Moving Beyond CAD: A Systems Information Model for Electrical and Instrumentation Engineering Design

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Documentation errors have been identified as a significant problem within the construction and engineering industry. Errors contained with contract documents can contribute to loss of profit, reduced productivity, and cost and time overruns as well as contractual disputes. Research has identified that as much as 60% of variations in construction and engineering projects are a result of errors and omissions contained within poor quality documentation. Using a case study, errors, omissions and information redundancy contained in the Electrical and Instrumentation (E&I) 'As built' drawings for a Stacker Conveyor is examined. A total of 449 errors and omissions were identified within 42 documents. In addition, 231 cables and components appeared once among the 42 documents; 86 cables and components appeared twice and 12 cables and components appeared three times. As a result of the errors, omissions and redundancy, requests for information (RFIs) are required. Retrospective analysis indicates that the indirect cost of raising the RFIs to the contractor was estimated to be 8.93% of the cost of the E&I contract. To address the problems of errors, omissions and redundancy, it is suggested that there is a need to adopt an object orientated system information model (SIM) for E&I engineering design and documentation. It is demonstrated in the case study that the use of a SIM could bring significant improvements in productivity and reduce the cost of engineering design.

Keywords: *'As-Built', CAD, DAD, systems information model, errors and omissions*

INTRODUCTION

Graphical and written representations developed by electrical engineers are typically represented in two dimensions (2D) and constructed using computer-aided-design (CAD). When a change is required, a 2D drawing and each corresponding view require a manual update, thus a 1:n relationship exists. The modification of drawings can be a very time-consuming and costly process. Furthermore, as drawings are invariably manually coordinated between views in 2D, there is a propensity for documentation errors to arise particularly in the design of complex Electrical and Instrumentation (E&I) systems, which may comprise of hundreds of drawings that are not to scale and have to be represented schematically. In this instance, information is often repeated on several drawings to connect each schematic together. Consequently, the time to prepare the schematics can be a lengthy and tedious process, especially as the design gradually emerges and individual documents are completed. Any inconsistencies that manifest between the documents require re-editing and crosschecking before they are issued for construction. Omissions and errors in contract documents have been identified as major sources of rework and thus contribute to significant productivity losses being experienced. For example, Love et al.'s (2013) analysis of 107 'As-Built' drawings of an electrical system for a stacker conveyor identified 449 errors and omissions, which required an estimated 859 extra man-hours to rectify and an additional cost of AU$128,850 to the engineering design process. Studies have indicated that between 50% and 60% of change orders that occur in projects are attributable to poor quality design documentation (Love et al., 2006). Moreover, the costs of rectifying errors that arise from the design and documentation process can potentially increase a project's cost by 5% (Gardiner, 1994).

The design and construction of resource and energy projects are complex and challenging and their success is heavily reliant upon effective communication between members of the engineering and construction teams. Good engineering design is effective when it serves its intended purpose and is constructible within desired budget, time and safety objectives (McGeorge, 1988). The ability to provide a contractor with the information needed to enable construction to be carried out as required, efficiently and without hindrance is a fundamental trait of quality documentation. Rarely, however, is design and engineering documentation produced with all the necessary information required for construction. There is a proclivity for contractors to be supplied with incomplete, conflicting and erroneous documents (Tilley et al., 1997). When a situation of this nature arises, the standard form of communication between the contractor and engineers is to raise a Request for Information (RFI). According to Tadt et al. (2012) the purpose of an RFI is to identify and resolve issues on-site that require solutions to avoid potential contract disputes and claims. Moreover, Hanna et al. (2012) suggests that RFIs are used to provide a systematic collection of the analysis and resolution of questions that arise before and during construction. There has been empirical research that has examined the nature of RFIs, particularly how they can adversely impact productivity. For the purposes of brevity, readers are referred to Tilley et al. (1997), Tadt (2012) and Love et al. (2013) for a detailed review of RFIs and subsequent emergence. However, the process of raising an RFI for a resource project that is procured using an Engineering, Procurement, Construction and Management (EPCM) contracting arrangement is described to provide a contextual backdrop for the research that is presented.

