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Assessing the impact of RFIs in electrical and instrumentation engineering contracts

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Assessing the impact of RFIs in electrical and instrumentation engineering contracts

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Using a case study, errors, omissions and information redundancy contained in the electrical and instrumentation (E&I) 'As-built' drawings 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 thrice. As a result of the errors, omissions and redundancy, requests for information (RFIs) were required. Retrospective analysis indicates that the indirect cost of raising the RFIs to the contractor was estimated to be approximately 9% 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: documentation; errors; omissions; RFIs; system information model; productivity

1. Introduction

The design and construction of infrastructure, 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 design and engineering 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 the 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, Mohamed, and Wyatt 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, Hanna, and Whited (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, Tadt, and Whited (2012) suggest that RFIs are used to provide a systematic collection of the analysis and resolution of questions that arise before and during construction.

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The production of an RFI can be a time-consuming process and costly for a contractor. There have been a limited number of studies that have examined the nature of RFIs and how they can adversely impact the performance of a contractor (e.g. Tilley, Mohamed, and Wyatt 1997; Hanna, Tadt, and Whited 2012). In this article, the impact of documentation errors contained within 'As-built' electrical and instrumentation (E&I) contract for a Stacker Conveyor is examined. The costs associated with producing the RFIs as a result of the errors and omissions contained with the contract documentation are quantified. To reduce documentation errors and omissions and subsequent RFIs, it is suggested that a system information model (SIM) is used to design and document instrumentation, electrical and power installations.

Within the construction and engineering industry, building information modelling (BIM) is being adopted to improve the management of information throughout a project's life cycle. BIMs are typically created using an array of software applications, and integrated to form a single point of truth. Increasing emphasis has been placed on the development and integration of software packages for architectural, structural, heating ventilation and air conditioning and hydraulics. Such elements have scale and geometry, and therefore can be visualised within the BIM. However, E&I systems have no scale or geometry and cannot be visualised in a three-dimensional (3D) view, though cable trays and components can be modelled. As a result, there is a reliance on the use of computer-aided design (CAD) to detail the connection and relationship between components. While BIM is beginning to be widely adopted by engineers within the construction industry, within the energy and resources sector CAD remains the primary tool to draft and design E&I systems (Love et al. 2013). Whenever an error or omission is identified through the raising of an RFI, drawings produced in CAD need to be manually checked, modified and re-issued, which is a time-consuming and costly process. In addressing this issue, retrospective analysis of 'As-built' documentation is undertaken to determine the impact that RFIs can have within a project and examine how the design and engineering process for E&I systems can be made more effective and efficient.

The article is organised as follows. In Section 2, a review of studies that have examined the nature of RFIs is provided. In Section 3, utilising participatory action research (PAR), a case study is used to examine the 'As-built' documentation for E&I system for a Stacker Conveyor. Section 4 analyses the impact of the RFIs that emerged from the E&I contract as a result of errors and omissions. Section 5 introduces the concept of a SIM, which is a generic term used to describe the process of modelling complex systems using appropriate software and is akin to the development of a BIM. The advanced engineering software, *Dynamic Asset Documentation* (DAD), which has been developed based on the concept of a SIM, is used to examine the productivity gains that can be achieved by eliminating errors and omissions and therefore the number of RFIs raised. Conclusions and limitations of the study are presented in Section 6.

2. Request for information

Research examining the nature of RFIs in construction and engineering projects has been limited (e.g. Tilley, Mohamed, and Wyatt 1997; Tilley and McFallan 2000; Hanna, Tadt, and Whited 2012; Tadt, Hanna and Whited 2012), though there have numerous studies that have examined the quality of contract documentation as it can have an adverse impact on a project's performance and productivity (e.g. Andi and Minato 2003; Love, Edwards, and Smith 2006). Despite the dearth of research examining the impact of RFIs, Tilley, Mohamed, and Wyatt (1997) have suggested that as a project's size and complexity increase, the quality of documentation provided by engineers decreases. As a result, the number of RFIs issued by contractors tends to increase (Tilley, Mohamed, and Wyatt 1997). Furthermore, Tilley, Mohamed, and Wyatt (1997) have suggested

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that contract strategies may have an impact on the quality of documentation that is produced. Tilley and McFallan (2000) suggested that projects should be procured using traditional (design–bid–construct) approaches, as these are far less susceptible to documentation errors in comparison with those procured using non-traditional means, where design and construction are undertaken concurrently. However, there exists no empirical evidence to support the claims of Tilley and McFallan (2000), particularly the impact of RFIs on project cost and schedule. In fact, research has revealed that cost and time overruns do not significantly vary by project size, complexity and contract strategy adopted (Love et al. 2010; Lopez and Love 2012).

