the activity schedule followed a 'Define ➔ Assign ➔ Work Package' mechanism. When formulating the plan for the EICS works to be undertaken, the first step was to determine the activities that needed to be performed to the target objects. The installation of an electrical cable on site, for example, typically involved the following activities: (1) cable drum handling; (2) cable pulling; (3) insulation test; (4) marker installation; (5) inspection and termination; and (6) termination inspection.

In the CFM 'Activity Type' view, users were able to create and define folders for specific activities. Fig. 6 illustrates the process of activity definition and assignment that took place. It can be seen that a number of activity folders were created based on the work classifications of the project. Under each folder, the activities relating to the specific work class were defined. For instance, in Fig. 6, the activities relating to the cable works can be found. These activities were then automatically assigned to the corresponding cables by importing them into each activity type using a 'filter' function. In Fig. 7, the method used for 'Activity Definition', which reflected the feature of the work, is presented using cables as an example. A verb is also used to denote the activity that was performed. Once the activities were defined and assigned to the objects, they were allocated to the 'Work Package' and assigned to the corresponding contractor who had agreed to undertake the works (Fig. 8).

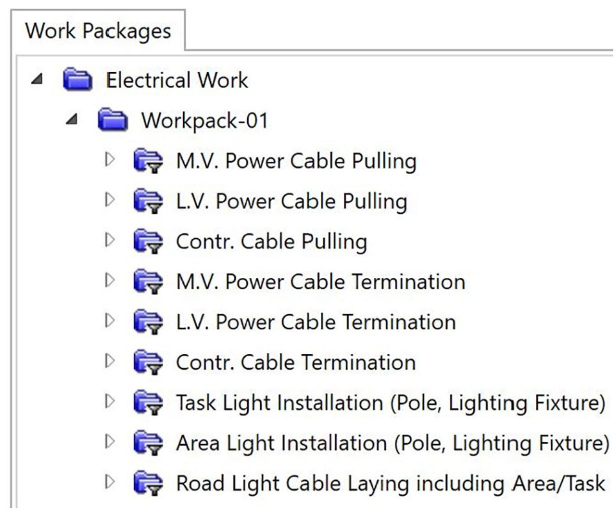

Fig. 8. 'Work Package' allocation.

By using the SIM, the activity definition and job assignment were

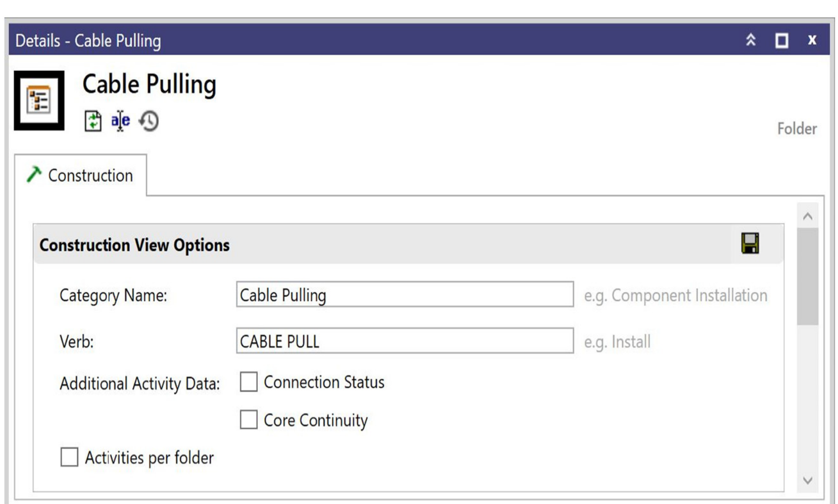

Fig. 7. Activity definition.