EPCM: REQUEST FOR INFORMATION

An EPCM is a common form of contracting arrangement used to deliver infrastructure, mining, resources and energy projects. Under this form of arrangement, a client selects a head contractor to manage the entire project on their behalf. The EPCM contractor coordinates the design, procurement and construction work and ensures that the project is completed in accordance with predetermined deliverables. Subcontractors are chosen by the EPCM contractor, but they have a contractual agreement with the client. In the case of an EPCM project, the process of raising an RFI commences with a contractor's site engineer identifying a specific problem with the information that has been made available to them (Figure 1). It is important that the generated RFI is succinct and clearly worded. The contractor's site engineer will need to demonstrate that information is missing and cannot be inferred from the available documentation. Once the RFI is generated, it is distributed to the EPCM site engineering representative who then forwards it to the design engineers. A response to the RFI from the EPCM contractor can be either a simple verbal clarification and may be confined to the site or it may involve revision of the contract documents to eliminate an error or omission. If contract documents need to be revised, a draftsman will amend the documents, then distribute to the design engineers for checking and approval who will subsequently distribute to the document controllers. Once the revised documents are catalogued, they are invariably issued simultaneously to the EPCM and contractor's site engineer. If the contractor considers the response to the RFI requires additional scope then there will be discussions about a variation before the work is executed. If additional engineering is required, then this may require a considerable amount of time and effort from the EPCM contractor to revise the drawings. Such additional costs are typically borne by the EPCM contractor. Depending on the scale and nature of the RFI, site work may have to be temporarily suspended, which may result in non-productive time (e.g., waiting, idle time) being experienced.

In fact, the contractor may also experience considerable non-productive time, as they aim to understand the nature of the drawings and schematics provided due to the considerable amount of information redundancy that is often contained on them (Love et al., 2013). Such redundancy hinders the identification of errors and omissions, which further exacerbates productivity. As a result of raising the RFI, changes in scope and/or subsequent rework may be required to address the issue that has arisen. Rework in this case may not only be confined to the trade contractor, but also to the consulting engineer and EPCM contractor as documentation and the like will need to be modified when 'changes' are required (APCC, 2003).

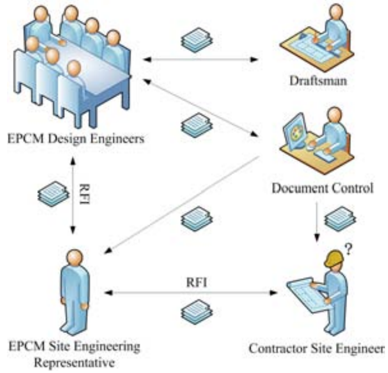


Figure 1
RFI process

RESEARCH APPROACH

Typically organizations are reluctant to allow researchers to examine the quality of documentation that has been provided to them due to reasons of commercial confidentiality and fear of potential litigation. Documentation errors are a chronic malaise and have become a 'norm' within the energy and resource sectors (Love et al., 2013). Active engagements from industry professionals who have intricate knowledge of the problem are needed to tackle this problem. Thus, a case study that utilizes a participatory action research (PAR) approach was adopted (Smith et al., 2010). In brief, PAR is: (a) participatory; cooperative, (b) engaging organizational members and researchers in a joint venture in which both equally contribute; and a way to balance research and action. In this context, the research aimed to address both the practical concerns of the organization, and the research goals (i.e. the quantification and productivity impact of errors in design documentation), by working collaboratively for a selected case study project. The characteristics of action research are: an action and change orientation, a problem focus, an organic process, involving systematic and iterative stages, and collaboration with participants from within the organization (Smith et al., 2010). As practitioner involvement was required, they were treated as both subjects and coresearchers. By adopting this approach, theory related to design error and practice acted in congruence.

CASE STUDY

Working in close collaboration with the participating organization, it was decided that a case study would be required to quantify documentation errors and their impact on productivity. The organization had access to a significant amount of completed projects but due to issues of commercial confidentiality the selection of cases available was limited. Moreover, within any given E&I package, the number of drawings that are produced varies depending on its complexity and size. Thus, a small project with a complete set of drawings was initially required to gain an understanding of the 'problem' extent and to work through new issues that may have potentially arisen. The participating organization had been asked to convert all CAD generated electrical 'As Built' drawings for a Port facility into a digital SIM using software DAD (Dynamic Asset Documentation) for the future life of the plant. DAD is leading edge engineering software, which has been developed to describe connected systems such as control, power and communications using a single digital representation. The electrical package for a Stacker Conveyor (CV911) was selected as a complete set of documents where 106 drawings and a cable schedule were readily available for analysis.