As projects increase in size, there is a propensity for design tasks to be undertaken concurrently, particularly in the case of large-scale infrastructure, resource and energy projects. Rather than adopting an 'over-the-wall' approach to design, whereby information is passed on to the next task when deemed complete, preliminary information is released earlier to the proceeding task (Evbuomwan and Anumba 1996). This approach is typically adopted to reduce design time and errors as well as to provide feedback to solve problems that may have manifested earlier (Love and Gunasekaran 1997). Using preliminary information in overlapping design tasks often leads to information changes, which arise due to evolutions in design. Eastman (1980) has asserted that the early release of information can cause unnecessary rework due to data redundancy and therefore increase the time and effort to prepare for the release of information, as checks and quality assurance processes need to be implemented. Furthermore, Terwiesch, Loch, and Meyer (2002) revealed that up to 50% of total engineering capacity is spent in resolving rework issues as a result of early information release. Arundachawat et al. (2009) contended that a major source of rework is the updating of preliminary information.

The updating of preliminary information can be a lengthy process as the relevant information is likely to be contained within several documents (n). Fundamentally, there is a 1:n relationship, where n is unknown (i.e. an object will appear on many drawings). As noted above, this becomes more of a problematic issue when drawings generated using CAD need to be updated once they have been issued for construction and errors, omissions and conflicts arise as a result of RFIs. Thus, as documentation evolves, it is not often possible to determine those that contain the same or related information. Accordingly, documents need to be constantly checked when an amendment occurs. Information that is produced and is required on several drawings must be identical so as to avoid the need for further clarification.

A response to an RFI needs to be provided on a timely basis so as not to impact a project's schedule (Tilley 2005; Love, Edwards, and Smith 2006). RFIs can be time-sensitive to resolve, yet the responding party needs to make a significant effort to produce an accurate response on a timely basis. A number of issues, however, can impact the time it takes to respond to an RFI. For example, staffs who were originally involved in the design having intricate tacit knowledge of the project may have left the organisation, been allocated to another project or be on leave/holiday. As a result, an alternative or new engineer will be required to attend to the RFI that has been raised.

Site engineers rely on complete and accurate documentation to schedule and complete the works that their organisation is contractually obliged to undertake. The contractor's site engineer has to be able to determine what information is needed to undertake the works. As a result, RFIs are generated to address issues that are identified. RFIs that require a 'yes' or 'no' answer should be avoided (Hanna, Tadt, and Whited 2012; Tadt, Hanna and Whited 2012). Furthermore, RFIs should not be used to address minor questions, but instead focus on addressing significant issues that may impact cost and schedule (Tadt, Hanna and Whited 2012). Matthews (2005) states that RFIs are typically used when:

- necessary information appears to be missing from the design drawings/schematics or specifications, or where information contained within them appears incomplete;

- the contractor seeks clarification of the design drawings/schematics or specifications;
- discrepancies are found within the design drawings/schematics, such as conflicting information between plans and details or between drawings and specifications;
- the contractor requests permission to use alternative materials or products. Depending on the nature of the request, this could be interpreted as request for substitution and could be subject to other provisions of the contract documents;
- the contractor seeks an alternative method to resolve conflict issues; and
- it is required to confirm verbal understandings between an architect/engineer and the contractor related to any of the foregoing.

In contrast to Tilley, Mohamed, and Wyatt (1997) and Hanna, Tadt, and Whited (2012), the raising of an RFI is not necessarily a good measure of documentation quality. For example, an engineer raising an RFI may not understand the drawings due to their inexperience, or they may be reluctant to spend time sourcing the information from the documentation provided. Furthermore, a contractor may raise an RFI to acquire additional time to perform works.