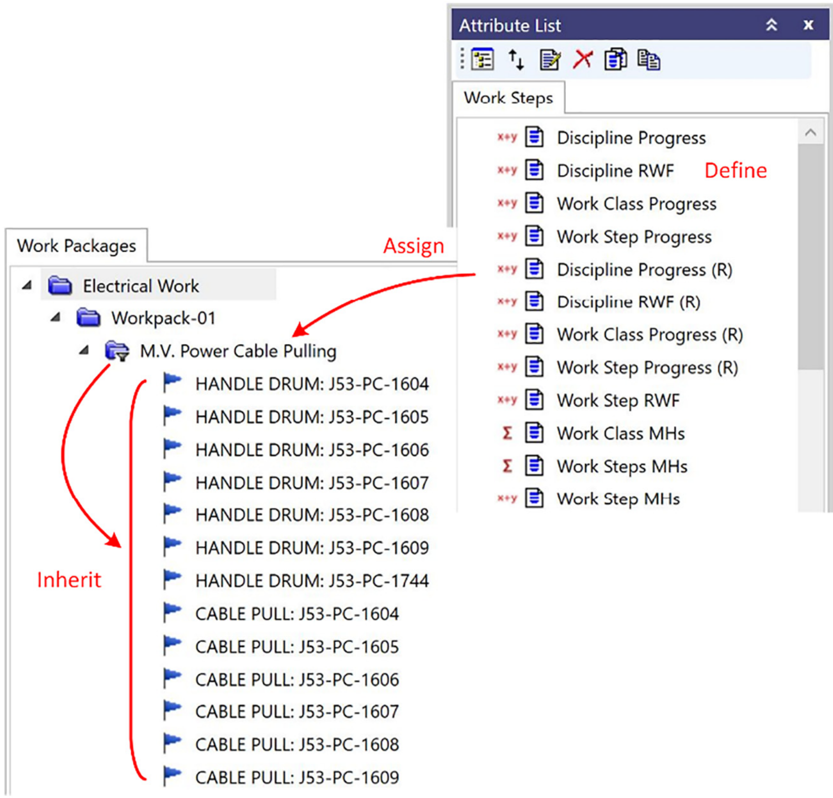

Fig. 9. Attribute management.

able to be detailed at the object level. The corollary being that project progress monitoring and control could be undertaken at this level. To facilitate the project monitoring and control, various types (e.g., string, numeric, date and equation) of attributes (e.g. planned start/finish date, man-hours, and weighted factors) were defined and assigned to the 'Work Package' folders, which are inherited by the children tasks under the folder (Fig. 9).

The value of an attribute was then assigned at the 'Work Package' level such that the children tasks could inherit the value from their parent. The attribute value could also be managed at the task level so as to reflect the status of each individual task. Using this method, project managers were able to measure the progress precisely based on the status of the tasks and 'Work Package'.

Noteworthy, this level of detail is unable to be achieved when CAD is adopted in a project as 'Work Packages' tend to be comprised of numerous drawings where it is often difficult to identify components and cables as they are often mislabeled or missing [20,25]. The 'Work Package' developed in the case study for the EICS was divided into 'Electrical' (i.e. 35,369 activities) and 'Instrumentation' (i.e. 52,323 activities) to reduce their size and complexity. Both the electrical and instrumentation works accounted for 10.5% to the total construction costs.

4.2. On-site job recording and submission (do)

When tasks from within the 'Work Package' were assigned to contractors, site engineers who had been given authorized access to the SIM were able to acquire the design data and the job schedules. The SIM data was accessible both 'locally' (without the need for a network connection) and 'remotely'. When local mode was used, the SIM database, which was supported by the DAD software, was installed on mobile devices. To ensure the consistency and traceability of the changes made to the SIM database by users, which may have occurred due to status updates and the attachment of new documents, it needed to be synchronized with the master database on a regular basis. For example, synchronization was necessary to reflect the project's progress and changes over a 24-h period. In this case, delays between events and synchronization could have potentially caused issues and disagreements between different parties, as the users may not have been aware of any changes made by other users. When the 'remote' approach was used, users could simultaneously access the database stored on a server from their local devices using SQL authentication. That is, multiple users were able to concurrently perform different activities on the same SIM model.

A change made to the SIM by one user was instantly available to others, which enabled them to access the latest data. Noteworthy, to access the remote SIM database required the 'Parallels Client' software to be installed to enable users to access the services that were hosted on the remote server. This reduced software licensing costs and also simplified the maintenance and upgrade process. Mobile devices such as PC tablet and smartphone were used by the site engineers to access the database remotely (Fig. 10).