The Stacker Conveyor selected for this research was part of an AUD$2.8 billion Iron Ore Mining project that was undertaken in the Pilbara in the northwest of Western Australia (WA), which was constructed in 2008. The project consisted of two stages: (1) Construction of Port facilities and rail infrastructures to connect to mining operations, (2) Mining operations and railway connections. In the mine's first year of operation, it was estimated that 27 million tons of iron were mined, railed, shipped to customers in China. This increased to 40 million tons in 2011, and it is anticipated that this will increase to 155 tons by 2013/2014. The increase in production has resulted in several expansion projects being undertaken, such as the Port, which includes the development of additional outloading and inloading circuits, berths, ship loaders, reclaimers, stacker, train unloaders, conveyor and material handling systems, transfer stations and power and control systems. The Stacker Conveyor examined in this research is located at the Port. The Port expansion cost AUD$486 million, with AUD$59.3 million being dedicated to the EPCM, of which approximately 35% ($20.76 million) was expended on the electrical related design and documentation.

The 106 drawings and the cable schedule for the iron ore conveyor used in the study were denoted as being 'As Built'. The 106 drawings can be classified into four diagram types: (1) Block, (2) Schematic (3) Termination and (4) Layout. The 107 documents describe the function of the iron ore conveyer and its affiliated equipment and facilities, which include 469 components and 589 cables. The 107 documents account for 5% of all the electrical documents issued for the port's facilities. To facilitate the analysis, information contained in these 107 documents was extracted and modeled into a SIM through the application of DAD. As modeling progressed, a plethora of errors were identified within the 'As Built' documentation. The errors were classified as missing labels, labeling mistakes, inconsistent labeling, incorrect connection, drawing omissions, cable schedule omissions, and incorrect design (Love et al., 2013). In addition, a considerable amount of information redundancy was identified in the drawings. For example, 357 cables and components appeared on at least two drawings with as many as 42 items appearing on five different drawings. Building on this analysis, the consequences and impact of the errors and omissions identified are determined for this particular case study.

ASSESSING THE IMPACT OF DOCUMENTATION ERROR

A total amount of 589 cables and 469 components were contained within the 107 documents for the electrical system of the conveyor CV911. With the assistance of several experienced electrical engineers 230 cables (39% of all the cables) and 101 components (21.54% of all the components) were identified with errors and omissions, which distributed among 42 (39.25%) of the 107 documents. A total of 449 errors and omissions were identified. Table 1 demonstrates the number of times the 42 documents for the cables and components have been identified with errors and omissions. It can be seen from Table 1 that 231 cables and components appeared once among the 42 documents; 86 cables and components appeared twice and 12 cables and components appeared three times. One cable appeared four times and one component appeared six times. Redundancy, in some cases, may provide additional information for engineers to understand drawings. Such redundancy can, however, hinder an engineer's ability to obtain their required information in a timely manner, as they need to refer to a number of drawings and documents. This can be especially unproductive if reference numbers are labeled incorrectly. As a result, the link between drawings ceases to exist and information traceability is reduced.

The number of times each drawing was modified as a result of an RFI being raised was also identified. A description of the errors and omissions in drawing 04900-EL-DR-2001_6, for example, can be found in Table 2.

With the assistance of several engineers from the participating organization, it was estimated that, if the information was provided with the traditional CAD drawings, six man-hours would be required to generate an RFI, which includes the time to identify and define the problem. Assuming that the pay rate is $150/hour (i.e. the market rate) for a site engineer the generation of each RFI would cost the contractor $900. In the case of drawing 04900-EL-DR-2001_-6, all the errors and omissions were categorized into 10 RFIs. Thus it can be calculated that 60 man-hours will be consumed and therefore costing AUD$9000 to raise RFIs for this schematic. A description of the errors and omissions in drawing 04900-EL-DR-2571_4 can also be found in Table 2. These errors and omissions were categorized into 6 RFIs. Thus, a total of 36 man-hours and $5400 is required to raise the RFIs