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2.1. *RFI process*

In the case of an Engineering Procurement Construction Management (EPCM) mining project, the process of raising an RFI commences with the contractor's site engineer identifying a specific problem within 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 either can be a simple verbal clarification or may be confined to the site or it may involve revision of the contract documents to eliminate an error or omission.

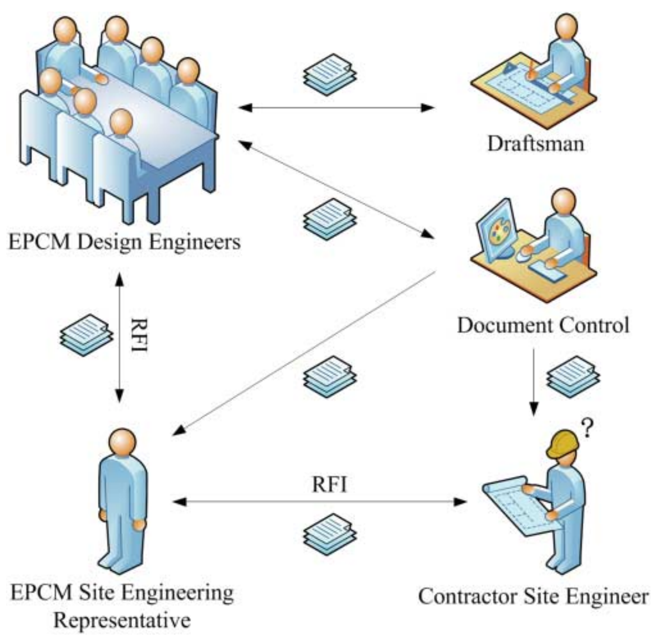

Figure 1. RFI process.

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If contract documents need to be revised, a draughtsman 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).

3. Research approach

As previously mentioned, there has been limited research that has sought to examine the impact of documentation errors and the subsequent RFIs that may rise, particularly in the context of E&I contracts. Many organisations have been 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 construction and engineering industry (Love, Edwards, and Irani 2008). Active engagements from industry professionals who have intricate knowledge of the problem are needed to tackle this problem. With this in mind, a case study that utilises a PAR approach was adopted (Peters and Robinson 1984; Baskerville 1997; Smith et al. 2010). In brief, PAR is (Susman and Evered 1978):

- participatory;
- cooperative, engaging organisational 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 organisation 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 organisation (Baskerville 1997; Smith et al. 2010). As practitioner involvement was required, they were treated as both subjects and co-researchers. By adopting this approach, theory related to design error and practice acted in congruence.

3.1. *Case selection*

Working in close collaboration with the participating organisation, it was decided that a case study would be required to quantify documentation errors and their impact on productivity. The organisation 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's extent and to work through new issues that may have potentially arisen. The participating organisation had been asked to convert all CAD generated electrical 'As-built' drawings for a port facility into a digital SIM using software DAD 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.

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3.2. *Data collection*

Triangulation formed the basis for the data collection, which took place at the offices of the participating E&I organisation. Triangulation involves the use of multiple research methods and/or measures of a phenomenon, in order to overcome problems of bias and validity (Taylor and Bogdan 1984; Denzin 1988). The data collection methods used in this research were unstructured interviews and documentary sources (e.g. drawings, contract documents), which were undertaken over a six-month period. In addition to the active day-to-day involvement of the participating organisation with a researcher in their offices, another researcher who was not positioned within the office environment also undertook unstructured interviews with key personnel. This was undertaken to provide additional context to the problem and provide validity to the research process.