Traditionally site engineers need to manually record work progress and sign-off its completion. In this case study, this would have been a time-consuming process for site engineers considering the sheer number of tasks involved. Moreover, if progress had been recorded manually then there would be an increased likelihood for errors to be made. Manually completed progress reports would also have needed to be submitted to a project manager for review. Extracting information from the reports is a tedious process (e.g., incomplete information is provided) and can hinder decision-making when being subjected to budget and schedule constraints. The use of a SIM-enabled the status of tasks to be recorded chronologically to ensure information traceability. As all EICS works had been scheduled in the digital SIM, site engineers were able to directly update the task status once it had been completed (Fig. 11). The updated task status was automatically attached with a digital signature of the engineer. As a result, there was no need to sign on each task that had been completed. The history log of the task

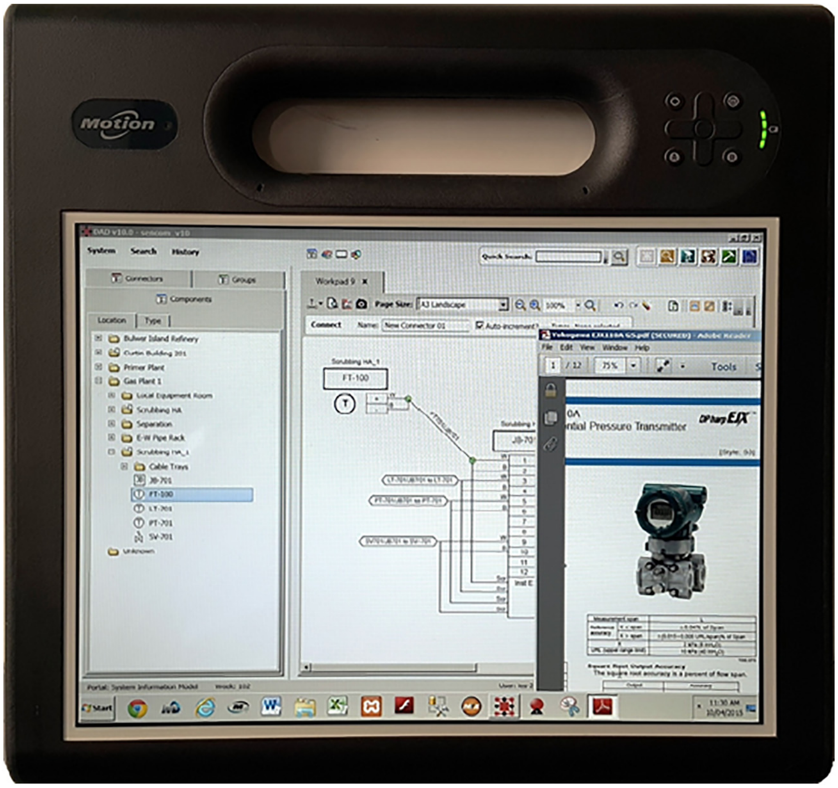

Fig. 10. Accessing SIM data through a mobile device.

indicated the users and the corresponding activities that had been performed (Fig. 12). This simplified the project recording process and enabled better traceability and accuracy to be obtained. The status change was visible to the project manager instantly who was also connected to the master database.

4.3. Project progress monitoring and control (check & act)

Inspecting the progress of electrical and instrumentation works was a time-consuming and labor-intensive process in the cases when it had to be conducted manually. Technologies, such as laser scanning and Radio Frequency Identification which are popular technologies for checking those elements that contain geometry, are unable to be used for electrical and instrumentation systems. Thus, the process of inspection for electrical and instrumentation systems is different from other aspects of a project performed during construction. In addition to checking that a device has been installed, the inspector also needs to confirm that it is the required model, from the right manufacturer. Moreover, the cable terminations need to be checked such as power, signal and grounding connections. Usually, specialized equipment can be used to assist the inspection to ensure that the electrical connections are reliable. However, in this instance, the inspector also needed to confirm that the parameters of the devices were set and calibrated in accordance with the specification. For those smart devices that had been installed, such as Programmable Logic Controllers (PLC), it was necessary to ensure that the correct coding had been uploaded.