Table 1
Number of times shown on documents of cables and components

Number	1	2	3	4	6
Cables	150	68	11	1	0
Components	81	18	1	0	1
Total	231 (69.79%	86 (25.98%)	12 (3.63%)	1 (0.3%)	1 (0.3%)

Table 2
Description of errors and omissions

Drawing No.	Error and Omission Types													
	Labeling Mistake		Inconsistent Labeling		Omission from Drawing		Omission from Cable schedule		Missing Label		Wrong Design		Incorrect Connection	
	Cable	Component	Cable	Component	Cable	Component	Cable	Component	Cable	Component	Cable	Component	Cable	Component
04900-EL-DR-2001_6	1	4	16	0	8	5	0	0	0	0	7	3	0	0
04900-EL-DR-2571_4	1	0	0	0	22	0	0	0	0	0	0	0	0	0

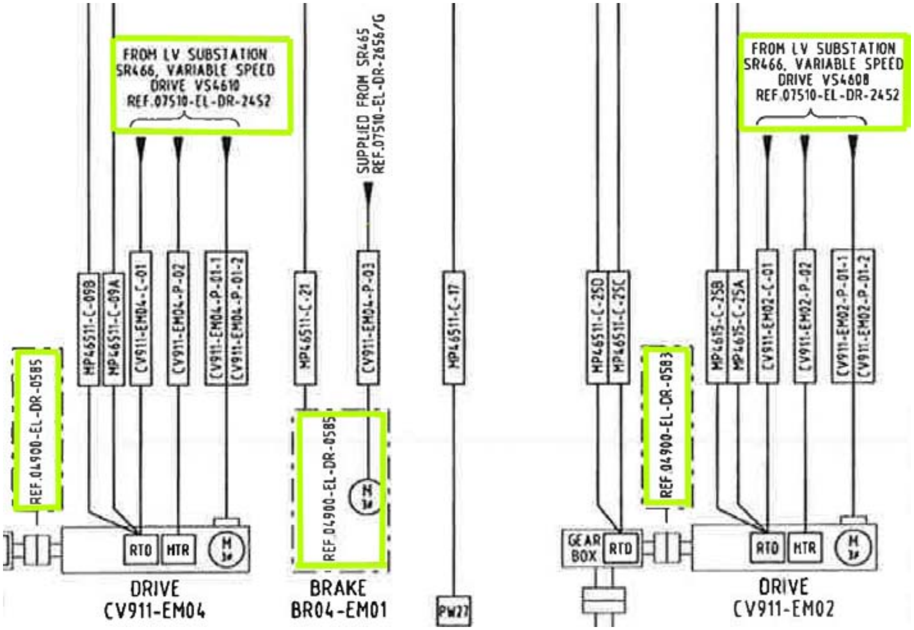


Figure 2
Reference information

for this drawing. In total, 103 RFIs are required to address the problems identified in the 42 documents. Similarly, a total 618 man-hours was required to raise the 103 RFIs at a cost of $92700. The total contract value for the E&I system design and documentation is $20.76 million. The documents in this study account for 5% of all the documents of the electrical related contract. Assuming the documents are of the similar quality, then the cost for raising RFIs accounts for 8.93% of the cost of the electrical related contract. Noteworthy, this is an indirect cost that is borne by the E&I contractor. The non-productive time associated with raising the RFI is not reimbursable. Moreover, the cost associated with raising an RFI represents a small proportion of the total indirect costs of RFIs. In practice, once a RFI is raised, the engineers on site may not be able continue their work until the correct information has been issued. Additionally the response time is lengthy as the resources may not be available to deal with the work required. Interviews with the contractor indicated that it typically takes one day to identify the problem, the drawing and mark it up, then another day to revise and review the drawings and a further two days to go through the document control process. Noteworthy, in some instances the contractor had experienced RFIs taking as many as 20 days to obtain a response and the documents to be modified. Thus, the delay in responding to an RFI, particularly in E&I contracts, may cause a delay and adversely impact productivity and project costs.