Unstructured interviews were used as primary and secondary sources of data. As a primary source, they were used to determine the issues influencing the production and use of documentation. As a secondary source, information gathered from documentary sources was confirmed. The use of unstructured interviews enabled the interviewer to act as a research tool and learn about matters that could not be directly observed (Robson 1993). Interviews were undertaken with the Managing Director and Business Development Manager and varied in length from 30 minutes to two hours. The interviewees have extensive experience in designing and implementing E&I contracts. For example, the Managing Director, who was actively involved in the research, has over 40 years' industrial experience. Moreover, engineers involved in the research all had more than 10 years' experience and had worked on an array of projects. Interviews were open to stimulate conversation and break down any barriers that may have existed between the interviewer and interviewee. The interviewee was allowed to talk freely without interruption or intervention, so as to acquire a clear picture of their perspective. Note taking was generally used as the medium to record the interviews.

4. Case study

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, 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 tonnes of iron were mined, railed and shipped to customers in China. This increased to 40 million tonnes in 2011, and it

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Figure 2. Stacker Conveyor.
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is anticipated that this will increase to 155 tonnes 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 and can be seen in Figure 2. 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 modelled into a SIM through the application of DAD. As modelling progressed, a plethora of errors were identified within the ‘As-built’ documentation. The errors were classified as missing labels, labelling mistakes, inconsistent labelling, 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.

4.1. *Assessing the impact of documentation error*

A total 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 (e.g. Managing Director, project engineers, site engineers) 230 cables (39% of all the cables) and 101 components (21.54% of all the components) were identified with errors and omissions, which were distributed among 42 (39.25%) of the 107 documents. A total of 449

Table 1. Distribution of errors and omissions.

Drawing number	Number of errors and omissions	Times modified ($Revs_i$)	Man-hours (work time)	Cost ($150/hour)
04900-EL-DR-2001_6	44	10	60	9000
04900-EL-DR-2002_6	14	6	36	5400
04900-EL-DR-2003_5	22	8	48	7200
04900-EL-DR-2004_3	13	6	36	5400
04900-EL-DR-2570_4	4	3	18	2700
04900-EL-DR-2571_4	23	6	36	5400
04900-EL-DR-2572_4	6	2	12	1800
04900-EL-DR-2576_4	11	2	12	1800
04900-EL-DR-2580_2	6	1	6	900
04900-EL-DR-2581_2	12	2	12	1800
07510-EL-DR-2352_5	3	1	6	900
07510-EL-DR-2452	17	2	12	1800
07510-EL-DR-2652_7	42	1	6	900
07510-EL-DR-2656_8	15	1	6	900
07510-EL-DR-3361	1	1	6	900
07510-EL-DR-3365_5	1	1	6	900
07510-EL-DR-3366	4	2	12	1800
07510-EL-DR-3371	1	1	6	900
07510-EL-DR-4428	6	3	18	2700
07510-EL-DR-4429	6	3	18	2700
07510-EL-DR-4430	7	3	18	2700
07510-EL-DR-4474_2	8	2	12	1800
07510-EL-DR-4482	1	1	6	900
07510-EL-DR-4483	9	2	12	1800
07510-EL-DR-4484	1	0	0	0
07510-EL-DR-4485	9	2	12	1800
07510-EL-DR-4486	1	0	0	0
07510-EL-DR-4487	8	2	12	1800
07510-EL-DR-4489	8	2	12	1800
07510-EL-DR-4493	1	2	12	1800
07510-EL-DR-4494	1	1	6	900
07510-EL-DR-4497	2	1	6	900
07510-EL-DR-5654_2	1	1	6	900
07510-EL-DR-5655_2	10	2	12	1800
07510-EL-DR-5657_2	3	2	12	1800
07510-EL-DR-8433_3	2	1	6	900
07510-EL-DR-8475_3	2	1	6	900
07510-EL-DR-8476_3	2	1	6	900
07510-EL-DR-8477_3	3	1	6	900
07510-EL-DR-8482_5	3	1	6	900
07510-EL-DR-8552_3	2	1	6	900
Cable schedule	114	12	72	10,800
Total	**449**	**103**	**618**	**92,700**

Table 2. The number of times cables and components are shown in documents.