Traditionally the inspection process was conducted manually using drawings, manuals and the production 'Inspection Test Reports' but in this study, this was replaced by PC tablets enabling the SIM's digital capability to capture and store information. The design data and the construction schedules were digitally stored in the SIM enabling them to be accessed by the onsite inspectors through mobile devices. The

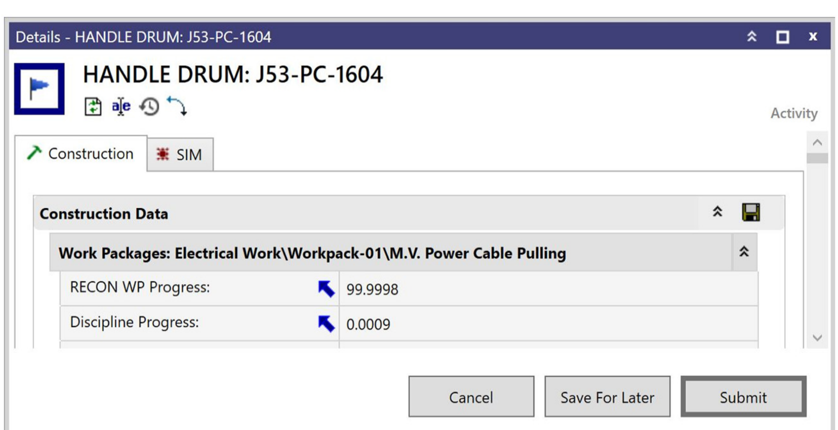

Fig. 11. Submission of a finished job.

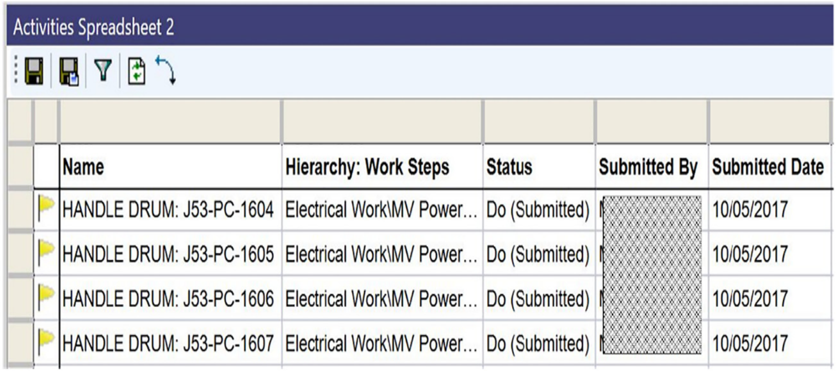

Fig. 12. Activity history.

inspection tasks were scheduled within the SIM to provide guidance for the inspectors to complete their works. The inspection tasks were created in detail for each construction object and activity by describing the items that needed to be examined. Comments were attached as notations for further actions.

The history log recorded the activities that had been performed by the inspector and therefore their signature was no longer required as they could be readily identified. Fig. 13 illustrates a portion of the items to be checked regarding the installation of an electrical cable. Here the inspector selects the status for each item based on the inspection result. When all the items have been checked, the inspector passes and the submitted tasks to be reviewed by their project manager. If the inspection had been failed, then it would be sent back to the construction team for them to rectify the problem. Project managers were able to oversee the progress of works using a dashboard in real-time (Fig. 14).

Real-time project progress monitoring requires a wireless network to be readily available on site to enable engineers to access the SIM through the construction portal. In remote locations, this is not always feasible and therefore a local copy of the SIM can be uploaded to a mobile device and used to record performance. Then, when the engineer returns to their office, the local copy can be synchronized to the master, which will be made available to the project manager. A delay, however, exists between the completion of activities and when progress is reviewed by a project manager.