SYSTEMS INFORMATION MODEL

The information contained within the documentation produced by CAD is presented using a 1:n relationship. This resulted in a considerable amount of information redundancy being created and contained in the documentation. The production of such redundant information comes at a cost. Such cost manifests as additional time for the EPCM engineers to produce and check the documentation and then for the contractor to understand and decipher what is required to install and construct the Stacker Conveyor. In the case of the 'As Built' documentation was examined, it was revealed that many of the drawings did not marry with one another. In several instances, the drawing reference numbers were incorrect, which made it very difficult to locate the required information. A typical example of the reference information contained within a particular drawing is highlighted in Figure 2. In this selected drawing a total of 29 reference drawing numbers were identified. Two of these references were mistakenly labeled. Assuming all the information is available and can be retrieved, an engineer will need to compare and contrast multiple drawings to establish the information that is wrong or missing.

To effectively and efficiently address errors and redundancy information, which are typically found in E&I engineering contracts, it is suggested that switch from a 1:n drawing based documentation process, inherent within CAD, to a 1:1 SIM based relationship is required. In contrast to conventional CAD software, a SIM can be applied to projects where a system's design describes the interrelationships of the connected components that exist within the system. For example, in a SIM based electrical control system, all the equipment and cables that are connected are digitally modeled in a single database, which can be accessed through specific software (e.g. DAD). The model that is created replicates the design to be achieved in the 'real world'. Information stored in the database is dynamically linked so that any modification to the design is automatically generated in the model. DAD software can be applied to the entire lifecycle of E&I systems and is specifically useful for asset managers as it enables information to be stored in a single digital model. In the case of designing an electrical control system, all the equipment and cables that are constructed in the real world will only need to be modeled once when DAD is used. DAD offers users with greater flexibility to customize their designs. Attributes, such as material types, number of connections, equipment dimensions, cable lengths, locations, prices, schedules, product images and files, can be attached to the model. These attributes and associated functions enable DAD to be applied to activities in engineering, procurement, construction, commissioning and maintenance.

A SIM model can be accessed either locally or remotely. More specifically, the SIM model database can be stored on a local workstation or a remote server, which can be accessed online. DAD can be used on a PC (Personal Computer) or mobile devices. The PC version is compatible with a 'Windows' operating systems. Its mobile version can be installed on industrial Tablets, which can be used in the field. When DAD is applied to engineer an electrical project, the design to be constructed will be modeled into a database forming a SIM. Then, a read only copy of the model can be created, exported and made available as a 'Kernel' to other project team members (Figure 3). A DAD Portal, which is designed basing on the 'Kernel' is the client software with its own users and security. The users of DAD portals could import and access all or part of the design information within the Kernel regarding to their respective authorization levels. Private user data can be established and managed via the DAD portal by editing attributes of the components or attaching additional documents to the model. To guarantee that all the parties involved in the project are working on an identical Kernel, users do not have the authorization to change the design.

As the information modeled using DAD is dynamically linked, errors and omissions can be readily identified. For example, when a site engineer identifies a potential connection error associated to a variable speed drive (VSD)5671, they can verify the problem by examining its connections within DAD (Figure 4). In this instance, there is no need for the site engineer to locate and compare the problem within an array of cross-coupled reference drawings, which is often the case with using conventional CAD. Thus, time spent on problem identification can be reduced significantly. Once the problem is verified, a dedi-