Times	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%)

errors and omissions were identified. The distribution of these errors and omissions can be seen in Table 1. Moreover, a considerable amount of information redundancy was found within the cables and components, which were identified with errors and omissions (Table 2). It can be seen from Table 2 that 231 cables and components appeared once among the 42 documents; 86 cables and components appeared twice and 12 cables and components appeared thrice. One cable appeared four times and one component appeared six times. Redundancy, in some cases,

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may provide additional information for engineers to understand drawings. Such redundancy can, however, hinder engineers' 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 labelled 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 is also identified (refer to Table 1, third column). For example, in the case of drawing 04900-EL-DR-2001_6, 44 errors and omissions were identified, which required this drawing to be modified 10 times (Table 1). A description of the errors and omissions in drawing 04900-EL-DR-2001_6 can be found in Table 3. With the assistance of several engineers from the participating organisation, 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. This estimate was derived through extensive discussions with engineers who had been working on the project identified in this article. Assuming that the pay rate is AUD\$150/hour for site engineer (which is currently the market rate), the generation of each RFI would cost the contractor \$900. Thus, the cost for raising the RFIs can be calculated using the following formula:

$$C = \sum_{i=1}^{n} \mathrm{Revs}_i \times T \times R, \quad i = 1, \ldots, n, \tag{1}$$

where C is the total cost; Revs_i the number of RFI on each drawing, $i = 1, \ldots, n$; T the man-hours consumed on raising each RFI; R the pay rate of the site engineer and n the number of documents.

In this study, we assume that $T = 6$ hours and $R =$ AUD\$150/hour. In the case of drawing 04900-EL-DR-2001_6, all the errors and omissions were categorised into 10 RFIs. Thus if we apply $n = 1$, and $\mathrm{Revs}_1 = 10$ to Equation (1), it can be calculated that 60 man-hours will be consumed and therefore costing AUD\$9000 to raise RFIs for this schematic. Similarly, it can be seen that 23 errors and omissions were identified in drawing 04900-EL-DR-2571_4 (Figure 3). A description of the errors and omissions in drawing 04900-EL-DR-2571_4 can be found in Table 3. These errors and omissions were categorised into six RFIs. Using Equation (1), a total of 36 man-hours and AUD\$5400 is required to raise the RFIs for this drawing. Similarly, a total 618 man-hours was required to raise the 103 RFIs within the 42 documents at a cost of AUD\$92700. The total contract value for the electrical instrumentation and control system design and documentation is AUD\$20.76 million. The documents in this study account for 5% of all the documents of the electrical-related contract. Assume the documents are of the similar quality, then the cost for raising RFIs accounts for approximately 9% of the cost of the electrical-related contract. It is worth noting that 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

Table 3. Description of errors and omissions.

	Error and omission types													
	Labelling mistake		Inconsistent labelling		Omission from drawing		Omission from cable schedule		Missing label		Wrong design		Incorrect connection	
Drawing no.	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

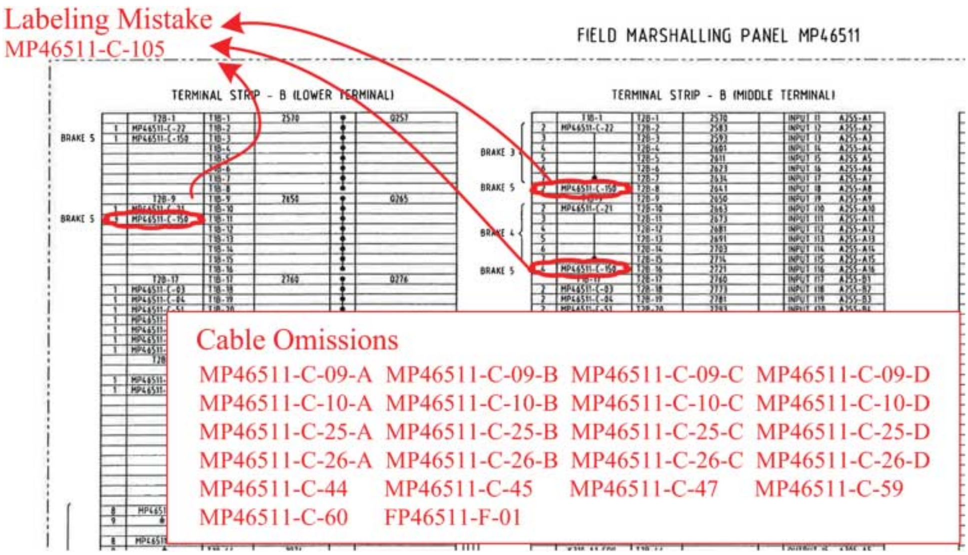

Figure 3. Example of errors and omissions.