5. Discussion

Project monitoring and control requires processes to be tracked, reviewed and changes to plans to be initiated should they need to be undertaken. Thus, works need to be inspected and comparisons between the planned and actual made to determine progress. In the case of EICS, particularly in energy and mining, this process has been conventionally based upon manual paper-based systems, which has stymied the ability to make an accurate and timely assessment of progress and valuations of work that has been undertaken. Despite technological advances (e.g., BIM, computer vision, and sensors) being made to monitor and control work in real-time during construction, EICS documents tend to contain duplication, errors and information redundancy as they are prepared in a CAD-based environment where pdf. file formats are issued for construction. Within a SIM environment, EICS are designed and engineered in an object-oriented environment, which provides the number of drawings produced for construction to be significantly reduced. For example, Fortescue Metal Group employed a SIM during the construction of their North Star Magnetite project, which resulted in being paperless for EICS [29]. The corollary in this instance being a reduction from 20,000 to 10,000 h required to inspecting and testing equipment due to the accuracy of the information contained in the digital SIM that had been issued for construction [29]. In the case study presented when final system checks were undertaken, technicians were required to simply tick checkboxes, which were

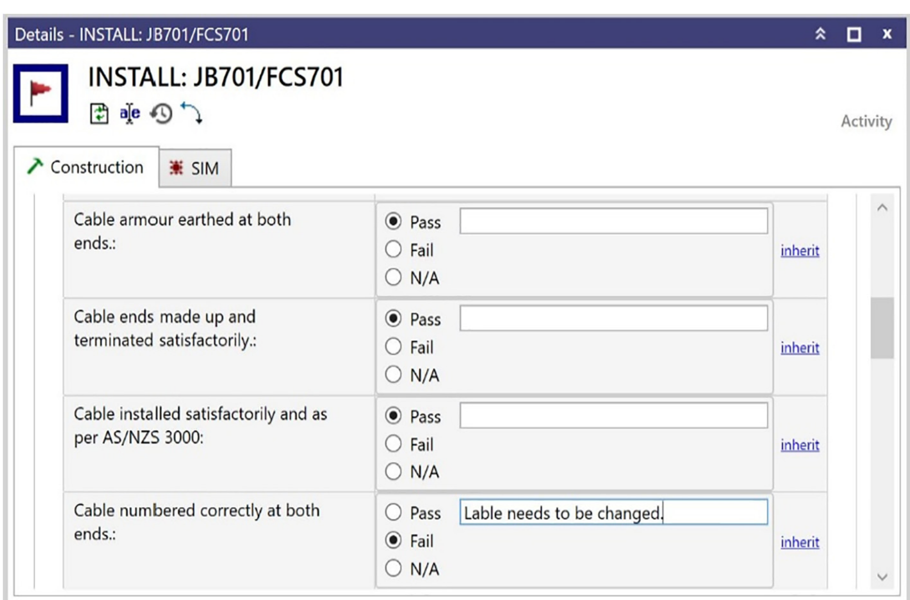

Fig. 13. Scheduled inspection tasks.