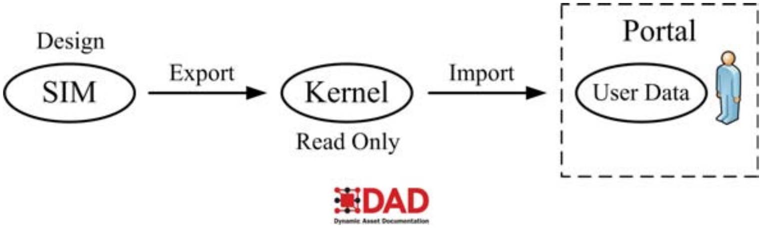


Figure 3
DAD portal/SIM relationship

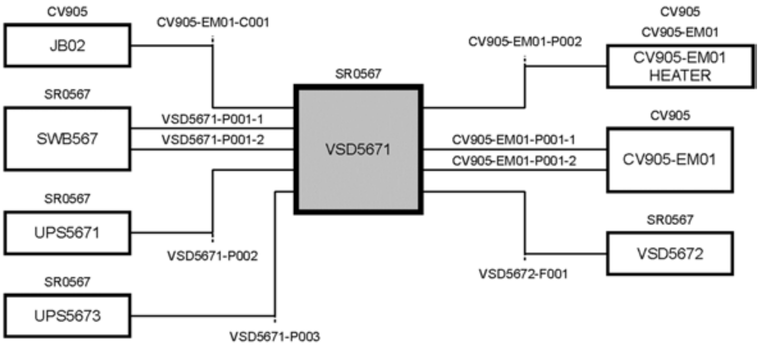


Figure 4
Example of a connection

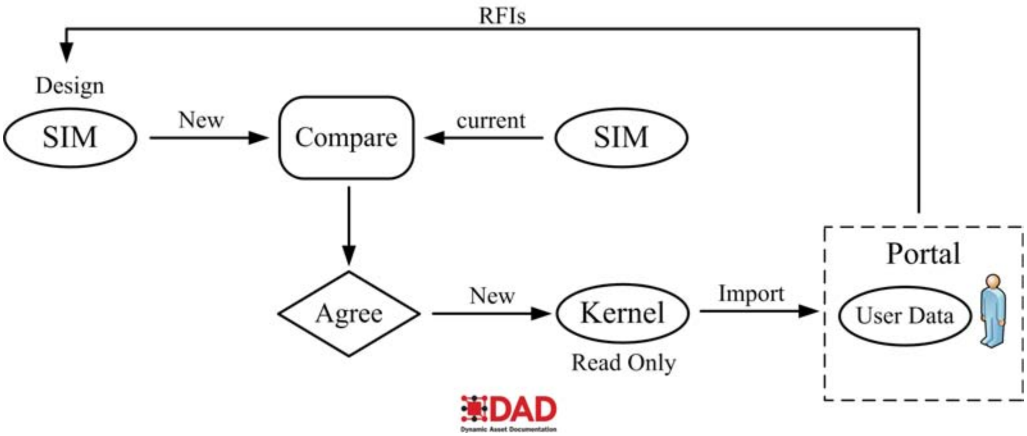
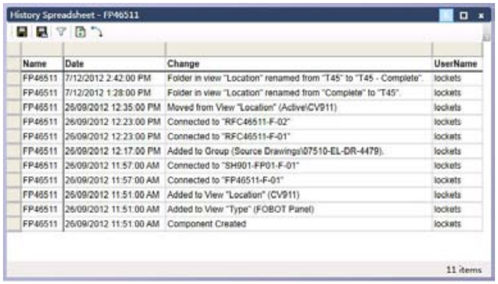


Figure 5
Kernel revision process

cated RFI folder can be created within DAD containing the problem to be solved. The site engineer can mark and describe the problem in DAD, which will be recorded by either a 'pdf' file or a snapshot of the selected area on the screen. A 'spreadsheet' can also be automatically generated containing all the information of those objects either in 'Excel' or 'pdf' file format. Then, the RFI will be sent to the design team by email using DAD. As the site engineer cannot continue their work without authorized information, the work relating to the error identified has to be stopped before correct information is issued. On receipt of the RFI folder, the design engineers can review and rectify the problem immediately.

If an error is identified, then the design can be readily modified within a DAD environment. A design engineer simply logins to the SIM model via DAD, reviews and then corrects the component that contains the error. As each piece of equipment in the real world has only one counterpart in the SIM, there is no need to correct the problem by revising those affected drawings. When a revision is complete, a new Kernel is generated and exported to the users for further application, as denoted in Figure 5. With the client portal, users can replace the old Kernel with the new one. All their private data saved can be retrieved and reused. As discussed above, DAD can simplify the procedure of raising and addressing RFIs. Through observations that have arisen from this research, ½ an-hour is needed to locate a problem and raise an RFI when using DAD. Using a pay rate of AUD$150/hour, the total man-hours to raise all the 103 RFIs will be 51½ hours at a cost of AUD$7725. Thus, a reduction of over 90% man-hours and cost can be achieved compared with using conventional CAD software. Noteworthy, for an experienced engineer, the average time spent to review an RFI and revise the SIM model would be a little as ¼ of an-hour.