an RFI represents a small proportion of the total indirect costs of RFIs. In practice, once an RFI is raised, the engineers on-site may not be able to continue their work until the correct information has been issued. Interviews revealed that the steps to attend to an RFI typically involve the:

(1) time to identify if there is a real issue – 2–4 hours;
(2) time to identify the drawings to be revised, as a result, assuming the revised information will typically affect, say three drawings – 1–2 hours;
(3) time to mark up the three drawings – 2 hours;
(4) time to revise the three drawings – 2–6 hours;
(5) time to review – 1–2 hours;
(6) time for various document handling activities – 2 hours.

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 address steps 1–3. Steps 4 and 5 each will also need a day, and finally two days are required to complete step 6. It is worth noting that 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.

Errors and omissions in documentation are a common problem in construction and engineering projects. Numerous studies have indicated that errors and omissions are key contributors to cost and schedule overruns (e.g. Love, Li, and Mandal 1999; Chang 2002; Frimpong, Oluwoye, and Crawford 2003; Han, Love, Pena-Mora 2013) and disputes (Kumaraswamy 1997). The findings presented in this study provide a detailed contextual backdrop about the nature of the problem that is embedded within the documentation process for E&I contracts. Fundamental changes to the documentation process are required if errors, omission and redundancy are to be eliminated and productivity improvements realised. In the next section of the article, an alternative to the use of CAD for designing and documenting E&I contracts is proposed.

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5. 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 4. In this selected drawing, a total of 29 reference drawing numbers were identified. Two of these references were mistakenly labelled. 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. Essentially, a SIM is a generic term used to describe the process of modelling complex systems using appropriate software. A SIM is a digital representation of the connected system, such as electrical control, or power and communication systems. When SIM is applied to design a connected system, all physical equipment and the associated connections to be constructed can be modelled in a database. Each object is only modelled once.

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 modelled 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

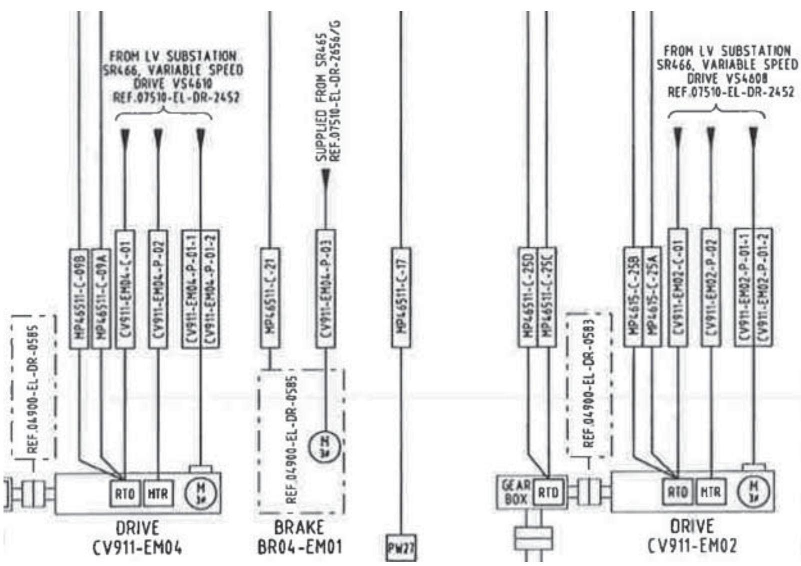

Figure 4. Reference information.

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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 life cycle of E&I systems and is specifically useful for asset managers as it enables information to be stored in a single digital model. DAD offers users with greater flexibility to customise their designs. Attributes, such as material types, the 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 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 modelled 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 5). A DAD portal, which is designed based 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 authorisation 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 authorisation to change the design.