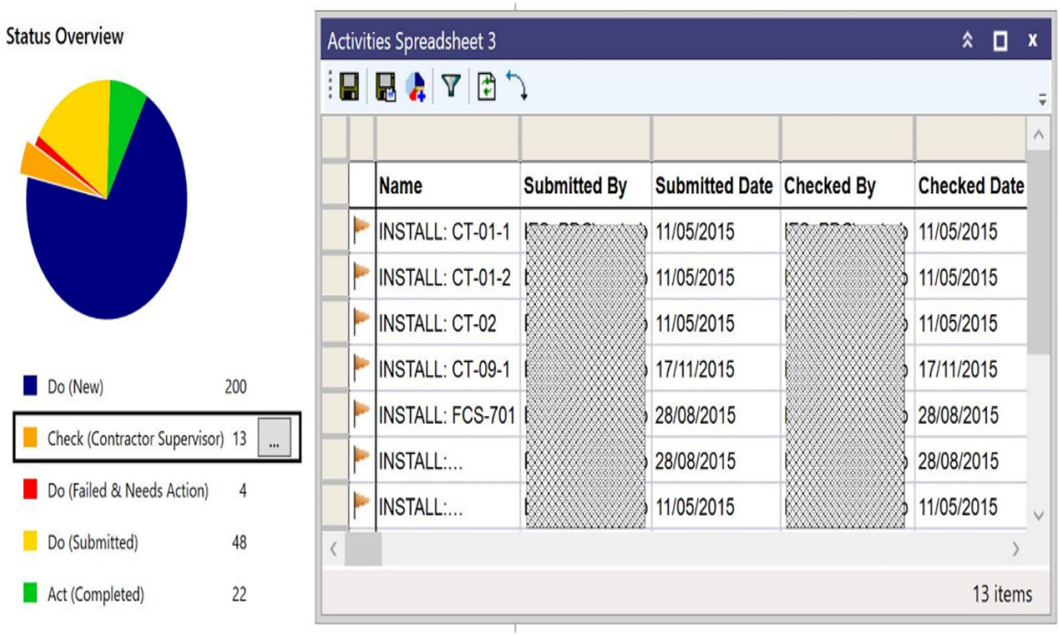

Fig. 14. Status overview.

immediately uploaded into the SIM allowing managers to have a real-time view of progress.

The use of a SIM enables the established document-oriented information exchanges that typically are used in EICS projects to become a collaborative data-sharing environment, and therefore enabling its monitoring and control activities to be viewed holistically against other ‘Work Packages’ [23]. A SIM is a discipline-specific model, therefore, needs to be created and maintained. It can be used to share data through the use of ‘Global Unique IDs’ (GUID) enabling it to be coordinated and shared across a variety of software platforms without the need for complex data exchanges [23]. However, in the case presented it was not able to be automatically synchronized with the process plant's 3D model that had been developed as it was not used to manage construction operations. Thus, real-progress monitoring only could occur at the ‘Work Package’ level, which only provided managers with a view of EICS, and therefore as it is not integrated with the entire project's schedule.

To ensure the integration of a SIM with building information model they can be linked together using an Industry Foundation Classes (IFC) data format. This is a neutral, open file format intended to describe construction data. This means that the 3D model can be created in any BIM software, exported to an IFC file and opened in the IFC viewer in order to link with the schedule imported into the SIM as well as other information. Such an IFC viewer, for example, can be developed using an open-source toolkit such as xBIM [18]. Future research will use the xBIM functionality to enable the IFC viewer to be programmatically linked to a SIM database so that information (attributes) can be retrieved and displayed about a component's status when selected in the viewer.

6. Conclusion

Accurate assessment of a project's progress enables managers to control and manage costs and schedule. While a considerable amount of research has made headway to automating the processes to monitor and inspect the progress works in construction, and ensure that the data acquired and retrieved is able to produce an accurate ‘as-built’ model, there has been an explicit emphasis placed on physical objects that possess geometrical properties. Yet despite EICS being critical to the operation and management of facilities they have received limited attention. Put simply, without EICS facilities are unable to function.

Ensuring that EICS are efficiently and effectively installed, inspected, tested and commissioned is a challenge as the process is typically undertaken manually using CAD in energy and resource based-projects, despite technological advances being made in the area of OOP. Such documentation tends to be reliant on the production of paper-based systems, which may be electronically transferred in a Portable Document Format. A SIM presents an alternative method to produce engineering documentation for ECIS where a 1:1 relationship is created between the model and the real objects. By constructing a 1:1 model, information redundancy can be eliminated, which reduces the propensity for errors and omissions to be made by engineers, which can result in rework and losses of productivity manifesting during construction. The shift toward embracing real-time progress monitoring of construction requires the design of EICS systems to be produced in an object-oriented environment and a ‘Construction Portal’ for the SIM to be created and aligned with a PDCA workflow. Ideally, the schedule should be produced collaboratively between the EPCM's project managers and contractors to produce a ‘look ahead plan’ that can be realistically achieved given the available time and resources.

In this paper, the design and development of a SIM and its implementation for progress monitoring of EICS in a mega-project development are presented. The architecture of the system and its role in enacting progress monitoring is described. It is shown that the SIM provides a valuable platform for ensuring the accuracy and timely transfer of information from the workface to a consolidated point of truth that projects managers can access in real-time. A SIM is discipline-specific and there is a need to ensure its interoperability with building information modeling software. Therefore, a bi-directional link between the SIM and the project's overall schedule and 3D model needs to be developed in the future.