DAD also provides a complete history log for each object (Figure 6). Any modification to a particular object, including the person who performed this activity, is automatically recorded in the system for future checking and verification. As a result, this function can be used to trace the revision history and assists engineers to compare previous and current design versions. However, in a drawing based design, revisions of drawings have to be maintained manually. All the revised versions of a drawing and its original copy must be categorized and archived so as to keep the design traceable.


History Spreadsheet - FP46511

Name	Date	Change	UserName
FP46511	7/12/2012 2:42:00 PM	Folder in view "Location" renamed from "T45" to "T45 - Complete".	lockets
FP46511	7/12/2012 1:28:00 PM	Folder in view "Location" renamed from "Complete" to "T45".	lockets
FP46511	26/09/2012 12:35:00 PM	Moved from View "Location" (Active\CV911)	lockets
FP46511	26/09/2012 12:23:00 PM	Connected to "RFC46511-F-02"	lockets
FP46511	26/09/2012 12:23:00 PM	Connected to "RFC46511-F-01"	lockets
FP46511	26/09/2012 12:17:00 PM	Added to Group (Source Drawings\07510-EL-DR-4479).	lockets
FP46511	26/09/2012 11:57:00 AM	Connected to "SH901-FP01-F-01"	lockets
FP46511	26/09/2012 11:57:00 AM	Connected to "FP46511-F-01"	lockets
FP46511	26/09/2012 11:51:00 AM	Added to View "Location" (CV911)	lockets
FP46511	26/09/2012 11:51:00 AM	Added to View "Type" (FOBOT Panel)	lockets
FP46511	26/09/2012 11:51:00 AM	Component Created	lockets

11 items

Figure 6
History spreadsheet

CONCLUSION

The graphical and written representations developed by engineers, for example, are typically represented in two dimensions (2D) and constructed using computer-aided-design (CAD). When a change is required to a 2D drawing, then the drawing and each corresponding view has to be manually updated. This can be a very time-consuming and costly process. Furthermore, as drawings are manually coordinated between views in 2D, there is a propensity for documentation errors to arise particularly in the design of complex E&I systems, which comprise of hundreds of drawings that are not to scale and have to be represented schematically. In such cases, information is often repeated on several drawings to connect each schematic together. Consequently, the time to prepare the schematics can be a lengthy and tedious process, especially as the design gradually emerges and individual documents are completed. Inconsistencies can manifest between the documents and therefore they must be re-edited and crosschecked before they can be issued for construction.

There is a proclivity for contractors to be supplied with incomplete, conflicting and erroneous documents. When a situation of this nature arises, the standard form of communication between the contractor and EPCM firm is to raise an RFI. The raising of an RFI can be a costly and adversely impact productivity for the contractor. Using a case study, errors, omissions and information redundancy contained in the 'As built' for a Stacker Conveyor were examined. A total of 449 errors and omissions were identified within 42 documents. In addition, 231 cables and components appeared once among the 42 documents; 86 cables and components appeared twice and 12 cables and components appeared three times. As a result of the errors, omissions and redundancy RFIs were raised. Retrospective analysis indicates that the indirect cost of raising the RFIs to the contractor was estimated to be 8.93% of the cost of the E&I contract. Noteworthy, the estimate is deemed to be conservative as it is based upon 'As Built' and not the 'For Construction' drawings, which is suggested to contain a higher rate of error proneness.

The findings presented have been based upon a single case study and therefore it is not possible to generalize the results that have been produced. Moreover, the inputs of the EPCM's design engineers were not solicited and therefore the times estimated to attend to the RFIs are estimates, though based on the advice provided by experienced industry professionals. Despite the limitations of using a single case, there is however a need to address the problems of errors, omissions and redundancy in design documentation. There needs to be a switch away from using traditional CAD documentation for E&I engineering, where a 1:n relationship exists, to a 1:1 object orientated SIM. It is demonstrated that the use of a SIM in the case example could provide significant improvement in cost reduction on identifying/raising the RFIs. Furthermore, the SIM that is presented is syntactically and semantically interoperable with a wide range of software solutions.

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