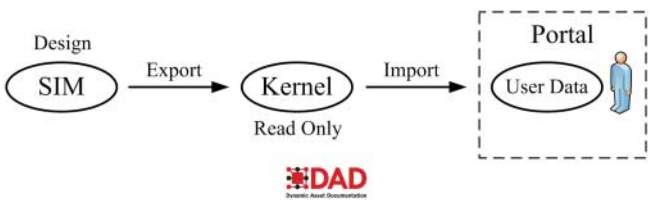

Figure 5. DAD portal/SIM relationship.

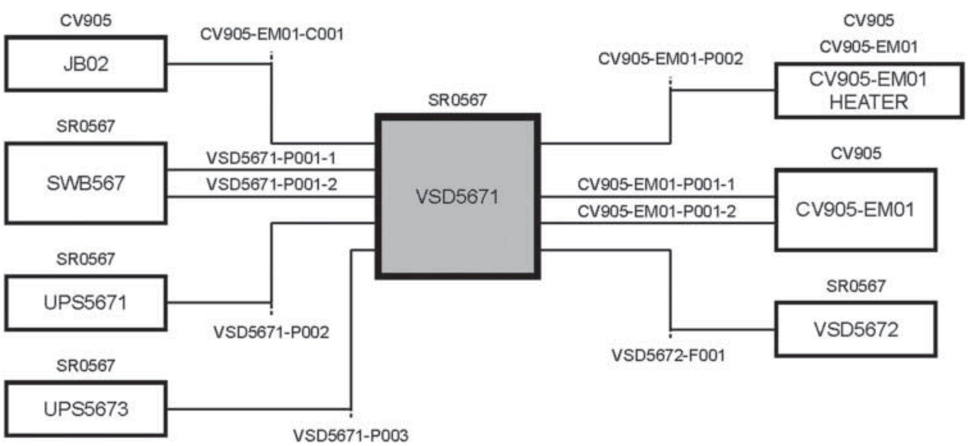

Figure 6. Example of a connection.

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As the information modelled 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 6). 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 dedicated 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 in '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 authorised 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 the 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 7. 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, half 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 51 1/2 hours at a cost of AUD\$7725. Thus, a reduction of 91.67% man-hours and cost can be achieved compared with using conventional CAD software. It is worth noting that, for an experienced engineer, the average time spent to review an RFI and revise the SIM model would be as little as 15 minutes.

DAD also provides a complete history log for each object (Figure 8). 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

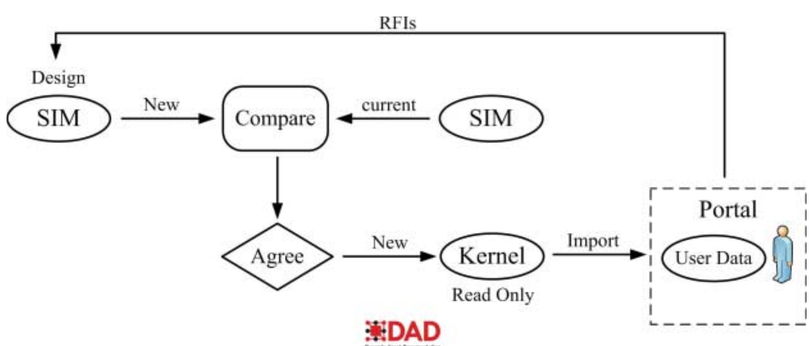
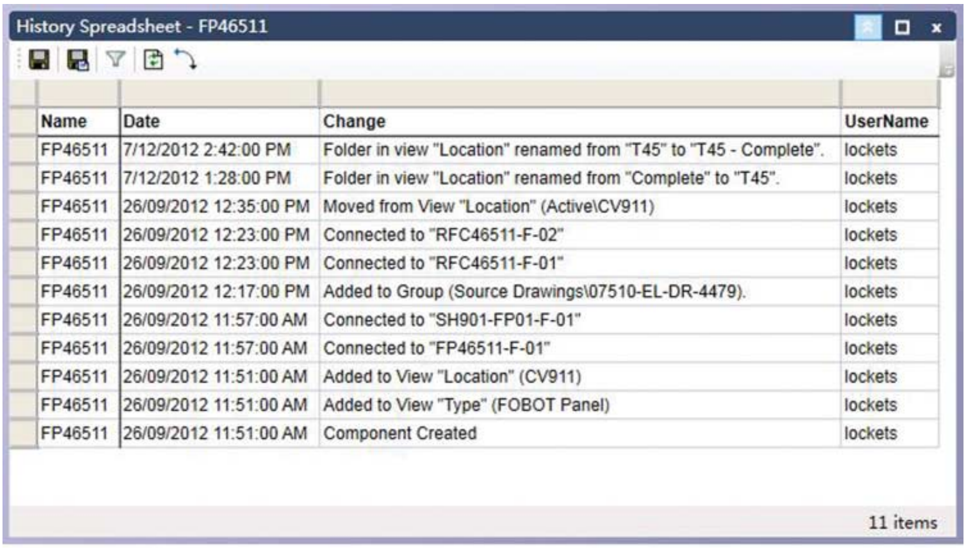