The EPCM organization that utilized the SIM in their project, however, recognized its potential to provide a new way of working as part of a strategy to engage with the digital future. Naturally, technological innovations such as a SIM that is incongruous with established work practices are often confronted with strong skepticism and a lack of legitimacy. But, how such legitimacy is created and enacted will not automatically result from championing a SIM through its advocacy, but also empirically identifying the failure and bottlenecks with using software systems (e.g. CAD) that are not object-oriented in nature. To this end, it is suggested that future emphasis needs to be placed on providing empirical evidence of both the direct and indirect benefits, costs and risks of engaging in new digital solutions so that lessons and experiences can be shared to ensure their successful adoption.

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References

[2] Aveva, Aveva world magazine, Issue 2, Available at http://view.digipage.net/?id=aveva_world_magazine_2012_issue2&page=38, (2012) , Accessed date: 28 January 2018.
[3] F. Bosché, Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction, Adv. Eng. Inform. 24 (1) (2010) 107–118 https://doi.org/10.1016/j.aei.2009.08.006.
[4] Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., and Haas, R. (2015). The value of integrating scan-to-BIM and scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: the case of cylindrical MEP components. Autom. Constr., 49(4), pp.201–213. doi.org/https://doi.org/10.1016/j.autcon.2014.05.014.
[5] Ding, L-Y., Weili F, Luo, H., Love, P.E.D., Zhong, B. and Ouyang, X. (2018). A deep hybrid model to detect unsafe behavior: integrating convolution neural networks and long-short-term memory. Autom. Constr., 86, pp.118–124. doi.org/https://doi.org/10.1016/j.autcon.2017.11.002.
[6] L. Cohen, L. Manion, Research Methods in Education, Fifth Editon, Routledge, 2000.
[7] Chu, M., Matthews, J., and Love, P.E.D. (2018). Mobile building information modeling and augmented reality systems: an experimental study. Autom. Constr., 85, pp.305–316. doi.org/https://doi.org/10.1016/j.autcon.2017.10.032.
[8] R. Davies, C. Harty, Implementing site BIM: a case study of ICT innovation on a large hospital project, Autom. Constr. 30 (2013) 15–24. doi.org/10.1016/j.autcon.2012.11.024.
[9] Fang, W., Ding, L-Y., Luo, H., and Love, P.E.D., (2018). Falling from heights: a computer vision-based approach for based safety harness detection. Autom. Constr., 91, pp.53–61, doi.org/https://doi.org/10.1016/j.autcon.2018.02.018.
[10] Golparvar-Fard, M., Peña-Mora, F., Arboleda, C.A., and Lee, S-H. (2009). Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. ASCE Journal of Computing in Civil Engineering, 23(6), doi.org/https://doi.org/10.1061/(ASCE)0887-3801(2009)23:6(391).
[11] Golparvar-Fard, M., Bohn, J., Teizer, J., Savarese, S., and Peña-Mora, F., (2011). Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques. Autom. Constr., 20(8), pp. 1143–1155 doi.org/https://doi.org/10.1016/j.autcon.2011.04.016.
[12] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Automated progress monitoring using unordered daily construction photographs and IFC-based building information models, ASCE Journal of Computing in Civil Engineering 29 (1) (2015), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000205.
[14] C. Kim, B. Kim, H. Kim, 4D CAD model updating using image processing-based construction progress monitoring, Autom. Constr. 35 (2013) 44–52 https://doi.org/10.1016/j.autcon.2013.03.005.
[15] M. Kopsida, I. Brilakis, P.A. Vela, A review of automated construction progress monitoring and inspection methods, Proceedings of 32nd CIB W-78 Conference, 27th–29th October, Eindhoven University of Technology, The Netherlands, 2015(Available at:), http://itc.scix.net/cgi-bin/works/Show?w78-2015-paper-044 , Accessed date: 18 December 2018.