Figure 7. Kernel revision process.



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 8. History spreadsheet.

versions of a drawing and its original copy must be categorised and archived so as to keep the design traceable.

As noted above, the basis of using a SIM is its innate ability to design and model a digital 1:1 realisation of the real world in a project. By using SIM/DAD, electrical engineering drawings can be eliminated throughout a project's life cycle. Many propriety software packages that have been developed to design and document electrical systems are reliant on producing CAD enabled drawings. Projects adopting CAD drawings will invariably assume the traditional mode for design, documentation, procurement, construction and maintenance, and thus the likelihood of errors and omissions occurring remains a pervasive issue. A comparison of the traditional mode of documentation and SIM/DAD is presented in Table 4. Additional benefits of using SIM/DAD include (Love, Matthews, and Zhou, forthcoming):

- instant access to design data;
- appending information to the SIM to establish a complete picture of all the system items;
- storage of all related files such as test reports, punch lists, pictures;
- efficient and effective measurement and reporting of progress on-site work and costs;
- an accurate and realistic view of a project's status at any point in time.

6. Conclusion

The graphical and written representations developed by engineers, for example, are typically represented in two dimensions (2D) and constructed using CAD. When a change is required to a 2D drawing, then the drawing and each corresponding view have 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 hundreds of component 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

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Table 4. Comparisons of traditional CAD- and SIM/DAD-enabled documentation.

Traditional	SIM
The system is described on multiple drawings, lists and other documents	The SIM describes the system
The representation is complex and hard to follow	The information in the SIM is structured to match the system
Materials and work must be found on the drawings and 'taken off'	All materials and work are listed in the SIM
Drawings present information in fixed formats	Users can extract data to make their own documentation on demand
Each object is typically shown on six drawings, and sometimes on many more	Each object in the system is represented by one software object
Connections are shown as fixed shapes and lines, circuits may cover multiple drawings	Connections link components in the model just like they do in the real system
Drawings contain errors and omissions. Users cannot distinguish between these and simple inconsistencies between the drawings	Errors and omissions can be reduced significantly as information is stored and expressed consistently
Finding information is slow	Finding information is fast
User may interpret the drawings differently	This risk is greatly reduced
Every construction activity may use a different application	Every activity can be estimated, measured and reported in DAD
Document control is complicated. Information traceability among documents is low	The SIM documents the design which can be used for the entire life cycle of the project

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 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 thrice. 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 approximately 9% of the cost of the E&I contract. It is worth noting that 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 generalise the results. 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. The research has provided evidence that there needs to be a shift away from CAD to design and document instrumentation and electrical engineering systems. A new SIM, which can be incorporated into a BIM, has been developed and can provide significant savings in productivity.

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While benefits of using a SIM enabled by DAD are clearly evident, it does have a number of limitations. For example, within DAD, connections between different components are illustrated using non-directional lines, which are not sufficient to describe mono-directional flows. To be more intuitive, it would be helpful that arrows can be shown on the lines where flows are only permitted to travel in a single direction. Interfacing between DAD and many other miscellaneous 3D applications is also being developed, which will enable DAD to co-operate with the advanced 3D graphic engines so as to explore its applications in variety areas.

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