[16] Kropp, C. Koch, C., and König, M. (2018). Interior construction state recognition with 4D BIM registered image sequences. Autom. Constr., 86, pp.11–32, doi.org/https://doi.org/10.1016/j.autcon.2017.10.027.
[17] K. Li, L.Y. Ding, Y. Zhou, P.E.D. Love, Industry foundation class quality information model for infrastructure projects: enabling real-time quality monitoring and control, Autom. Constr. 84 (2017) 96–110.
[18] S. Lockely, C. Benghi, M. Cerney, Xbim.Essentials: a library for interoperable building information applications, The Journal of Open Source Software 2 (20) (2017) 473 Doi.org 10.21105/joss.00473.
[19] Love, P.E.D., Holt, G.D., and Li, H. (2002). Triangulation in construction management research. Eng. Constr. Archit. Manag. 9(4), pp. 294–303. doi.org/https://doi.org/10.1108/eb021224.
[20] Love, P.E.D., Zhou, J., and Kim, J.T (2014). Assessing the impact of requests for information in electrical and instrumentation engineering contracts. J. Eng. Des., 25 (4–6), pp.177–193, doi.org/https://doi.org/10.1080/09544828.2014.935305.
[21] P.E.D. Love, J. Zhou, J. Matthews, H. Luo, Object-oriented modeling: retrospective systems information modeling for constructability assessment, Autom. Constr. 71 (2) (2016) 359–371, https://doi.org/10.1016/j.autcon.2016.08.032.
[22] Love, P.E.D., Zhou, J., Matthews, J., and Luo, H. (2016b). System information modeling: Enabling digital asset management. Adv. Eng. Softw., 102, pp.155–165. doi.org/https://doi.org/10.1016/j.advengsoft.2016.10.007
[23] P.E.D. Love, J. Zhou, J. Matthews, Systems information modeling: from file exchanges to model sharing for electrical instrumentation and control systems, Autom. Constr. 67 (2016) 48–59 doi.org/10.106/j.auto.con.206.02.010.
[24] Love, P.E.D., Zhou, J. Matthews, J. Sing, C-P. and Edwards, D.J. (2017a). Systems information modeling in practice: analysis of tender documentation quality in mining. Autom. Constr. 84, pp.176–183, doi.org/https://doi.org/10.1016/j.autcon.2017.08.034.
[25] Love, P.E.D. Zhou, J., and Matthews, J. (2017b). Safeguarding asset integrity with digitization: implementation and commissioning of a gas metering upgrade. Journal of Natural Gas Science and Engineering, 44, pp.9–21, doi.org/https://doi.org/10.1016/j.jngse.2017.04.00.
[26] P.E.D. Love, J. Zhou, J. Matthews, M. Lavender, T. Morse, Managing rail infrastructure for a digital future: future-proofing of asset information, Transportation Research A Policy and Practice 110 (2018) 161–176 https://doi.org/10.1016/j.tra.2018.02.014.
[27] J. Matthews, P.E.D. Love, S. Heinemann, C. Rumsey, R. Chandler, O. Olatunji, Real-time progress monitoring: process re-engineering with cloud-based BIM in construction, Autom. Constr. 58 (2015) 38–47, https://doi.org/10.1016/j.autcon.2015.07.004.
[28] McKinsey Global Institute, The social economy: unlocking value and productivity through social technologies, Available at McKinsey & Company, https://www.mckinsey.com/industries/high-tech/our-insights/the-social-economy, (2012) , Accessed date: 21 March 2018.
[29] C. Sheedy, Mining Goes Paperless, March Engineers Australia, 2016, pp. 58–63.
[30] Son, H. and Kim, C. (2010). 3D structural component recognition and modeling method using color and 3D data for construction progress monitoring. Autom. Constr., 19(7) pp.844–854. doi.org/https://doi.org/10.1016/j.autcon.2010.03.003.
[31] Turkan, Y., Bosché, F Haas, C.T., and Haas, R. (2012). Automated progress tracking using 4D schedule and 3D sensing technologies. Autom. Constr., 22, pp.414–421, doi.org/https://doi.org/10.1016/j.autcon.2011.10.003.
[32] Zhou, J., Love, P.E.D., Matthews, J., Carey, B., and Sing, C-P. (2015). An object-oriented model for life cycle management of electrical instrumentation control projects. Autom. Constr., 49, pp.142–151, doi.org/https://doi.org/10.1016/j.autcon.2014.10.008.